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Active integration of electric vehicles in the distribution network – theory, modelling and practice

Aktiv integration af elektriske biler i distributionsnettet – teori, modellering og praksis

Ph.D. Thesis, by Katarina Knezović

Supervisors:
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DTU - Technical University of Denmark, Roskilde - December 2016

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As the saying goes, the Stone Age did not end because we ran out of stones; we transitioned to better solutions.

— Steven Chu

To my parents

Preface

This thesis is prepared at the Department of Electrical Engineering of the Technical University of Denmark in partial fulfilment of the requirements for acquiring the degree of Doctor of Philosophy in Engineering. The Ph.D. project was funded by the Danish Research Project "NIKOLA - Intelligent Electric Vehicle Integration" under ForskEL kontrakt nr. 2013-1-12088.

The dissertation summarizes the work carried out by the author during her Ph.D. project. It started on 14th of December 2013, and it was completed on 14th December 2016. During this period, she had been hired by Technical University of Denmark as a Ph.D. student at the Center for Electric Power and Energy (CEE), DTU Electrical Engineering.

The thesis is composed of 7 chapters, 2 appendices, and 8 attached scientific papers, 6 of which have been peer-reviewed and published, whereas the remaining 2 are currently under the reviewing process.

Katarina Knezović

Katarina Knezović
December 2016

Acknowledgements

During the last few years, I owe a debt of gratitude to a lot of people who have brought me to this stage. It was a period of great personal growth, and I would like to take this opportunity to show my appreciation to all who have contributed to it.

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Finally, I am particularly grateful to Petar, the man who enlightens my days, who shared with me both the happy and the stressful periods of my PhD, and without whose support I would not have reached this far. Thank you for putting up with me. :)

Katarina

Abstract

Increasing environmental concerns are driving an evolution of the energy system, in which the electrification of the transport sector is considered to be a crucial element. Successful electric vehicle (EV) introduction potentially allows the reduction of CO_2 emissions, but also represents a substantial challenge for the power system, especially at the distribution level where high EV concentrations cause various detrimental effects. More specifically, the low-voltage grid operation becomes challenging since uncontrolled EV charging typically coincides with the peak residential consumption, resulting in a considerable peak load and severe voltage deviations. However, EVs hold potential for providing services beyond transportation and, thus, should not be considered merely as passive loads. If managed properly, EVs become flexible resources which can enhance the grid operation, making them an attractive asset for the distribution system operator (DSO).

This thesis investigates how EVs can mitigate the self-induced adverse effects and actively help the distribution grid operation, either autonomously or in coordination, e.g., with an EV aggregator. The general framework for EV integration is presented, including the contemporary technology, the relevant stakeholders and the most important challenges. EV flexibility provision to DSOs is studied both from the technical and the regulatory perspective in order to identify the barriers for active EV involvement, and provide a set of policy recommendations for overcoming them.

The potential benefits and drawbacks of introducing EV reactive power capability for voltage support are analysed. A decentralised reactive power control is proposed which can, given the appropriate equipment sizing, support the distribution grid independent of the active power modulation. Such an autonomous controller relies only on the local voltage measurement and can be implemented in the short-term future by using the inherent functionality of the EV power electronics. The impact of the proposed control is investigated on a Danish low-voltage grid with the assessment of grid parameters in various conditions.

A multi-objective framework is developed for the optimal EV day-ahead scheduling in unbalanced distribution grids. The framework assesses the trade-off between the DSO's and the EV aggregator's economic concerns, and uses a fuzzy-satisfying method to balance the interest of both parties. Moreover, the impact of the additional EV reactive power support is analysed when EVs are the only flexible resource, as well as when combined with other demand response.

Experimental activities were conducted to validate the technical feasibility of contemporary EVs to provide flexibility services, both in a laboratory environment and in a real distribution grid. The emphasis was put on assessing several EV parameters, such as EV responsiveness and EV accuracy, to provide basis for future theoretical work, as well as recommendations for improvement.

Overall, it is shown that EVs can actively support the distribution grid operation, but there is a critical gap between the political sustainability plans, and the implemented standards and regulatory framework. Moreover, it is demonstrated that DSOs can benefit from the potential EV reactive power control without substantially influencing the losses or the EV aggregator's cost. Finally, it is proven that series-produced EVs are capable of providing various flexibility services within several seconds, but their accuracy might arise as a topic of concern.

Resumé

Den øgede fokus på klimaproblemer fører til en udvikling i energisystemet, hvor elektrificering af transportsektoren betragtes som et essentielt element. En succesfuld introduktion af el-biler kan potentielt fremme reduktionen af CO_2 udledning, men kan samtidig være en udfordring for el-nettet, specielt i distributionsnettet, hvor en høj andel af el-biler kan forårsage overbelastnings situtationer. Mere specifikt bliver driften af lavspændingsnettet mere udfordrende, da ukontrolleret opladning af el-biler typisk forventes samtidigt med forbrugernes øvrige spidsbelastning, hvilket kan fører til en betydelig overbelastning af nettet og dermed alvorlige spændingsafvigelser. Dog har el-biler potentialet til at levere ydelser ud over transport og skal derfor ikke betragtes alene som et passivt element i nettet. Med en korrekt styring bliver el-biler fleksible ressourcer, som kan styrke driften af nettet, hvilket gør dem til et attraktivt aktiv for netoperatøren.

Denne afhandling udforsker, hvorledes el-biler kan benyttes til at dæmpe de selvforårsagede og uønskede effekter på nettet og istedet aktivt hjælpe netoperatøren, enten autonomt eller koordineret, f.eks. gennem en el-bilsaggregator. Rammerne for integration af el-biler præsenteres, herunder den nuværende teknologi, de relevante aktører og de vigtigste udfordringer. El-bilernes fleksibilitet i forhold til netoperatøren undersøges både fra et teknisk og et regulatorisk perspektiv, så barriererne for el-biler aktive engagement kan identificeres og overvindes gennem regulatoriske anbefalinger.

De potentiele fordele og ulemper, der følger af at introducere understøtning for håntering af reaktiv effekt i el-biler undersøges. En decentral styring af reaktiv effekt foreslås, som, givet en korrekt dimensionering af komponenter, kan understøtte distributionsnettet uafhængigt af variationer i den aktive effekt. Sådan en autonom styring afhænger kun af lokale spændingsmålinger og kan implementeres i den nære fremtid ved at udnytte den indbyggede funktionalitet i el-bilernes effektelektronik. Indvirkningen af den foreslåede styring er studeret i et virkeligt dansk lavspændingsnet ved at evaluere netparametrene under forskellige forhold.

En multi-objektiv optimeringsmodel udvikles med henblik på en optimal daglig planlægning af opladning i et ubalanceret distributionsnet. Denne optimeringsmodel afvejer netoperatørens og el-bilaggregatorens økonomiske interesser, og bruger en *fuzzy-satisfying* metode til at balancere begge parters økonomiske interesser. Derudover undersøges el-bilens understøtning af reaktiv effekt når denne er den eneste resurse, samt når når den kombineres med andre former for forbrugsstyring.

Der er blevet udført eksperimentelle aktiviteter for at validere de tekniske muligheder i nyere el-biler for at tilbyde fleksibilitetsydelser, både i et laboratoriemiljø og i et virkeligt distributionsnet. Der blev lagt vægt på at bedømme adskillige el-bilsparametre, såsom responstid og præcission, for at bygge et grundlag for fremtidig teoretisk arbejde, såvel som anbefalinger af forbedringer.

Overordnet, vises det at el-biler aktivt kan hjælpe driften af distributionsnettet. Der er dog en betragtelig kløft mellem de politiske grønne planer, de implementerede standarder og de regulatoriske rammer. Desuden, demonstreres at netoperatøren kan drage fordel af el-bilernes mulighed for styring af reaktiveffekt uden at det nævneværdigt påvirker tab eller omkostninger til en aggregator. Til sidst, vises at masseproduceret el-biler er i stand til at tilbyde forskellige fleksibilitetsydelser med få sekunders responstid, men vil det være nødvendigt med en øget nøjagtighed.

Table of Contents

Collection of relevant publications

Chapter 1
Introduction

1.1 On the justification of research in electric vehicles

There is no scientific doubt that climate change is a fact and that global warming has a considerable negative impact on the society [1]. Not only does the abundant use of fossil fuels as a primary energy resource lead to a global temperature increase, it also leads to a global mortality increase due to substantial air pollution. In order to tackle these issues and face up to the challenge of sustainable development, in 2008 the European Commission published the climate and energy package [2], which is commonly referred to as "20-20-20" agreement. The main objectives of this agreement are to reduce at least 20% of CO_2 emissions as well as to increase the production of renewable energy sources (RES) by at least 20% until 2020. The global sustainability effort has been extended with the Paris climate conference (COP21) agreement [3] signed by 195 countries in 2015. It is the first-ever legally binding global climate deal, which will enter into force in 2020, with the goal to limit the global warming below 2°C. On the other hand, the Danish government has set an interim goal to reduce the national CO_2 emissions by 40% in 2020 and to reach the 100% renewable energy target in 2050 [4]. This is aimed to be achieved in three intermediate steps: (1) covering 50% of electricity consumption with wind energy by 2020, (2) covering 100% of electricity and heating supply with renewable resources by 2035, and (3) being completely fossil fuel independent by 2050. Since transport accounts for approximately 25% of global CO_2 emissions [5], the electrification of the transport sector is considered to be a crucial element in achieving both the Danish and the global objectives [6].

Successful electric vehicle (EV) introduction represents not only a challenge of daunting proportions for the power system, but also an exceptional potential for the society. The use of electricity as a transportation "fuel" allows to reduce the dependency of the transport section upon fossil fuels [7, 8], its CO_2 emissions [9] and local pollutant emissions [10]. However, EVs represent a considerably high load for the power system and should not be considered only as passive assets, but rather as an integrated active resource. EVs could adapt their electricity consumption patterns to improve the grid conditions and help further integration of renewable energy resources [11]. The synergy between EVs and RES allows the simultaneous reduction of fossil-fuel dependency in both the electricity generation and the transportation sector. Still, achieving such ambitious plans means there are only a few decades left to push for technological developments in order to fundamentally change the existing electric power system.

To understand the relevance of this research project, it is important to firstly define emerging changes in the power system and present the challenges in the new power system framework. The following subsections give a general overview of the expected changes and introduce the background of this thesis.

1.1.1 Historical power system operation

Historically, the electric power system shown in Figure 1.1 has been established as a government controlled monopoly with a full control and ownership over the complete value chain. It was designed to follow the consumption by producing electricity at large generating units, and delivering it to the consumers through the transmission and the distribution grid, sometimes over considerably large distances. In the late 1980s and early 1990s, the state-owned companies in many countries were privatised and liberalisation was introduced to the electricity sector as well [12]. This process introduced competition with respect to the electricity generation and retail, yet the transmission and distribution grid operation remained regulated monopolies due to the system's centralised nature. Hence, among the most important entities in the contemporary power system are the **transmission system operator** (TSO) and the **distribution system operator** (DSO).

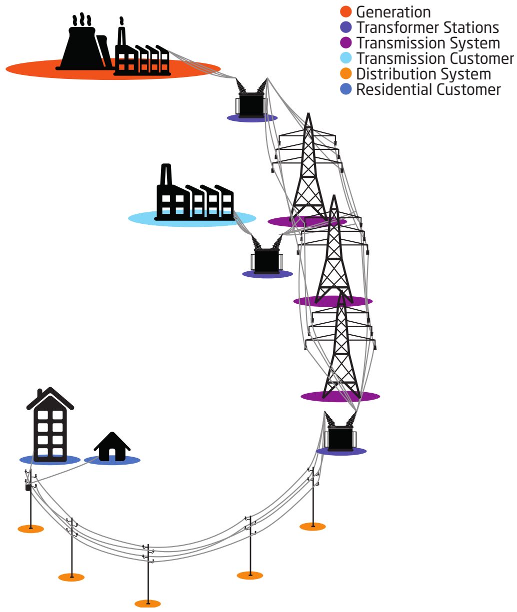

Figure 1.1: The traditional electric power system. Source: [13].

TSO is the entity responsible for keeping the production balanced with the consumption and ensuring the secure operation of the transmission system. In the power system, the supply and the demand must be kept in balance at all times, with the system frequency commonly used as metrics for evaluating the imbalance. System imbalances can have two causes: (1) expected imbalances due to deviations between the planned generation and actual demand, or (2) unexpected imbalances due to system contingency such as generation or line failure. In order to deal with these imbalances in daily operation, the TSO must procure ancillary services which maintain the power system operating at a nominal frequency. The terminology and classification of frequency ancillary services varies from country to country, but can generally be divided into primary, secondary and tertiary control.

Primary frequency control is the fastest reserve (in seconds range) which must ensure that the balance between the consumption and production is restored. The frequency is stabilised close to the nominal frequency, but still deviating from it. These reserves are usually automatic and provided by large generators equipped with droop control capabilities, in which the power output change is proportional to the locally measured frequency. On the other hand, secondary frequency control is a slower ancillary service (in seconds to minutes range) which takes over for the primary frequency control and restores the frequency to the nominal value by controlling the output of participating resources. Secondary frequency regulation is usually provided by generation or consumption units which respond to the central TSO signal. Finally, tertiary reserves are usually manual reserves activated after 15 minutes to relieve the secondary control.

The peculiarity of the Danish power system is that it belongs to two synchronous regions, namely DK1 and DK2, as seen in Figure 1.2. DK1 includes western Denmark which is connected to the continental Europe and follows the requirements regulated by the ENTSO-E Continental Europe Operation Handbook [14] where the frequency ancillary services are divided into primary, secondary and tertiary (manual) reserves. Contrary to DK1, DK2 is connected to the Nordic synchronous region and operates according to the Joint Nordic System Operation Agreement [15] with a different terminology. Here, the frequency ancillary services are categorised as frequency-controlled normal (FCN) operation reserves, frequency-controlled disturbance (FCD) reserves, and manual reserves. Both FCN and FCD reserves can be mapped to primary frequency reserves as they require fast response which stabilises the frequency by balancing the supply and the demand. Hence, traditional secondary frequency reserves do not exist in the Nordic classification. Table 1.1 summarizes the technical conditions for each of the required services defined by the Danish TSO Energinet.dk [16].

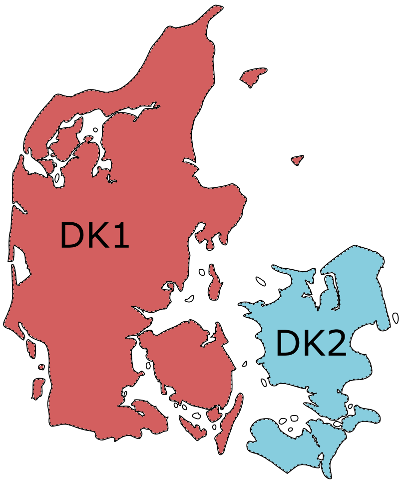

Figure 1.2: Danish power system belongs to two synchronous regions - DK1 to continental Europe and DK2 to the Nordic region.

Table 1.1: Overview of frequency ancillary services required by the Danish TSO Energinet.dk [16].

Area	Service	Response time	Deviation range	Dead-band	Duration
DK1	primary reserve	50% within 15 s; 100% within 30 s	50±0.2 Hz	±20 mHz	max 15 min
	secondary reserve	100% within 15 min	-	-	continuous
	manual reserve	100% within 15 min of activation	-	-	-
DK2	FCN reserve	100% within 150 s	50±0.1 Hz	-	continuous
	FCD reserve	50% within 5 s; 100% within 30 s	49.5-49.9 Hz	-	continuous
	manual reserve	100% within 15 min of activation	-	-	-

On the other hand, *DSO* is the entity concerned about the efficient and reliable electric power delivery to the end customer. Its main tasks include maintaining the distribution network and ensuring the power quality according to the international and national regulations. Whereas in Europe the TSO is usually unique for the whole transmission system of a country, the distribution sector is characterised by a high diversity of DSOs. They differ both in number and the magnitude of the corresponding control areas. Some operate large sets of distribution grids over several regions while others operate a limited amount of feeders with a small number of customers. In order to provide a brief overview of the current system complexity, Table 1.2 summarizes the number of DSOs for several European countries, including Denmark. As seen from the values, the DSO number is often large, even when there is a dominant DSO which is responsible for most of the distribution feeders.

Table 1.2: Active DSOs in selected European countries, adapted from [17, 18].

Country	**Total DSOs**	**DSOs with <100000 customers**	**Dominant DSO (>80% of distributed power)**
Denmark	76	68	n/a
France	148	143	ERDF
Germany	883	780	n/a
Italy	151	124	ENEL Distribuzione
Ireland	1	0	ESB Networks

However, essentially everywhere, all DSOs have historically operated grids with radial topology and unidirectional flows, where consumption was largely inflexible, so grid security issues could be dealt with by planning and network development methods [19]. As a matter of fact, DSO activities are mainly focused on long term planning and design rather than on real-time operation. In relation to the distribution grid operation, DSOs' main concerns include solving grid contingencies as classified by constraint type in Figure 1.3. In this context, they mainly focus on voltage regulation and congestion management.

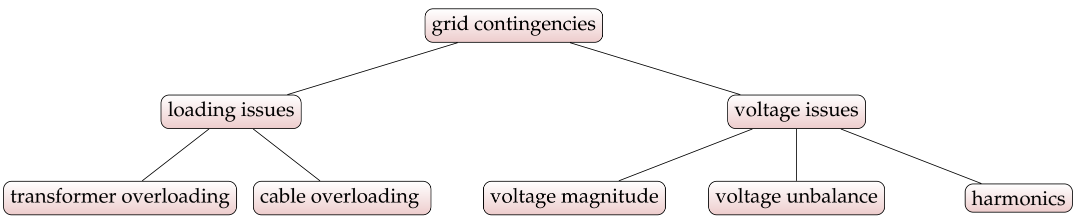

Figure 1.3: Classification of distribution grid contingencies by constraint type.

Voltage regulation is of paramount importance as it can cause equipment dysfunctions, tripping of sensitive loads, overloading of induction motors, and higher losses. In Europe, DSOs must comply with the European standard EN 50160 [20] which defines several requirements concerning the voltage quality. Among others, the standard defines the acceptable deviations for voltage magnitude and voltage unbalances[1] as summarized in Table 1.3. Additionally to the acceptable $\pm 10\% U_n$ voltage deviation, some countries have already proposed stricter national requirements. For example, Germany is considering to lower the acceptable voltage deviation band to $\pm 4\% U_n$ [21]. Regardless of the specific limits, the responsible DSO must ensure that its distribution feeders

[1] The definition of the voltage and the current unbalance factor is given in Appendix A.

Table 1.3: Selected supply voltage requirements according to the European standard EN 50160 [20].

Parameter	Requirements
voltage magnitude variations	mean 10 minutes rms values within: $\pm 10\% U_n$ for 95% of the week, $+10\% U_n / -15\% U_n$ for 100% of the week
short voltage interruptions (<3 min)	few tens-hundreds per year; 70% shorter than 1 s
long voltage interruptions (>3 min)	10-50 per year
voltage unbalances	mean 10 minutes rms values up to 2% for 95% of the week
voltage harmonics	total harmonic distortion below 8%

Table 1.4: Assets cost, adapted from [24, 25].

Component	Estimated cost
MV lines/cables	100-200 k€/km
LV cables	70-100 k€/km
LV lines	30-65 k€/km
ground-mounted MV/LV transformer	14-35 k€
pole-mounted MV/LV transformer	5 k€
HV/MV transformer	1700-5200 k€

are operated within the suitable voltage range to ensure the voltage quality to its end customers. Nowadays, DSOs mainly perform voltage regulation by adding capacitor banks or installing transformers with on-load automatic tap adjustment [22]. If such strategies are not successful, the distribution feeders are usually reinforced.

In addition to voltage regulation, DSOs are also dealing with congestion issues as grid components are manufactured to operate at a given rated power or current, so overloading will inevitably result in shorter life expectancy. Reducing the components' lifetime can significantly increase the cost since, as shown in Table 1.4, replacing large amount of components is rather costly. In Denmark, the capacity limit is typically kept at 70% as a "rule-of-thumb" since the remaning 30% is saved for supplying neighbouring feeders in case of a fault [23]. Hence, if components are often operating above their 70% capacity, the DSO needs to reinforce the grid by upgrading to components with a higher rated power.

In Europe, the distribution business is generally regulated as a natural monopoly and the regulator defines the way in which the DSO is remunerated. The DSO remuneration scheme is usually based either on a cost-of-service method or an incentive-based method [19]. The first one is based on the DSO expenditure and investment records, whereas the latter one incentivises the DSO to achieve better performance by making the DSO a partial claimant of the residual gains. For both methods, DSO costs are calculated by evaluating operational expenditures (OPEX) and capital expenditures (CAPEX) which are then included in the regulatory formula for the chosen remuneration approach. Incentive regulation is a common practice across Europe after deregulation of the electricity sector [26]. In such a scheme, the regulator sets the allowed yearly revenues for the regulatory period and the DSO can gain an extra profit by decoupling the costs from the revenue and increasing the efficiency. However, in practice, it is difficult to regulate the long technical and economic lifetime of grid components, so regulators exclude the CAPEX from the efficiency requirements and remunerate the actual cost of grid reinforcement, which effectively discourages DSOs from active grid management. This historical DSO methodology is called the "fit-and-forget" approach.

1.1.2 Smart grid paradigm and the role of electric vehicles

In the recent decades, the Danish energy system has transformed from a centralised to a distributed one as seen in Figure 1.4. Large-scale central power plants powered by fossil fuels are being replaced with distributed energy resources (DER) such as photovoltaic installations (PV), combined heat and power plants (CHP), and wind turbines. This trend is not unique for Denmark, but is also globally present. As one of the mature distributed renewable technologies, the share of PV installations is rapidly growing with the global share amounting to 139 GW in 2013 [27]. Similar trends are observed for other resources such as wind turbines whose global installed capacity had increased from 17.4 GW in 2000 to 432.9 GW in 2015 [28]. With increasing DER penetration, the reliability and the economical operation of the power system become non-trivial. The new resources impose additional constraints and challenges such as unpredictability, intermittency and bi-directional flows, which cannot be easily solved by the traditional system operators' means.

Figure 1.4: The Danish energy transition. Blue dots stand for centralised CHP plants, red dots for decentralised CHP plants, and yellow dots for wind turbines. Source: [29].

In order to address the emerging problems, it is expected that consumers will take an active role in the power system by providing different services to system operators through the so-called *smart grid* paradigm, which is depicted in Figure 1.5. It is almost impossible to exactly define the smart grid considering it is not a single concept or a single technology, but consists of many different layers and components. However, several basic functionalities are commonly agreed upon. According to IEEE, the smart grid *"has come to describe a next-generation elecrical power system typified by the increased use of communication and information technology in the generation, delivery and cosumption of electrical energy"*[30]. Here, it is sufficient to say that the smart grid concept combines four defining properties which enable successful integration of emerging technologies:

(1) *sensing* - enhancing the monitoring to improve the grid observability,

(2) *control* - installing more controllable devices and deploying better control architectures to improve the system efficiency and reliability,

(3) *intelligence* - introducing various control algorithms to optimise the physical grid operation and coordinate the use of controllable resources, and

(4) *communication* - deploying the communication infrastructure for accomplishing the first three tasks.

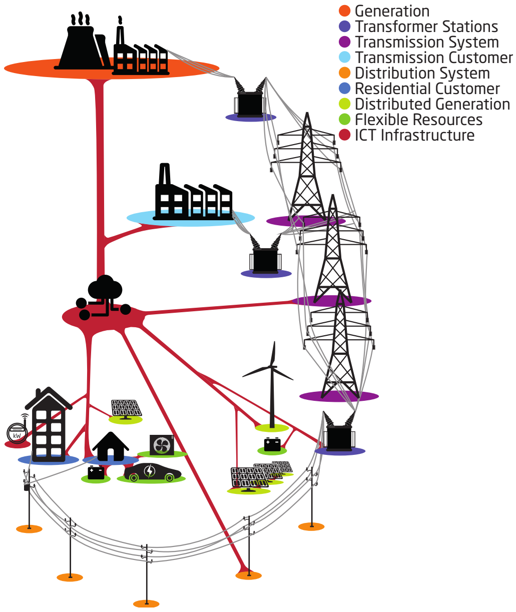

Figure 1.5: The future smart grid paradigm. Source: [13].

In the smart grid context, it is neccesarry to establish three domains in addition to the physical grid [31]: markets, operations and service providers. The market domain operates and coordinates all the participants in the electricity market, provides trading of energy services and ensures a competitive market environment. By introducing smart metering, the market will consist of significantly larger number of participant allowing for a faster diffusion of smart grid technologies. The second important domain is the operation domain which will get far more complex as the current state of operating hundreds of substations will be extended to operating millions. Naturally, it cannot be expected that the system operators will deal with individual home-owners which is why a new domain arises, namely the service provider. The service provider, also referred to as an aggregator, is a group of people or a business which works with individual customers and aggregates their flexibility to offer system services at the market. Here, the term *flexibility* is used for the active/reactive power portion which can be adjusted on demand by external instances. A short summary on the differences between the existing electric power system and the emerging smart grid paradigm is given in Table 1.5.

Table 1.5: Comparison of the existing power system and the smart grid paradigm.

Category	Existing grid	Smart grid
consumers	no active participation	informed and involved consumers
generation and storage	dominated by central generation	many distributed resources
markets	limited opportunities for consumers	new electricity market for consumers
power quality	focus on outages	variety of quality options
asset optimisation	little integration of operational data with asset management	data acquisition with focus on prevention
system disturbances	protection units follow faults	prevention and minimising fault impact
resiliency	vulnerable to cyber attacks and natural disasters	resilient to cyber attacks and natural disasters

In the recent years, the EV market share is slowly but steadily increasing, both globally, as seen in Figure 1.6, and in Denmark where there was 7842 EVs at the end of 2015 compared to only 148 EVs at the end of 2010 [32]. Moreover, the IEA Electric Vehicle Initiative aims at deploying 20 million electric cars worldwide [33] in order to meet the 2030 decarbonisation and sustainability goals, whereas according to [34], it is estimated that the EV number in Denmark will reach more than 200,000 by 2030 in a moderate penetration scenario.

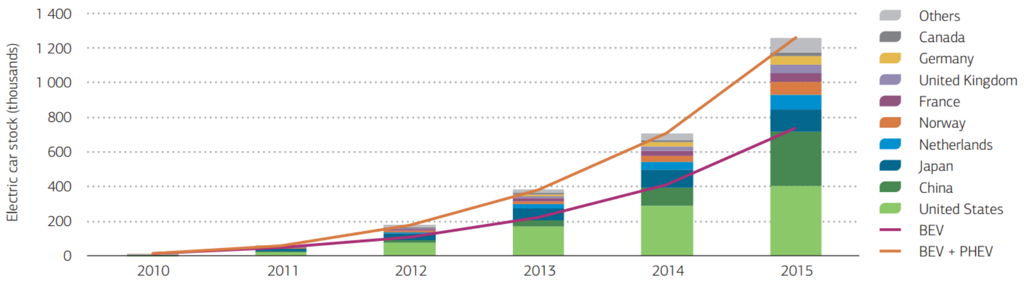

Figure 1.6: Global electric vehicle stock from 2010 to 2015. Source: [33]

Even though the global EV market share is still relatively low, it is expected that EVs will play an important role in the future smart grid due to their defining characteristics:

(1) They are a considerably **large load** compared to conventional residential appliances.

(2) They are idle more than 90% of the day with a **high degree of flexibility** [11].

(3) They are a **quick-response** unit (seconds range) with an attached **storage** and potentially **bi-directional** power flow capabilities [11].

Hence, EVs should not be considered merely as passive loads. The potential for providing services beyond transportation makes them an attractive asset for the end-user and an active resource for the power system. In order to systematically investigate and experimentally validate the potential services EVs can offer to the power system, the Danish research project with international collaboration named "NIKOLA - Intelligent Electric Vehicle Integration" [35] has been established. This project aimed at studying four main categories for EV integration:

(1) *System-wide services* for the TSO which will grant high benefits for the society, e.g., primary frequency regulation.

(2) *Distribution grid services* for the DSO which will help in mitigating the adverse affects of distributed resources, e.g., voltage regulation.

(3) *User value-added services* which will make EVs more cost competitive and help in empowering EV owners.

(4) *Enabling technology* which include contemporary technologies and standards for supporting all of the above mentioned services.

Within the NIKOLA project, the PhD project "Control strategies and modelling of electric vehicles in the distribution network", whose part is this thesis, was formed to focus on the EV integration and the potential services at the distribution level.

1.2 Research objectives

This thesis deals with the EV integration issues at the distribution level, in particular the challenges and opportunities for the distribution system operator. It focuses on the methods and requirements for utilising EV flexibility to assist the system operation, and investigates the issues arising in practical implementation. In this thesis, the studies are performed on a Danish residential low-voltage grid which is similar to grid topologies occurring throughout Europe, making the results applicable to other European countries as well.

The primary research question this thesis seeks to answer is: ***How can electric vehicle mitigate the self-induced adverse grid effects and actively help with the secure system operation?*** The overarching question can be split into the following sub-questions along with the corresponding research objectives:

[Q1] *What is the impact of uncontrolled EV charging and the potential of EV interacting with the power system?*

It is important to identify the operational challenges that EVs introduce to the power system as well as the potential opportunities of controlled EV charging through literature survey, distribution grid modelling, and simulation of various scenarios.

[Q2] *Focusing on the distribution level, what are the prerequisites for supporting active EV involvement?*

In addition to recognising various flexibility services that EVs can provide at the distribution level, the requirements for enabling the active EV participation need to be defined from the technical perspective as well as from the organisational and regulatory framework.

[Q3] *What is the potential of introducing EV reactive power control for distribution grid support?*

Contemporary EV chargers can be extended to perform more advanced charging strategies, such as providing reactive power, with limited modifications to the current technology. The main advantage of implementing the reactive power control is that, given that the equipment is properly sized, it can support EV integration independent of the active power modulation. Therefore, it is necessary to investigate how the system could benefit from such a new EV capability, as well as the possible detrimental impacts it could have.

[Q4] *How can the EV aggregator's economic concerns be combined with the distribution system concerns?*

Future power system entities such as EV aggregators and system operators may have competing economic objectives. It is valuable to analyse how such partially competing objectives can be combined in order to provide a best-compromise solution when scheduling the EV charging. Moreover, the unbalanced nature of distribution grids should be included in such a framework as the results must be feasible in the corresponding grid.

[Q5] *What are the issues arising with practical implementation of EVs providing flexibility services according to contemporary standards and requirements?*

It is crucial to investigate the issues arising with practical implementation of EVs providing flexibility services, both in the laboratory environment and in real distribution grids with limited amount of measurement equipment. One of the major concerns is evaluating technical parameters of currently available series-produced EVs to assess the compliance with the existing requirements and provide basis for further theoretical studies.

1.3 Thesis outline and research contributions

The thesis is organised in six self-contained chapters in addition to the Introduction, two appendices, and eight attached scientific papers in appendices A through H. The main results are published in the scientific papers which are referenced throughout this thesis as needed, but they may also be read independently of this report. The description of each chapter is as follows.

Chapter 2 reviews the contemporary EV technology status and the related standards, as well as the impact of uncontrolled charging on the power system. Additionally, it elaborates on the potential value of EV flexibility provision through identifying service for different power system stakeholders, and provides an overview of the EV related projects with their main focus areas.

Chapter 3 focuses on the EV flexibility services for the distribution grid support with the corresponding state of the art. Additionally, the chapter presents key prerequisites for enabling active EV involvement at the distribution level, and includes several recommendations for overcoming the recognised technical, organisational and regulatory barriers. The chapter includes contents of Pub. A and Pub. B.

In Chapter 4, an autonomous EV reactive power control for local voltage support is proposed. The control relies only on local voltage measurements, and avoids the additional communication infrastructure between individual EVs and grid operators. Given that the equipment is properly sized, such a strategy enables EVs to partially mitigate the self-induced voltage problems and provide support to the local grid without influencing the EV owner. Potential benefits and challenges are studied both for balanced and unbalanced distribution grid conditions. The contents of papers Pub. C, Pub. D and Pub. E are included in this chapter.

In Chapter 5, the focus is moved on developing a collaborative multi-objective optimisation framework which combines the EV aggregator's with the DSO's economic concerns with respect to the EV day-ahead scheduling. The framework includes the unbalanced nature of distribution grids and provides a set of solutions from which the best-compromise one can be chosen to satisfy both entities. Additionally, the chapter investigates the impact of EV reactive power scheduling when EVs are the only flexible resource as well as when combined with other demand response. The chapter is based on Pub. F.

Chapter 6 focuses on validating the technical feasibility of series-produced EVs to provide various flexibility services through a set of field and laboratory experiments, which are presented in Pub. G and Pub. H. A smart charging controller is proposed which can function with any EV compliant to contemporary standards, making it suitable for a wide range of applications. The chapter focuses on assessing the current EV capabilities in terms of EV responsiveness and EV accuracy to provide recommendations for future improvements.

Finally, Chapter 7 summarizes the results, concludes the thesis and provides a preview of future work.

1.4 List of publications

The relevant core publications are listed as follows:

A K. Knezović, P. Codani, M. Marinelli, Y. Perez "Distribution grid services and flexibility provision by electric vehicles: A review of options," in *Power Engineering Conference (UPEC), 2015 50th International Universities*. Stoke on Trent, United Kingdom, Sep. 2015.

B K. Knezović, M. Marinelli, A. Zecchino, P. B. Andersen, C. Træholt, "Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration", in *Energy*. under review.

C K. Knezović, M. Marinelli, R. J. Møller, P. B. Andersen, C. Træholt, F. Sossan, "Analysis of voltage support by electric vehicles and photovoltaic in a real Danish low voltage network," in *Power Engineering Conference (UPEC), 2014 49th International Universities*. Cluj-Napoca, Romania, Sep. 2014.

D K. Knezović, M. Marinelli, P. B. Andersen, C. Træholt, "Concurrent provision of frequency regulation and overvoltage support by electric vehicles in a real Danish low voltage network", in *IEEE International Electric Vehicle Conference, 2014*. Florence, Italy, Dec. 2014.

E K. Knezović, M. Marinelli, "Phase-wise enhanced voltage support from electric vehicles in a Danish low-voltage distribution grid," in *Electric Power Systems Research*, 140:274-283, Nov. 2016.

F K. Knezović, A. Soroudi, A. Keane, M. Marinelli, "Multi-objective PQ scheduling for electric vehicles in flexible unbalanced distribution grids," *IET Generation, Transmission and Distribution*, under review.

G K. Knezović, S. Martinenas, P. B. Andersen, A. Zecchino, M. Marinelli, "Enhancing the role of electric vehicles in the power grid: Field validation of multiple ancillary services," *IEEE Transactions on Transportation Electrification*, PP:1-9, in press.

H S. Martinenas, K. Knezović, M. Marinelli, "Management of power quality issues in low-voltage networks using electric vehicles: Experimental validation," *IEEE Transactions on Power Delivery*, PP:1-9, in press.

The following publications have also been prepared during the course of the Ph.D. study, but have been omitted from the thesis because they are not directly related to the primary objective, or they are partially covered by other presented papers.

Peer-reviewed journal papers

- M. Marinelli, S. Martinenas, K. Knezović, P. B. Andersen, "Validating a centralized approach to primary frequency control with series-produced electric vehicles," in *Journal of Energy Storage*, 7:63-73, Aug. 2016.

- J. García-Villalobos, I. Zamora, K. Knezović, M. Marinelli, "Multi-objective optimization control of plug-in electric vehicles in low voltage distribution networks," in *Applied Energy*, 180:155-168, Oct. 2016.

- B. Morvaj, K. Knezović, R. Evins, M. Marinelli, "Integrating multi-domain distributed energy systems with electric vehicle PQ flexibility: Optimal design and operation scheduling for sustainable low-voltage distribution grids," *Sustainable Energy, Grids and Networks*, 8:51-61, Dec. 2016.

Peer-reviewed international conference papers

- A. Zarogiannis, M. Marinelli, C. Træholt, K. Knezović, P. B. Andersen, “A dynamic behaviour analysis on the frequency control capability of electric vehicles”, in *Power Engineering Conference (UPEC), 2014 49th International Universities*. Cluj-Napoca, Romania, Sep. 2014.
- P. Lico, M. Marinelli, K. Knezović, S. Grillo, “Phase balancing by means of electric vehicles single-phase connection shifting in a low-voltage Danish grid,” in *Power Engineering Conference (UPEC), 2015 50th International Universities*. Stoke on Trent, United Kingdom, Sep. 2015.
- J. Lin, K. Knezović, “Comparative analysis of possible designs for flexible distribution system operation,” in *European Energy Market (EEM), 2016 13th International Conference on*. Porto, Portugal, Jun. 2015.
- J. N. Alvarez, K. Knezović, M. Marinelli, “Analysis and comparison of voltage dependent charging strategies for single-phase electric vehicles in an unbalanced Danish distribution grid,” in *Power Engineering Conference (UPEC), 2016 51st International Universities*. Coimbra, Portugal, Sep. 2016.

Chapter 2

Challenges and opportunities of EV integration

In this chapter, first the current state-of-the-art EV technology with the relevant standards is summarized, followed by the identification of operational challenges EVs introduce to the power system. After describing the potential EV adverse effects, the benefits of EV interaction with the power system are provided. Finally, an analysis of relevant EV research and development projects is conducted to recognise the trends and the current research focus.

2.1 Contemporary EV technology

During the last decade, the interest in battery electric vehicles (BEVs) has increased both from the manufacturers' and users' side. In 2014, around 320.000 EVs have been sold worldwide [36], with the majority sold in the USA (37%), Europe (31%), China (17%) and Japan (10%) [36, 37]. In Europe, the largest number of BEVs have been sold in Norway followed by France and Germany [37]. Many of the top-selling BEV models are available in the USA, Europe and Japan, whereas the Chinese market is almost exclusive to the Chinese brands. In the remainder of this section, the focus is put on the global EV models which are highway capable (>110 km/h), omitting the Chinese ones due to limited amount of information.

According to [38], the top five sold BEV models during 2014 and 2015 in the USA, Europe and Japan were: (1) Nissan LEAF, (2) Tesla Model S, (3) BMW i3, (4) Renault Zoe and (5) Volkswagen e-Golf. In addition to them, the most important characteristics for other 13 BEV models are given in Table 2.1 due to their non-negligible sale numbers. All compared models utilise lithium-based batteries although the energy capacity varies, which also impacts the driving range. The specified EV range and energy consumption data are usually given for driving cycles defined by standard test procedures which are then adjusted with a correction factor to resemble the real-world driving [39]. However, as indicated by the values for different driving cycles, driving range cannot be estimated exactly as it is not dependant only on the battery capacity, but also on the driving conditions and external circumstances such as temperature. Naturally, the larger the battery capacity is, the greater will the EV driving range be. However, EV battery is one of the most expensive components, so it is currently non-viable to install very high capacities while maintaining a reasonable price. Fortunately, in the last years due to technology development and economy of scale, the average energy battery density has increased, while the cost per kWh has decreased [40]. It is expected that the battery cost will continue falling, resulting in larger installed battery packs and, consequently, greater driving ranges for the same EV price. The driving range remains one of the main reasons for wide-spread reservations about EVs as primary transportation resources, since users believe

Table 2.1: Comparison of the top-selling battery EV models. Adapted from [38]

Brand	Model	Model year	Battery warranty (years)	Battery energy capacity (kWh)	Standard AC charging power (kW)	DC charging power (kW)	Range NEDC[1] (km)	Range EPA combined cycle[2] (km)
BMW	i3	2014	8	22	7.4	50	190	130
Chevrolet	Spark EV	2015	8	18.4	3.3			132
Citroen	C-Zero	2014	8	14.5	3.2	50	150	
Fiat	500e	2015	8	24	6.6			140
Ford	Focus electric	2015	8	23	6.6		162	122
Honda	FIT EV	2014	5	20	6.6			132
Kia	Soul EV	2015	10	27	6.6	50	212	150
Mercedes	B-class electric	2015	8	36	10		200	140
Mitsubishi	i-MiEV	2014	8	16	3.7		160	100
Nissan	Leaf (Visia)	2015	5	24	3.6	50	199	135
Nissan	Leaf (Acenta)	2016	8	30	3.6	50	250	172
Nissan	e-NV200	2015	5	24	3.6		170	
Peugoet	iOn	2014	5	14.5	3.2	50	150	
Renault	Zoe	2015	5	22	43		240	
Smart	fortwo ED	2014	4	17.6	3.3		145	109
Tesla	Model S	2015	8	85	10	120	502	426
Volkswagen	e-Golf	2015	8	24.2	22	50	190	134
Volkswagen	e-Up!	2013	8	18.7	3.7	40	160	

[1] New European Driving Cycle is defined in United Nations ECE R101

[2] U.S. Environmental Protection Agency combined cycle is a weighted average considering 55% of the city consumption and 45% of the highway consumption

they will not be able to arrive to the desired destination. This phenomenon is also known under the name "range anxiety". Until the average driving range increases, this issue is tackled mostly by user education about EV capabilities as well as by indicating real-time information such as the battery status and traffic conditions.

With respect to the EV charging process, the most common method is conductive charging where the electric energy is delivered through a charging cable, either using AC or DC supply. Inductive charging, where the energy is transferred via magnetic fields, is also possible, but such methods have been omitted here as they are still under development. EVs typically come with a standard conductive AC charger of a lower power level, whereas some can also utilise the external DC charging stations for fast charging. Considering that the charging power is the most relevant parameter when assessing the grid impact, the relevant standards related to the EV charging equipment are explained further on.

In different regions of the world, various standards are utilised for EV charging with the most important ones summarized in Table 2.2. Most of them are based on International Electrotechnical Commission (IEC) and Society of Automotive Engineers (SAE) standards. More precisely, SAE J1772 is the North American standard for EV electrical connectors which covers physical, electrical and communication aspects of the EV conductive charging. On the other hand, IEC 62196 is an international standard which defines a set of electrical EV connectors and incorporates different standards including the SAE J1772 available in North America, VDE-AR-E 2623-2-2 (also known as the Mennekes connector) available in Europe, and the DC charging standard CHAdeMO introduced by Japanese automakers. IEC 62196 is mostly based on the international standard IEC 61851 which applies to on-board and off-board EV charging equipment, as well as to providing electrical power for any additional services. Among others, IEC 61851 describes the communication protocol between the EV and the EV supply equipment (EVSE) with the specified contact sequencing as well as the control ability via the Pulse-Width-Modulation (PWM) signal. The PWM principle will be explained in more detail in subsection 3.2.1.

Table 2.2: Relevant standards for EV conductive charging.

Standard		Scope
IEC 60309: Plugs, socket-outlets and couplers [41]	IEC 60309-1	Explains general requirements for EV charging stations.
	IEC 60309-1	Describes different sizes of plugs and sockets with different pin numbers based on the current supply and phase number; defines color-coded connectors based on voltage range and frequency.
IEC 60364 [42]		Defines electrical installations for buildings.
IEC 61851: Conductive charging systems [43]	IEC 61851-1	Defines cables and plug setups.
	IEC 61851-23	Describes electrical safety, grid connection and communication architecture for DC charging stations.
	IEC 61851-24	Explains digital communication for DC charging control.
IEC 62196: Plugs, socket-outlets, vehicle connectors and inlets [44]	IEC 62196-1	Explains general requirements for EV connectors.
	IEC 62196-2	Describes coupling types for different charging modes.
	IEC 62196-3	Defines connectors and inlets for DC stations.
SAE J1772: Conductive charging systems [45]		Defines connectors for AC charging; describes new Combined Charging System for DC charging.
SAE J2293 [46]	J2293-1	Describes the EV energy transfer system with EV and EVSE requirements.
SAE J2344 [47]		Describes guidelines for EV safety.
SAE J2847: Communication [48]	SAE J2847-1	Describes the communication medium and criteria for EV connection to the utility (AC Level 1 and Level 2).
	SAE J2847-2	Defines additional messages for DC charging.

For the EV charging process, it is important to distinguish the difference between the EV charging mode and the EV charging level. First of all, the EV charging mode is defined by the IEC 61851 and primarily describes the safety communication protocol between the EV and the EVSE. As summarized in Table 2.3, there are four charging modes in total - three for AC charging and one for DC charging. The main difference among them is that the safety in Mode 1 depends on the external installations, leaving the responsibility of installing the required safety devices to the user. Several countries do not allow Mode 1 due to many residential installations without sufficient safety measures. The remaining three modes include the control and proximity pilot conductor which has several safety functions:

- determining whether the connector is properly inserted both in the EV and the EVSE, and disabling the EV movement via the internal propulsion system as long as the EV is physically connected to the EVSE,
- continuously checking the protective earth conductor continuity,
- disabling the system energisation as long as the pilot function between the EV and the EVSE is not established correctly, as well as interrupting the power supply if the pilot function is interrupted, and
- limiting the charging rate and controlling the bi-directional flow if available.

On the other hand, SAE J1772 defines charging levels which describe the power level of the charging outlet, either AC or DC, as summarized in Table 2.4. Whereas the first two levels are completely defined, the third level is only proposed, but is presented here for illustrative purposes.

Table 2.3: Standard charging modes defined by IEC 61851-1.

Mode	Description	Phase	Maximum current	Maximum voltage
Mode 1 (AC)*	home charging from a standard power outlet	1	16 A	250 V
	without any safety measures	3	16 A	480 V
Mode 2 (AC)	home charging from a standard power outlet	1	32 A	250 V
	with an in-cable EVSE supplied with the EV	3	32 A	480 V
Mode 3 (AC)	wired-in AC	1	32 A	250 V
	charging station	3	250 A	690 V
Mode 4 (DC)	wired-in DC charging station	-	400 A	600 V

* prohibited in the US by national codes

Table 2.4: Typical EV charging levels, upper limits defined by SAE J1772.

Level	AC	DC
Level 1	1.4 kW (12 A, 120 V)	up to 36 kW (80 A, 200-450 V)
	1.9 kW (16 A, 120 V)	
Level 2	2.4 kW (10 A, 240 V)	up to 90 kW (200 A, 200-450 V)
	3.8 kW (16 A, 240 V)	
	7.7 kW (32 A, 240 V)	
	19.2 kW (80 A, 240 V)	
Level 3*	>19.2 kW	up to 240 kW (400 A, 200-600 V)

* proposed values, standard ones yet to be defined

For the AC charging, Level 1 specifies single-phase 120 V charging up to 16 A which is used in case the Level 2 EVSE is not available. For this reason, it is often referred to as "occasional charging". AC Level 2 indicates the 240 V charging up to 80 A which is the most preferred charging method since it requires charging equipment with a dedicated circuit and a measurement device. Even though the standard defines the upper limit to be 80 A, in practice, the charging current is typically up to 32 A. AC Level 3 indicates the charging power above 19.2 kW. For the DC charging, the standard defines the upper limits for Level 1 and 2 to be 36 kW and 90 kW, respectively, whereas the preliminary upper limit for Level 3 is set to 240 kW in accordance with the Mode 4 charging defined in IEC 61851.

Nowadays, DC fast charging stations are around 50 kW, whereas the typical residential charging level is 16 A corresponding to 3.7 kW under the nominal voltage $U_n = 230$V. However, recent trends in increasing the battery capacity indicate that the typical residential charging levels could increase as well, e.g., to 32 A resulting in 7.4 kW under the nominal voltage conditions. Moreover, the series-produced EVs are currently unidirectional, meaning they cannot provide power back to the grid. The EV bidirectional power flow, also known as *Vechicle-to-Grid* (V2G) concept, requires a more complex charger capable of both drawing and returning the current. Such chargers are still in prototype versions, but it is expected that the charging levels will be the same as the unidirectional ones.

2.2 EV mobility and user behaviour

EV impact on the electricity demand profile can be rather high, but it highly depends on the users' driving behaviour. Questions such as how many kilometres per day are done, and where and when the EVs are plugged-in and plugged-out are the key factors for analysing the EV demand.

The answers to these questions are not straightforward as they depend on many aspects including the geopolitical location, type of day (weekday or weekend), type of area (rural or urban) and other random factors such as weather conditions and local events. Fortunately, various studies have aimed at developing approximate models for estimating the EV user behaviour, which can then be used for estimating the grid impact. Among them, the Green eMotion [49] study is the most important one in the European context, whereas the Test-en-EV [50] study is relevant for the Danish case. Hence, these two studies will be presented here and briefly compared with other European studies.

Green eMotion project has been carried out in different European cities including Berlin, Copenhagen, Dublin and Madrid, with the analysis of user behaviour being one of the main objectives. Within the project, more than 650 EVs, 2600 EVSEs and 1300 users were registered across Europe, and more than 77000 charging events and 94000 trips were recorded within a three year period. It was concluded that, on average, private EV users drive 34.3 km per day with most of the travels being less than 100 km [49]. However, the average trip distance was observed to be below 10 km meaning that users tend to make several short trips per day. As an example, the trip distance distribution for the Danish and the Irish demo regions are given in Figure 2.1 from which it is clear that around 70% of all recorded trips are below 10 km. Nevertheless, private users tend to charge their EVs more frequently even though the trips are relatively short and the battery is not fully depleted, on average at least once per day. This is mainly due to range anxiety which prompts the users to charge whenever possible and not only when the battery levels are low. Consequently, the initial state of charge (SOC) remains quite high and only 20% of the recorded charge events start with the battery being less than 40%. Furthermore, most users tend to fully charge their EV prior to the departure time, so the end SOC is predominantly close to 100%. The average initial SOC findings as well as the percentage of registrations with the initial SOC smaller than 20% are summarized in Table 2.5. From the presented values, it is clear that the average initial SOC does not fall below 50% in any of the Green eMotion demo regions, and similar SOC findings have been

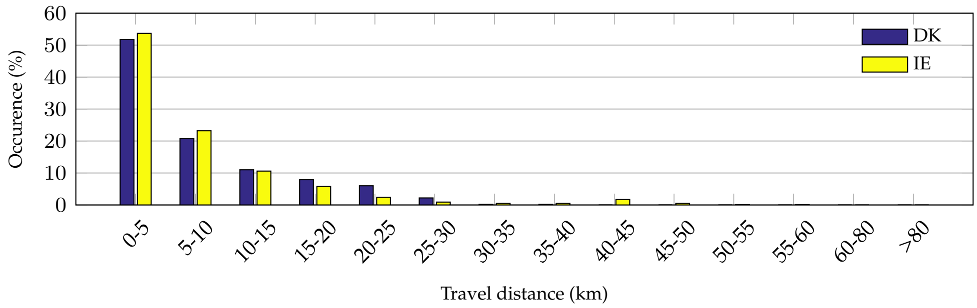

Figure 2.1: Trip distance distribution for the Danish and the Irish demo region of the Green eMotion project. Adapted from [49].

Table 2.5: Average initial state of charge by EV use obtained from the Green eMotion project [49].

	Average initial SOC (%)	**Initial SOC<20% (%)**
Business use	62.7	3.9
Captive fleet	64.2	2.3
Private use	58.6	4.8
Rental	62.5	7.1

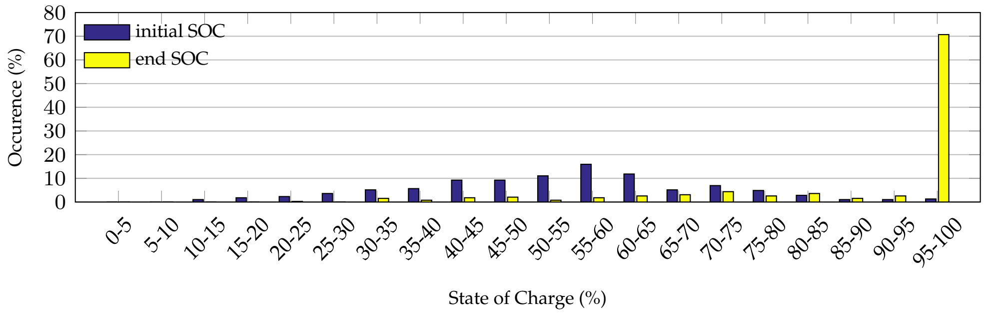

Figure 2.2: EV initial and end SOC for charge events in the Danish demo region of the Green eMotion project. Adapted from [49].

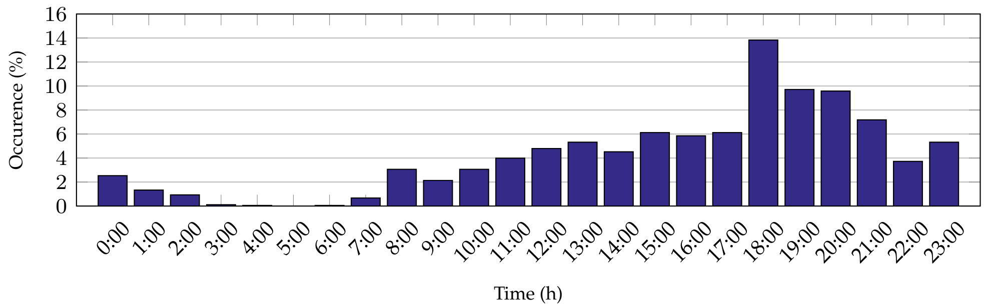

Figure 2.3: Private use vehicle charge start time distribution for the Italian demo region of the Green eMotion project. Adapted from [49].

obtained for the Danish demo region as well, as depicted in Figure 2.2. Another observed common trend across all studied regions is that a relatively low number of residential charging events starts between 22:00 and 8:00, as seen in Figure 2.3 for the Italian demo region, which corresponds to the well known "dumb charging" phenomenon. More precisely, EV users plug-in their vehicles as soon as they arrive home, usually between 17:00 and 21:30, and EVs immediately start charging.

Similar findings have been observed in the Danish project Test-an-EV, where 184 EVs were distributed to 1600 different Danish families over a three year period. The project was supported by the Danish Energy Agency and the Danish Transport Authority, and run by the electric mobility operator Clever. The study collected charging and driving records for all involved EVs, from which similar parameters as in the Green eMotion project have been examined. As reported in [51], the average initial SOC was found to be 49% which is somewhat lower than in the Green eMotion project, but still corresponds to the general trend, whereas the end SOC was again predominantly around 100%. Likewise, the average connection time was found to be around 19:00 and the average plug-out time around 8:00, meaning that EVs have been plugged-in for 13 hours on average. The main findings are summarized in Table 2.6, whereas the plug-in distribution for a single EV is given in Figure 2.4 as an example. It is obvious how the vehicle often connects to the grid in the evening hours, which, as concluded by the study, coincides with the typical commuting habits.

Several other European studies observed a similar EV user behaviour as the ones in Green eMotion and Test-en-EV projects. The Amsterdam municipality carried out a 2-year EV usage study across the public charging infrastructure [49] with the conclusion that the EV plug-in time starts around 8:00 and steadily increases with a peak at 18:00 after which the distribution decreases. The

Table 2.6: Average SOC and charging time derived from the Test-en-EV project dataset. Adapted from [51].

	Mean value	Standard deviation
Plug-in duration	12:43	41 (min)
Charge duration	4:00	17 (min)
Initial SOC	49	4 (%)
End SOC	100	2 (%)
Plug-in time	19:10	39 (min)
Plug-out time	7:53	29 (min)

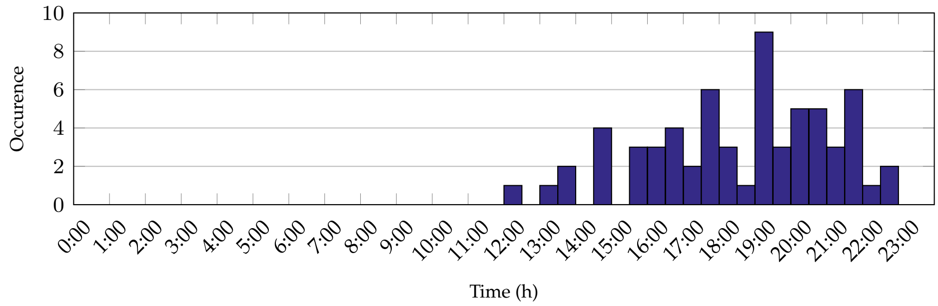

Figure 2.4: Start time distribution for a single EV from the Test-en-EV trial over a three month period.

SwitchEV trial conducted in North East of England over a three year period found that users tend to make short trips resulting in the average initial SOC of 53%, whereas the peak plug-in time has been shortly after 18:00 [52]. In addition to the empirical EV data, much research has focused on the national transport surveys and deriving the electro-mobility models from the available data. For example, in [53], the electro-mobility model is based on the Flemish Mobility Study, where it is observed that EVs would mostly start charging in the morning hours for the business areas and in the evening hours for the residential areas. On the other hand, in [54], the electro-mobility model is based on the US National Household Travel Survey with similar observations regarding the arrival and departure times. With respect to the charging location, due to typically long standstill times at home and the low average daily driven distance, home charging is usually sufficient to fulfil the majority of the mobility needs, and is, therefore, the most preferred EV charging way. For instance, [55] monitored 8400 EVs over a 3 year period in the US, and showed that 84% of recorded charging sessions belonged to home charging. Similarly, [56] reports the results of a Norwegian survey which concludes that 83% of EV users charge at home to start with a full battery every morning, whereas [57] reports that home charging points would be dominant even with the mass roll-out of work and public infrastructure.

Altogether, the conducted studies and surveys agree that, assuming there is no control and EVs start charging as soon as they are connected, the typical user behaviour could lead to issues for the power system since the EV plug-in time would often coincide with the peak residential consumption.

2.3 EV uncontrolled charging and impacts on the power system

To demonstrate the potential problems EVs could bring, first some illustrative calculations are provided based on the Danish power system. In 2015, around 2.1 million private cars were registered in Denmark [58]. Assuming 5% of vehicles become electric in the near future, approximately 105,000 EVs would be on the road. On one hand, assuming none of them can be controlled and all charging processes with the typical Level 2 power of 3.7 kW coincide at one point of time, the peak EV consumption would in total be $105,000 \cdot 3.7 \approx 390\ MW$. On the other hand, the Danish instantaneous peak load is around 6000 MW [59]. If the EV peak consumption would coincide with the peak load, the total peak demand would increase by around 6.5%. From this value, one could wrongly assume that accommodating such a large EV number would not present a problem since the Danish installed capacity is more than twice the peak load [59]. On the contrary, before EVs would start causing significant issues on the system level, substantial problems would appear on the local distribution grid level.

The average Danish household peak load is around 1 kW [60] meaning that connecting an EV at the typical Level 2 charging power of 3.7 kW would result in almost five times larger peak demand. Naturally, if the charging power would increase, the peak demand would also increase proportionally. As described in subsection 1.1.1, distribution grids are operated in such a way that all components are sized to be of somewhat bigger capacity than the expected peak load. Introducing only one EV in the local distribution grid effectively means an introduction of four new households from the peak loading perspective. Since grid components are not sized accordingly, this leads to several issues such as overloading and high voltage drops, which makes the grid operation more challenging.

To investigate the impact of random uncontrolled EV charging on the transformer loading and voltages, simulations are conducted for a typical Danish low-voltage (LV) grid located in Borup, Zealand. This particular analysis is conducted in DigSILENT PowerFactory, which is a commercially available software commonly used for analysing the power system. The distribution grid is described in Appendix B in more detail and will be used throughout the thesis for various analysis. Here it is sufficient to say that it is a real LV grid with a 400 kVA transformer supplying around 120 customers through 4 feeders. For one of the four feeders, consumption and PV production data is available for individual households on hourly basis for a one year period. Hence, this feeder is modelled in detail, whereas the remaining three feeders are modelled as an aggregated load connected to the LV side of the transformer. Based on the DSO experience, the grid is heavily unbalanced, so the load is divided in the ratio 42%:29%:29% among the phases. Different EV numbers are added to the modelled feeder in order to assess their grid impact, i.e., from 20% to 100% penetration rate in 20% increments. The penetration rate is defined as the ratio between the number of EVs and the number of houses in the observed feeder, so the total EV number varies from 8 to 43 depending on the observed case. All randomly added EVs are assumed to be Nissan Leafs, since it was the top-selling EV in 2015, which are single-phase connected with P_n=3.7 kW (16 A at U_n=230 V). Moreover, the used electro-mobility model is based on the model developed in [54] which is adjusted to the Danish system in terms of the average vehicle number per house as well as the average plug-in and plug-out time according to the Test-an-EV project. After rendering the random EV population with the initial parameters according to the predefined model, simulations are run for a one year period.

The impact of different EV penetration rates on the transformer loading can be seen in Figure 2.5a. Since the Danish distribution grids are often oversized, as is the case here, EVs do not cause any transformer overloading until an 80% penetration level is reached. Even then, the overloading occurs only in the winter period. However, as the grid is heavily unbalanced and EVs introduce additional unbalances due to their single-phase connection, voltage issues occur already for a lower penetration of 40% as seen in Figure 2.5b. The summary of the obtained results, i.e., the EV impact on the peak load and the minimum phase-to-neutral voltages is given in Table 2.7. From the presented values, it is obvious that EVs can have substantial adverse effects on the LV grid operation if they remain uncontrolled. In addition, it is worth noting that the phase-to-neutral voltage of phase b increases while the other two decrease. The reason behind is the 3-phase 4-wire topology with a floating neutral point grounded only at the transformer substation. Thus, voltage reduction on one phase causes changing of the neutral point and, consequently, a voltage increase on one of the other two phases.

Similar EV impact studies have been conducted across various countries, , as summarized in Table 2.8, in order to assess the potential loading problems both at the local distribution and at the national level. For a Belgian test grid, a 10% increase in voltage deviations is reported for a 30% EV

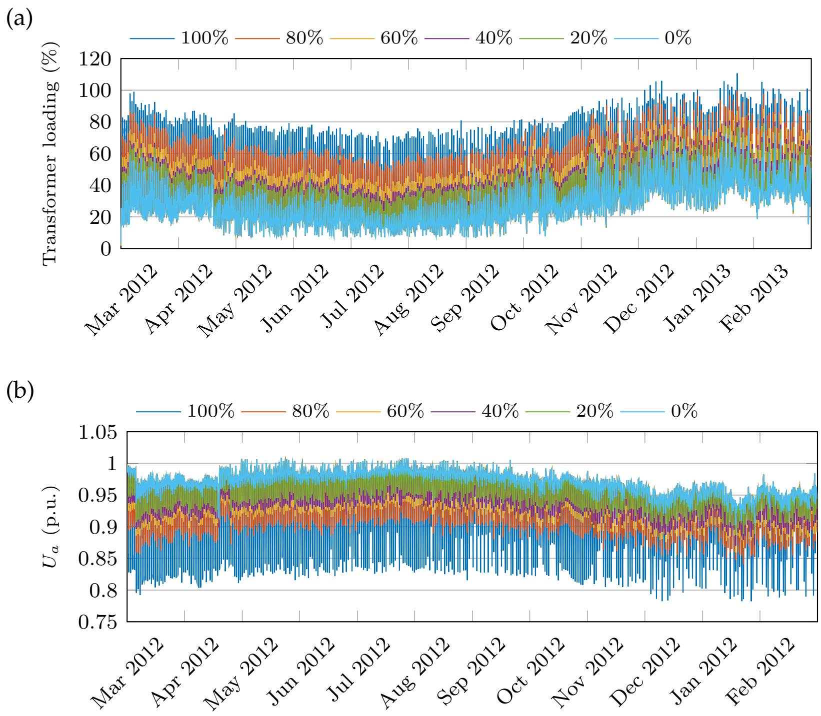

Figure 2.5: Impact of uncontrolled EV charging on (a) transformer loading, and (b) minimum voltage of the Danish LV grid for different EV penetration rates on the observed feeder.

Table 2.7: Impact of uncontrolled EV charging on the Danish LV grid for different EV penetration rates on the observed feeder.

EV penetration rate	Peak load increase (%)	$\Delta U_{a,min}$ (%)	$\Delta U_{b,min}$ (%)	$\Delta U_{c,min}$ (%)
20%	5.6	-3.11	+0.98	-0.99
40%	8.5	-4.49	+0.98	-2.06
60%	13.1	-5.60	+0.61	-2.45
80%	23.5	-8.70	+0.98	-3.07
100%	31.6	-14.43	+0.98	-2.25

penetration rate [61]. A study conducted in the Netherlands shows that the national peak load would increase 7% for a 30% EV penetration rate, whereas the impact on the household peak load would be much higher amounting to 54% [62]. Similarly, in the UK, a 10% EV market penetration would results in 17.9% increase in the daily peak load, whereas the 20% market penetration would lead to 35.8% increase [63]. Various studies have also been conducted for Australia and the USA with similar results. It is mainly agreed upon that EVs will bring challenges to the distribution network, such as congestions and voltage drops, since they are considerably large loads compared to conventional loads, and there is a high probability of many EVs charging at the same time.

Table 2.8: Impact of uncontrolled EV charging on the peak load for various simulations studies from the literature.

Simulation study	Reference	EV penetration rate	Peak load increase (%)
United Kingdom	[63]	10% (distribution level)	17.9
		20% (distribution level)	35.8
Belgium	[61]	30% (distribution level)	56
Netherlands	[62]	30% (national level)	7
		30% (distribution level)	54
Portugal	[64]	10% (distribution level)	11.2
		14% (distribution level)	16.3
		52% (distribution level)	84.7
Los Angeles, USA	[65]	5% (national level)	3.03
		20% (national level)	12.47
California, USA	[66]	10% (distribution level)	17
		20% (distribution level)	43
Western Australia	[67]	17% (distribution level)	37
		31% (distribution level)	74

In addition to congestions and adverse voltage affects, massive EV penetration also imposes other power quality issues including harmonic distortion and voltage unbalances. As EVSE contains nonlinear characteristics, high EV penetrations cause harmonic distortions which stress the network components such as cables and fuses [68]. The studies conducted in [69–71] revealed that EV fast charging produces high harmonic distortions, whereas the slow charging does not introduce significant distortions. Moreover, in [71], it is concluded that harmonic measurements are not needed for small-sized EVSEs, but become necessary for fast charging EVSEs. Another power quality aspect which is affected by high EV penetration is the voltage unbalance, i.e., the difference between the voltage magnitudes and the angles among the phases. As the loads are usually unequally distributed per phase, voltage unbalances are common occurrences in the distribution grids, to which the single-phase EV connections can additionally contribute. It is shown in [72] that EVs have a negligible impact on voltage unbalances if connected at the beginning of the feeder, but can have significant impact if connected towards the end. Similarly, in stochastic and deterministic studies conducted in [73–75], it is observed that EVs can introduce high voltage unbalances, especially in case of high charging levels. Unless the EV connection point is regulated or EV charging is controlled, single-phase connected EVs can have a detrimental effect on the unbalances.

2.4 EV controlled charging and interaction with the power system

Considering the previously described EV adverse effects, the integration of high EV numbers cannot be done by the traditional "fit-and-forget" approach as great grid reinforcement would be needed, resulting in an overall high cost for the society. Instead, different control strategies need to be designed and implemented, which represents one of the biggest challenges for the successful transition to electric mobility.

In general, based on the level of control, EV charging strategies can be divided in three categories as seen in Figure 2.6. In addition to the uncontrolled EV strategy where EVs charge at the maximum power as soon as connected to the grid, passive strategies are nowadays widely used due to the simplicity of their implementation. Passive strategies usually encourage EV owners to shift their charging period to the off-peak time by using the so-called Time-of-Use tariffs. Usually the day is divided in several periods, with the electricity price being much lower in the off-peak periods which motivates EV owners to decrease the charging cost by shifting their consumption. However, such strategies often have detrimental effects as the delayed charging process is typically automatised, resulting in a sudden demand increase in the off-peak period when all EVs start charging almost simultaneously [76]. Therefore, passive control is sufficient to separate the flexible from the inflexible demand, but other measures must be taken to distribute the flexible demand itself. In other words, such passive strategies are feasible solutions only for small EV numbers, and as EV market share increases, active charging strategies need to be adopted.

The topic of EV integration via active smart charging strategies is a common topic in the EV research community. Flexible EV charging allows customer and network operator to schedule the EV charging profiles in order to achieve different economic or technical objectives. Such objectives include providing frequency control, reducing the transformer loading, avoiding voltage violations and minimising the charging cost. For achieving the chosen objectives, two EV operating modes can be utilised - either unidirectional charging where EVs can only modulate the charging power, or bidirectional charging (V2G) where EVs can also inject power back to the grid.

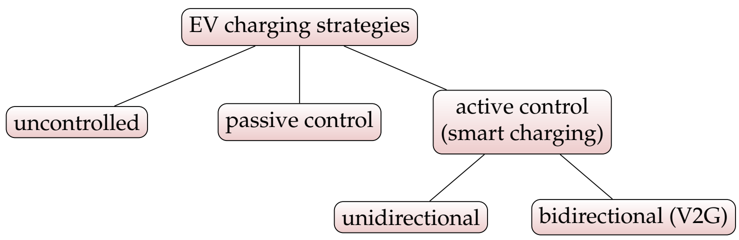

Figure 2.6: Classification of possible strategies for EV adoption.

In general, EV flexibility service can be defined as *a* ***power adjustment*** *maintained from a particular* ***moment*** *for a certain* ***duration*** *at a specific* ***location***. Thus, as seen in Figure 2.7, EV flexibility service is characterised by five theoretical attributes: (1) the direction, (2) the power capacity, (3) the starting time, (4) the duration, and (5) the location. Naturally, if EV is not V2G capable, the flexibility direction is always the same. Even though V2G technology is not widely adopted, this extension is expected to make EVs more market competitive as the flexibility range would increase.

From the system operator's point of view, EVs can be considered merely as passive electric loads, or as distributed flexible loads, depending on the chosen strategy for EV integration. As with any solution, each strategy has potential advantages and drawbacks, which are summarized in Table 2.9.

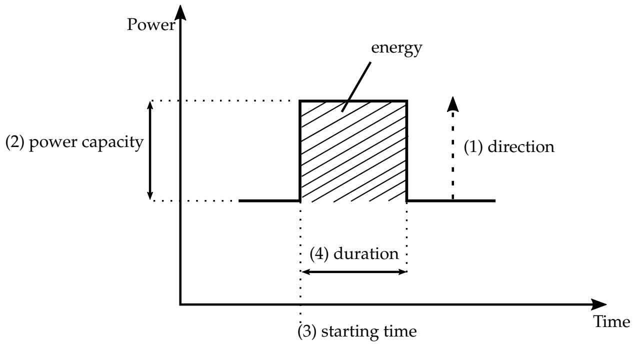

Figure 2.7: Theoretical attributes of an EV flexibility service (excluding the location).

Table 2.9: Advantages and drawbacks of different strategies for EV adoption.

Strategy		Advantages	Drawbacks
Uncontrolled (dumb) charging		✓ easy to implement ✓ user friendly ✓ user convenient	× peak power increase × component overloading × voltage deviations × power quality degradation × additional reinforcement cost × electricity cost increase
Passive control (Time-of-Use tariffs)		✓ easy to implement ✓ consumption profile flattened ✓ grid reinforcement delayed	× unbalances due to fast load increase × possible component overloading × possible voltage deviations × possible power quality degradation × customer willingness required
Active control	unidirectional	✓ flexibility provision ✓ consumption profile flattened ✓ grid reinforcement delayed	× complex implementation × ICT required × customer willingness required
	bidirectional (V2G)	✓ flexibility provision ✓ consumption profile flattened ✓ grid reinforcement avoided ✓ peak power reduction ✓ optimal RES integration	× complex implementation × ICT required × customer willingness required × possible battery degradation × losses in grid-EV-grid energy transfers

2.4.1 Role and functions of an EV aggregator

Despite the fact that EV flexibility services can be provided by an individual EV, some of them have a significant impact only if provided by a large EV fleet. In order to make such management possible, the existence of a dedicated entity is required. This entity is often called EV aggregator or EV fleet operator, and it typically acts as the middleman between EV owners and other power system stakeholders [77]. The EV aggregator's main role is to bind a certain amount of EVs whose charging profiles can be controlled, and provide various flexibility services on their behalf. Its ability to provide such services depends on the number of controllable EVs and the available flexibility of each individual EV. As the number of connected EVs increases, more flexibility is available to the aggregator for achieving the set goals, which include:

- satisfying users' driving needs while performing the optimal EV charging management according to the set objective, and
- provision of flexibility services to system operators with optimal allocation of EV resources.

Whereas the first goal is necessary to ensure the user's willingness for having the EV controlled, the second one is primarily for increasing the aggregator's economic benefits even though supporting the power system indirectly provides benefits to EV users as well. EV aggregator's goals are dependent on four main functions [78]:

(1) *Information management*: The aggregator should foresee the EV energy demand based on historical data and user preferences in order to deduce possible time schedules for flexibility provision as well as the tradable amounts of flexibility. In addition, the aggregator must forecast the electricity price as well as the price of different flexibility services. In real time, it must collect data from the connected EVs including EV identification number, SOC and user preferences if available, which allows utilising various algorithms for achieving the set objectives while satisfying users' needs.

(2) *Service bundling*: The aggregator combines many different individual flexibility amounts into tradable values.

(3) *Matching and market clearing*: The aggregator bids the bundled services on different electricity markets, e.g., day-ahead or ancillary service market. If the bid is accepted, the aggregator will control the EVs in real time to meet the commitments made in the electricity market.

(4) *Transaction guarantee*: The aggregator manages the risk of flexibility delivery and should therefore execute ex-post transaction control. It must evaluate and verify the behaviour of individual units to ensure the capability of providing contracted services, as well as proper service remuneration.

The relationship among EV aggregator and other power system stakeholders is presented in Figure 2.8 by indicating flexibility services that can be provide to each of them. Generally, these

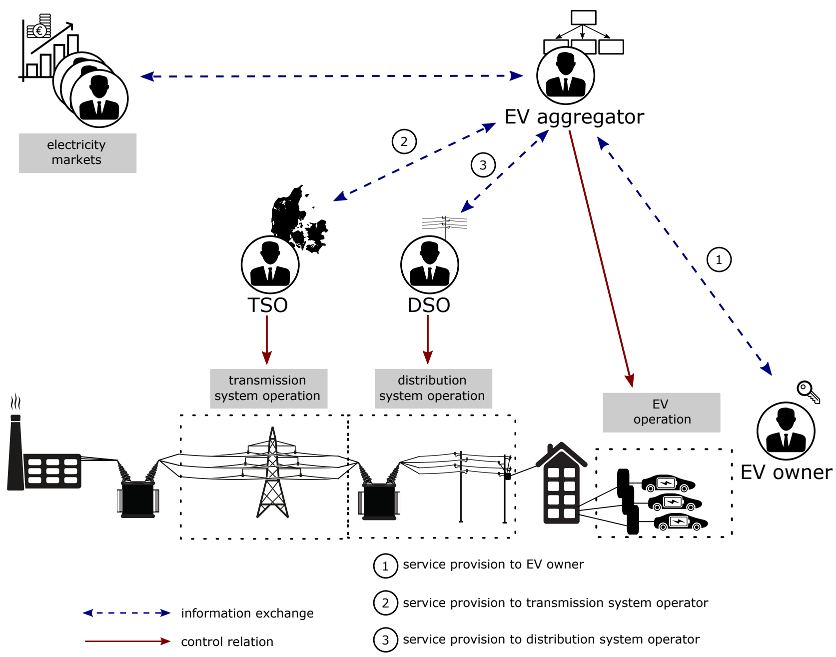

Figure 2.8: Relationships among EV aggregator and other power system stakeholders.

services can be divided into system-wide services provided to TSO for the secure and reliable operation of the transmission system, local services provided to DSOs for supporting and enhancing the distribution grid operation, and user services provided to EV owners for motivating their participation. Each of these services will be explained in more detail in the following subsections.

2.4.1.1 Service provision to EV owners

EV's potential as a flexible resource for the power system means little without EV owner's willingness to participate in such schemes. First of all, EV is not able to participate in any kind of service unless it is connected to the grid, which is dependent solely on the EV owner. On the other hand, even if the EV is available for service provision, the participation is not possible without the owner's permission. The main factors which influence the owner's willingness to participate in active management schemes are the information transparency, convenience and ease of use, and economic incentives. In order to stimulate the participation, EV aggregator can optimally schedule EVs to minimise the charging cost or it can share the profit from added-value flexibility services with the user.

Since the individual EV is a too small resource to participate in the market on its own, EV owner is obliged to pay a fixed electricity tariff unless it enters into an agreement with the aggregator who can manage its charging and participate in the market for him. Ref. [79–83] present frameworks where the aggregator participates in electricity markets in order to reduce the user's electricity bill. This objective can generally be formulated as:

$$\min f_{cost} = \sum_{t=1}^{T} P_t^{EV} \cdot \lambda_t \tag{2.1}$$

where $P_{EV,t}$ is the EV charging power at time instance t, and λ_t is the corresponding electricity price. Whereas these works assume that the aggregator is a price taker which does not impact the electricity price, [84, 85] investigate optimal EV management if the aggregator has a significant market share and such affects the price by its schedule. Besides the optimal charging from the fleet perspective, different cost minimisation strategies can be used by the individual EV controller. Such strategy is investigated in [86] where dynamic programming is used, whereas [87] additionally shows that such service can be implemented in practice. However, [85] concluded that individual EV performance in decentralised schemes can be significantly poorer compared to centralised schemes due to related price uncertainty risk which is no longer shared with other EVs controlled by the same aggregator. In any case, it is agreed that EV charging cost can be significantly reduced if the EV are properly managed.

Even though EV user's motivation to take part in various flexibility schemes is not analysed in this thesis, it is assumed they are willing to participate and, thus, their EVs can be controlled by the aggregator. This will be of particular importance for the framework presented in Chapter 5.

2.4.1.2 Service provision to transmission system operators

While the TSO has so far been able to maintain a secure system by acquiring ancillary services from large power plants, the changes in the power system introduce greater complexity. As more and more conventional generating units are being replaced by renewable resources, integration of intermittent renewable resources requires units that react faster for compensating the sudden generation changes, meaning there is an increased need for frequency regulation. A noticeable amount of research is focusing on the transition from the traditional system, where frequency is controlled by a small set of large generating units, to the future one where it is controlled by a vast amount of small distributed resources [88–92].

As EVs are essentially battery storages with a seconds-range response, the TSO can greatly benefit from EV participation in frequency service provision. As analysed in [11], EV participation in the ancillary service market appears to be one of the most promising applications as it can offer substantial earnings to EV aggregators and EV owners. Ref. [93] proved the effectiveness of using EVs in frequency regulation as a good alternative to large generating units with high prices, whereas [94] concluded that V2G capable EVs can provide great benefits to the ancillary service market, but battery degradation may represent a challenge for the viability. The typically proposed technique for EV primary frequency control, both in case of unidirectional and V2G capable EVs, can generally be expressed via the droop control method as:

$$P_{EV} = P_0 + (f - f_0)/k_p \tag{2.2}$$

where the EV active power output P_{EV} is dependent on the frequency deviation $f - f_0$ from the nominal frequency f_0, droop control characteristic (slope) k_p, and the active power offset P_0 at which the EV charges if no frequency deviation is detected. A frequency deadband can also be added if EVs should not respond to certain deviations, so the general control characteristic becomes as shown in Figure 2.9.

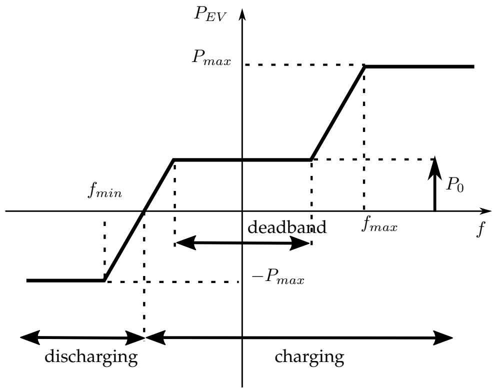

Figure 2.9: Possible EV droop control characteristic for primary frequency regulation.

Ref. [95] presents a primary frequency control which associates a participation factor to each EV. This factor is dependent on the EV state of charge and determines the droop characteristic on which the EV react. Similarly, [96] proposes a method which adapts the frequency droop control to achieve the desired SOC based on customer demands. Moreover, a comparative study performed in [97] evaluates benefits of EVs performing primary frequency regulation in an islanded system. All studies concluded that EVs can be effective in frequency regulation, likewise in isolated microgrids as in larger systems. Much of these studies include only simulations, while the experimental validation is widely neglected. The experimental work described in [98] tests the proposed frequency control, but on a set of custom-made Li-Ion batteries whose behaviour differs from commercially available units. On the other hand, [99] proves the ability of commercial EVs to maintain an islanded system with only unidirectional charging while the frequency measurement is routed via the Internet.

In addition to the required frequency regulation services, system inertia is becoming an increasingly significant service. Currently, inertia is a system property which inherently comes from the connected synchronous generators since their kinetic energy resists the sudden changes in system frequency. With an increasing amount of power-electronic-interfaced units connected to the system and large generation plants being decommissioned, system inertia is slowly reducing as the level of kinetic energy stored in the rotating masses is decreasing. However, a controller which emulates the inertial response can be implemented in the power-electronic-interfaced units, and such response is often referred to as synthetic or virtual inertia. Since EVs are power-electronic-interfaced, they are also potential providers of virtual inertia. In [100], the authors propose a primary frequency control with an inertia emulator and show that EVs providing virtual inertia introduce additional system robustness to frequency changes. Similarly, [101, 102] investigate the impact of single-phase connected EVs providing virtual inertia, whereas [103] developed and experimentally tested a virtual inertia controller applicable to V2G vehicles.

Even though it is agreed that EVs have great potential for frequency regulation provision, there is still a vast amount of research topics which must be addressed for successful implementation of such services. These topics, among others, include the development of different control strategies which can practically be implemented on large scales, as well as thorough experimental validation of the same. In this thesis, the main focus has not been put on EVs providing services to the transmission system operator, but the topic will be touched upon in Chapter 6.

2.4.1.3 Service provision to distribution system operators

In addition to services that EVs can provide to the TSO, they can also provide a range of services to the DSO. As mentioned in subsection 1.1.1, DSOs are mainly concerned with congestion management and voltage regulation to ensure the compliance with international and national requirements. However, while the services to be provided to TSOs are strictly defined, it is not the same for the DSO services since there is no available market for procuring such services. With the liberalization of the electricity industry and the recent technological improvements, DSO roles are evolving and a more active management should be introduced. A new kind of DSO is needed to take on the responsibility for balancing supply and demand variations at the distribution level as well as procuring flexibility services from distributed resources. The new design should also include a possible market mechanism at the distribution level in which available, feasible and cost-effective solutions become part of any distribution system planning efforts. This new methodology of investments, management and remuneration of decentralized flexibility resources at the distribution level is called the "proactive distribution system operation".

As EV provision of distribution grid services is the main focus point of this thesis, the possible services as well as the related literature will be presented in more detail in the following Chapter 3. Here, it is sufficient to say that EVs can provide services both to mitigate the self-inflected adverse effects and to compensate for the undesirable effects of other distributed renewable resources.

2.5 EV research and development projects

During the past years, EV integration has become a topic of growing interest, so a series of both commercial and public research projects have been launched for tackling the recognised challenges. As an illustrative example, Figure 2.10 provides an overview of European countries involved in EV research and development projects according to the Joint Research Centre of the European

Commission [104]. Most of these projects focus on facilitating large EV amounts and developing the needed charging infrastructure without analysing the controlled EV charging. Some focus more on the user side and the interoperability between different EVs and charging equipment, whereas other focus on the added value including the provision of flexibility services both to EV owners and to the power system.

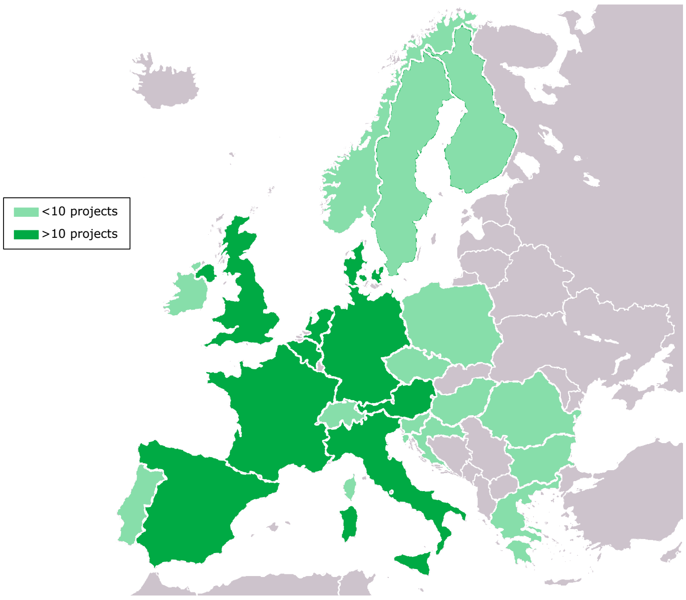

Figure 2.10: European countries participating in EV research and development projects. Adapted from [104].

In order to analyse the current research interests, a survey of finished and ongoing EV projects has been conducted. As a result, the most relevant projects are summarized here:

- *Concepts, capacities and Methods for Testing EV Systems and their Interoperability within the Smart Grids (COTEVOS)*: International project which lasted for 30 months and aimed at establishing the optimal structure for testing interoperability of all EV charging systems.
- *EDISON*: Danish funded project which lasted for 4 years and focused on PV and EV integration using open ICT standards. The project also aimed at developing and testing a demonstration platform with the corresponding infrastructure on the island of Bornholm.
- *Green eMotion*: International project between 43 European partners which lasted 4 years and aimed at exploring the basic conditions which must be fulfilled for Europe-wide electro-mobility.
- *Grid for Vehicle (G4V)*: International project between 12 European entities, including utilities and research institutions, which lasted for 18 months and aimed at exploring technical issues, regulatory barriers and business models for successful EV adoption by 2030.
- *Mobile Energy Resources in Grids of Electricity (MERGE)*: European project which lasted for 2 years and focused on EV control concepts as well as possibilities of forming virtual power plants by aggregating large EV numbers.

- *NIKOLA - Intelligent electric vehicle integration*: Danish funded project which lasted for 3 years and aimed at exploring the possible synergy between EVs and the power system by analysing and experimentally validating the potential flexibility services.
- *Nissan Leaf V2H*: Ongoing private project which aims at empowering the user by providing energy to his home via the V2G technology in emergency cases.
- *PlanGridEV*: International project which lasted 32 months and aimed at designing new planning rules for the optimal EV integration in different network topologies with various distributed energy resource penetration levels.
- *V2G demonstration project*: A national project initiated at University of Delaware, USA, to demonstrate the practical feasibility of EVs providing frequency regulation in real market environment.

Furthermore, mapping of selected projects to the previously presented EV flexibility aspects is presented in Table 2.10. The presented projects focus on different EV services including the related interoperability, but those focusing only on infrastructure installation or driving behaviour are omitted. As can be seen from the table, much research focus is put on load management and distribution grid services due to the described EV adverse effects, with an increasing interest in the local flexibility markets. Since most of the listed projects are research projects, services are being developed and analysed even if their regulatory or business feasibility is not completely validated. It is worth noting that the real applicability will highly depend on the local regulatory aspects, especially for the distribution grid services where a completely new framework must be formed. However, the general conclusion is that such services are needed for the efficient and reliable operation of the future power system.

Table 2.10: Selected EV research and development projects with the corresponding research aspects.

Name	**Type**	**Region**	**User services**	**TSO services**	**DSO services**
COTEVOS	EU	EU (various countries)	✓	✓	✓
EDISON	National	Denmark	✓	✓	✓
ElaadNL	National	The Netherlands	✓		✓
Energy Conservation	Statal	USA (California)		✓	
ESBN Trials	Private	Ireland			✓
Finseny	EU	Ireland			✓
Green eMotion	EU	EU (various countries)	✓		✓
Grid for Vehicle (G4V)	EU	EU (various countries)	✓	✓	✓
ICT 4 EVEU	EU	EU (various countries)	✓		
iZeus	National	Germany			✓
JUMP Smart Maui	Japan-USA	USA (Hawaii)			✓
MERGE	EU	EU (various countries)		✓	✓
Mobi.e	National	Portugal	✓		
Nissan Leaf V2H	Private	Japan	✓		
Nikola	National	Denmark	✓	✓	✓
Parker	National	Denmark	✓	✓	✓
PlanGrid EV	EU	EU (various countries)			✓
Power Up	EU	EU (various countries)	✓		✓
smartCEM	EU	UK, Spain, Italy	✓		
V2G demonstration project	National	USA (Delaware)		✓	

2.6 Summary

An overview of current EV technology including the contemporary EV standards has been presented in this chapter. Then, taking into account the conventional user behaviour in terms of charging time and location as well as that EVs are a high load compared to conventional appliances, the arising issues of uncontrolled EV charging have been demonstrated. With an increasing EV fast charging infrastructure, it would also be beneficial to analyse combined MV and LV impact since these grid levels interact one with another. However, as reported in [105], the distribution grid is currently far more sensitive to residential slow charging than to fast charging since fast charging stations are usually connected to the MV grid. Hence, the major focus of this thesis is put to residential EV charging at the low-voltage level.

It has been shown that the simultaneity between EV charging and residential peak load leads to detrimental grid effects at the low-voltage level, such as increased peak power and severe voltage deviations. Keeping in mind that the typical residential charging power is expected to increase, even larger adverse effects will be observed if EV charging remains uncontrolled. Hence, the benefits of controlled EV charging have been discussed with the possible added value to EV owners and power system stakeholders. A new entity, namely the EV aggregator, has been introduced for coordinating many EVs and aggregating their individual flexibility for providing various service. In general, it has been seen that EVs could support the efficient power system operation both locally and on the system-wide level. It has been recognised that EV flexibility is especially beneficial for the distribution grid operation since EVs cause considerable challenges at the local level before any significant issues arise at the system level.

Identifying how EVs can mitigate the self-inflicted adverse grid effects through provision of distribution grid services has been recognised to be of the utmost importance. In addition to the technical perspective, determining the requirements for supporting such services from the organisational and regulatory perspective is essential for successful EV integration. Therefore, the following Chapter 3 focuses on these aspects in more detail.

CHAPTER **3**

EV service provision to distribution system operators

The focus of this chapter is twofold. First, the state of the art is presented with respect to operational strategies for EV provision of distribution grid services. The emphasis is put on identifying open research questions which are tackled in the following chapters. Then, the focus is moved to recognising organisational and regulatory challenges for supporting EV distribution grid services. Various technical and non-technical prerequisites are determined, and recommendations for overcoming the identified barriers are given. The chapter includes results of the separate papers Pub. A and Pub. B which are included as appendices.

3.1 Prominent EV distribution grid services

As recognised in Chapter 2, in order to efficiently solve the operational challenges and fulfil the core responsibilities, DSOs could exploit flexibility for achieving the technical objectives linked to their physical assets and grid constraints. With respect to EV flexibility services which can be provided to the DSO, different objectives can be taken into account when defining EV charging strategies. One has to bear in mind how the classification described in this thesis is just one of the possible categorisations which is derived based on the literature survey and the current DSO operation. These services correspond to the DSO's needs, but may not be the exact products defined in the future.

The set objectives for EVs providing distribution grid services can be either technical, if they are formulated to directly address the technical issue, or economical, if they are formulated to address the cost of the technical issue, as well as a combination of both. In general, EV flexibility services for achieving the technical objectives can be divided in two groups depending on the targeted grid constraint, namely services for solving loading issues and services for solving voltage issues. These two groups can further be split into several distribution grid services as depicted in Figure 3.1.

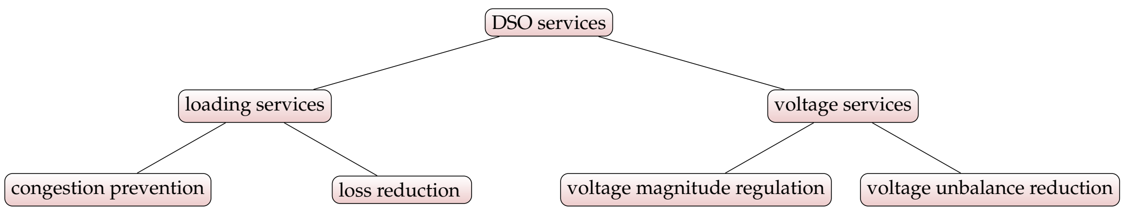

Figure 3.1: Classification of possible services EVs can provide to the DSO.

Thus, the prominent services EVs can provide to DSOs for achieving the technical objectives are as follows:

- *congestion prevention* - controlling EVs in order to prevent component overloading and postpone/avoid grid reinforcement (also known as "valley filling"); if V2G capability is available, EVs can also act as generating units for further reduction of other residential peak demand (also known as "peak shaving");
- *loss reduction* - controlling EVs in order to reduce the distribution grid losses in the observed period;
- *voltage magnitude regulation* - controlling EVs in order to provide overvoltage or undervoltage regulation for mitigating the self-inflicted voltage deviations as well as to support integration of other renewable resources; and
- *unbalance reduction* - controlling EVs in order to provide load/voltage balancing; if a three-phase connection is available for residential houses (as is the case in Denmark), a three-phase EV charger can be used for balancing the network by distributing the load across the phases, whereas the possibility of switching to the least loaded phase is viable if a single-phase EV charger is available.

Regardless if the set objective is of economical or technical nature, it is translated into a coordination system by using a certain control strategy. The EV integration methods found in the literature can generally be classified based on several aspects. Among others, they can be divided by their control approach, the temporal component, the mathematical solver and the control architecture, as seen in Figure 3.2. The final choice within each aspect is a trade-off between the strategy's purpose, functionality, optimality, complexity and execution time.

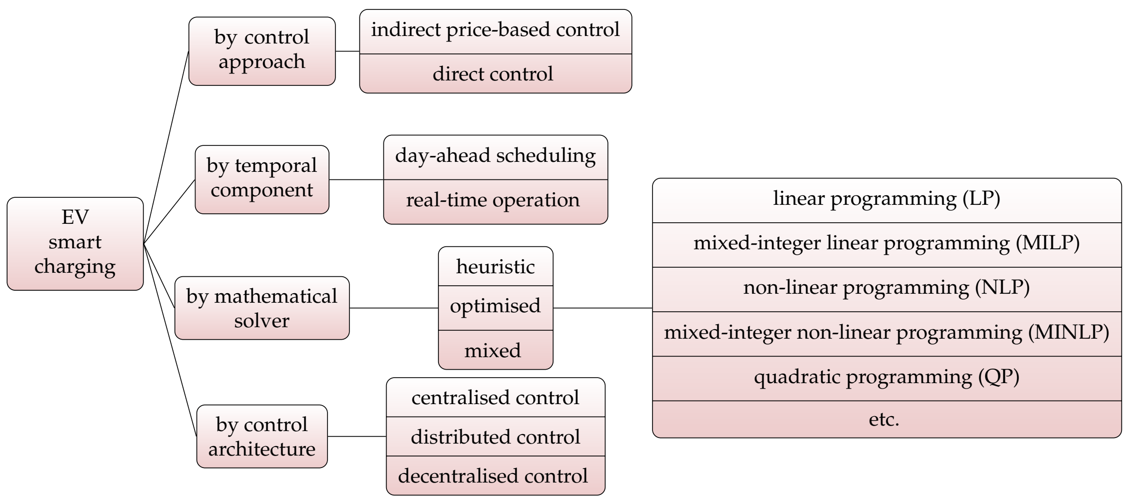

Figure 3.2: Classification of EV integration methods based on different aspects.

According to the **control approach**, the strategies can be categorised as price-based control or direct control. In the former one, the local nodal prices are changed to indirectly change EV charging profiles and implicitly solve grid issues by setting high prices for time instances when they are expected. This strategy is also known as "dynamic pricing". In the latter one, the control is applied directly on the EV charging profile to modify it according to the set objective. As pointed out in [106], indirect price-based strategies are an important element in releasing the flexibility value, but they are not good enough on their own as they bring high uncertainty to the controllers and cannot guarantee the desired response. Furthermore, based on the **temporal component**, EV methods can be divided as the ones for day-ahead scheduling, which are usually dependent on the day-ahead market, and the ones for real-time operation. From the mathematical point of view, EV integration strategies can be categorised by the type of used **mathematical method**. The main approaches are heuristic methods where problems are solved by using practical methodologies, so the solutions are not perfect, but good enough for the presented problem; optimised methods where optimal solutions are obtained under a set of constraints; and mixed methods where a combination of both is used. Finally, one of the most important aspects is the categorisation according to the **control architecture**, which divides the methods into: (1) centralised, (2) distributed, and (3) decentralised control. The main differences between them are depicted in Figure 3.3 and described further on.

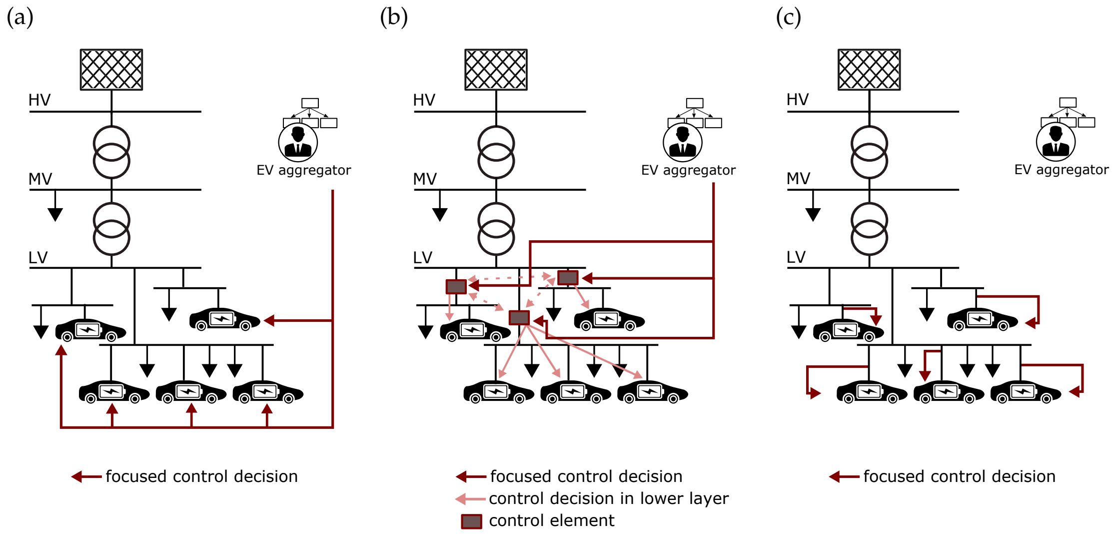

Figure 3.3: Examples of different control architectures for EV adoption: (a) centralised, (b) distributed, and (c) decentralised control.

Centralised control consists of setting the EV charging profiles by an external central entity, e.g., an EV aggregator. In centralised control, the control centre has the full knowledge of all available resources as well as the corresponding processes. Given this fact, a global optimal solution can be achieved for the set objective in the corresponding control area by using an algorithm to obtain the optimal profile for each vehicle simultaneously. However, with increasing number of controllable sources, the complexity of centralised strategies rises and the computational burden increases, so task parallelism at the central entity may be needed. Practically, the communication link between the central unit and all resources must be established which may arise as a significant cost. Due to centralised nature of data management, cyber security of such systems must be carefully addressed as system failure is inevitable if the communication link to the aggregator is broken.

Distributed control can, to some extent, be considered as a hybrid between centralised and decentralised control, since the decisions are not made centrally, but multiple control elements are involved in the decision making. Usually, a hierarchy exists among the control elements and the responsibilities are aligned with the physical hierarchical structure of distribution grids. Such architecture reduces the need for data and information exchange compared to centralised control since the local low-level objectives are hidden from the higher levels where system coordination is made. However, since the information exchanged with the lower levels is simplified and limited, the decision made in the high level may not derive the optimal system solution. A commonly used tool for distributed architectures is the multi-agent system (MAS) where two or more intelligent entities, namely agents, react autonomously to the changes in the environment, but cooperate and communicate among each other.

Decentralised control is also known as local control since the decision-making process is made locally by the individual EV without the knowledge on other units' behaviour. Each element is controlled independently from others and the charging profile is calculated based on the local measurement data without the need for external communication links. Decentralised controllers are easily scalable and the performance is guaranteed as long as the physical properties of the system do not change. However, since each controller knows only a fraction of the global state space, decentralised control may result in suboptimal solutions. Moreover, the operation transparency can be limited if there is no observability of individual controllers.

In the EV related literature, a wide range of algorithms for achieving the set objectives can be found for all three control architectures. Each of the described architectures has its benefits and drawbacks, as summarized in Table 3.1. The following subsections will present the relevant state of the art for two selected topics relevant for the remainder of this thesis. First, the focus is put on EV provision of voltage regulation with a particular emphasis on the real-time voltage magnitude regulation. Then, the focus is moved on EV load management for solving loading issues with the emphasis on EV day-ahead scheduling.

Table 3.1: Advantages and drawbacks of different control architectures for EV integration methods.

Control architecture	Advantages	Drawbacks
centralised	✓ mature architecture ✓ global optimality ✓ better utilisation of network capacity ✓ operation transparency ✓ compatible with current market setup ✓ monitoring from a single observation point	× high complexity × scalability and autonomy issues × high communication cost × complex data management × privacy issues × limited resilience to cyber attacks
distributed	✓ increased privacy ✓ decreased communication cost ✓ compatible with market setup ✓ increased autonomy and scalability	× suboptimal solution × limited operation transparency × limited resilience to cyber attacks × non-mature architecture
decentralised	✓ no privacy issues ✓ scalable and autonomous ✓ resilient to cyber attacks ✓ low communication cost	× suboptimal solution × non-compatible with current market setup × no operation transparency × possible avalanche effects of simultaneous reactions

3.1.1 EV control strategies for solving voltage issues

Voltage regulation is considered as one of the most vital issues when adopting large EV amounts since, as described in Chapter 2, uncontrolled EV charging may produce undesirable voltage deviations. In Figure 3.4, a simple LV feeder is used to explain the possible approaches for addressing the EV self-induced voltage violations.

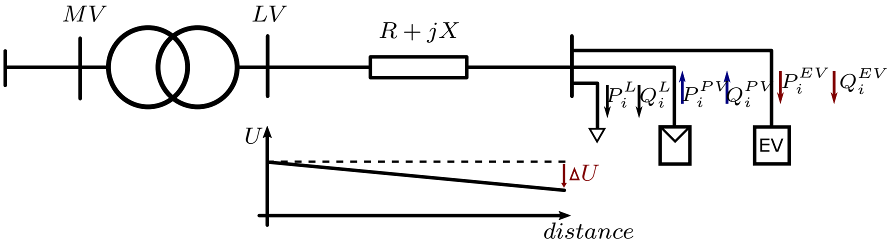

Figure 3.4: Voltage drop in a LV feeder with a high local distributed energy resource penetration ($P_i^{EV} > P_i^{PV}$).

Here, P_i^{PV} and Q_i^{PV} are PV active and reactive power injections at node i, respectively; P_i^L and Q_i^L are active and reactive power of the residential load, respectively; and P_i^{EV} and Q_i^{EV} are EV active and reactive power, respectively. The voltage drop across the feeder can be described as follows:

$$\Delta\hat{U} = (R + jX) \cdot \hat{I} = (R + jX) \cdot \left(\frac{\hat{S}_i}{\hat{U}_i}\right)^* = (R + jX) \cdot \frac{(P_i + jQ_i)^*}{\hat{U}_i^*} = \frac{RP_i + XQ_i}{\hat{U}_i^*} + j\frac{XP_i - RQ_i}{\hat{U}_i^*}$$

$$P_i = P_i^{PV} - P_i^L - P_i^{EV}$$

$$Q_i = Q_i^{PV} - Q_i^L - Q_i^{EV}$$

where U_i is the substation bus voltage and R, X are the cable resistance and reactance, respectively. Since the angle between the two nodes is very small, the imaginary part can be disregarded and the voltage drop can be approximated as:

$$\Delta U \approx \frac{R \cdot (P_i^{PV} - P_i^L - P_i^{EV}) + X \cdot (Q_i^{PV} - Q_i^L - Q_i^{EV})}{U_i} \tag{3.1}$$

Assuming there is no reactive power support neither from PVs nor from EVs, the equation can be rewritten as:

$$\Delta U \approx \frac{R \cdot (P_i^{PV} - P_i^L - P_i^{EV}) + X \cdot (-Q_i^L)}{U_i} \tag{3.2}$$

from which it is clear that as EV active power increases, the voltage drop increases as well. Therefore, modulating EV active power has a direct impact on the voltage magnitude profile. Driven by this fact, much of the existing literature focuses on controlling adverse EV voltage effects by modulating the active charging rate, either through centralised, distributed or decentralised strategies.

Often, centralised methods are not primarily used for achieving voltage regulation, but for other set objectives with voltage limits as constraints. In [64], the authors present a heuristic method to avoid congestions and implicitly improve the voltage profiles. First, a centralised algorithm is used to calculate power flows and analyse if operating conditions are suitable. Then, if any voltage violations are detected, EV charging process is paused and the corresponding vehicle is added to a waiting list until grid conditions improve. When grid conditions allow it, the charging process is restarted. Similar heuristic method is proposed in [107], where EVs are sorted in a priority list based on their impact on the power losses. Then, EVs are allowed to charge if voltage limits are not violated. In [61], a centralised algorithm is used for minimising power losses and reducing voltage deviations at the same time. Sequential series of optimisations and power flows is conducted until convergence is achieved and EV schedules are decided. While the user preferences were not taken into account in these methods, possible solution is given in [108], where a distributed random access algorithm is designed for avoiding voltage drops, but specific EV location greatly impacts the calculated access probability. Another distributed approach for voltage regulation is proposed in [109]. This approach is based on game theory and uses an iterative algorithm where all EVs send their charging profiles to the aggregator which then calculates voltage levels and sends the data back to the individual EV. Afterwards, each EV updates the charging profile to minimise the voltage deviation. However, fairness issues arise in all of the described methods since some EVs may not be allowed to charge if connected to critical nodes with high consumption and consequently low voltages.

Since voltage is a local grid characteristic, decentralised EV strategies arise as an intuitive solution for voltage regulation. The authors in [110] propose a decentralised unidirectional droop control method which limits the under-voltage problems by modifying the EV charging rate based on the local voltage measurements. Four different cases are considered and the importance of analysing unbalanced systems is pointed out since the individual EV behaviour is dependent on the phase-to-neutral voltage of the respective phase. Authors show that the proposed strategy is effective in solving EV self-inflicted voltage issues, but the charging time could increase up to three times. Moreover, EVs connected towards the end of the feeder are penalised due to their connection point, especially if other residential consumption is high. This fairness problem has been tackled in [111] where the voltage-dependent active power control is modified to take into account the EV connection point through a respective factor. Nevertheless, the charging time for a full charge is still increased more than twice.

Much of the literature focuses on modulating EV active power for voltage regulation, but considering that this affects the charging duration and consequently the user comfort, EV owners may not allow it. Ref. [112] studies various EV charging strategies for ensuring voltage quality in order to assess the degree of negative impact to users' comfort. It is concluded that such strategies could lead to undercharged EVs if not managed properly. Revisiting equation (3.1) and assuming active power P_i^{EV} is not controllable, EV reactive power Q_i^{EV} arises as a possibility for local voltage support. Moreover, if users allow active power modulation for other purposes, the reactive power support can be used for concurrent distribution grid support. Naturally, the benefits and limitations of such control must be carefully addressed, especially for unbalanced grid conditions. Motivated by these facts, a decentralised reactive power method based on droop control is proposed and studied in Chapter 4.

3.1.2 EV control strategies for solving loading issues

In addition to voltage regulation, congestion prevention is the second main concern when adopting large EV numbers. Contrary to voltage regulation which can also be provided by reactive power modulation, loading issues can be addressed only with EV active power modulation. As aforementioned, EV congestion alleviation can be divided into "valley filling" as depicted in Figure 3.5a, and "peak shaving" as shown in Figure 3.5b. Both strategies are widely found in the literature for various control architectures.

In [113], a heuristic valley filling strategy is presented where EV charging is based on a proportional controller. At each 1-min control cycle, the centralised controller counts and labels all connected EVs depending if they are charging or not. If transformer congestion is detected, the algorithm calculates which EV needs to be disconnected (the more charged ones are disconnected first). The disconnected EVs are reconnected when grid conditions allow it. The authors claim that such strategy can be implemented in real-time and provide a series of simulation on a real UK grid.

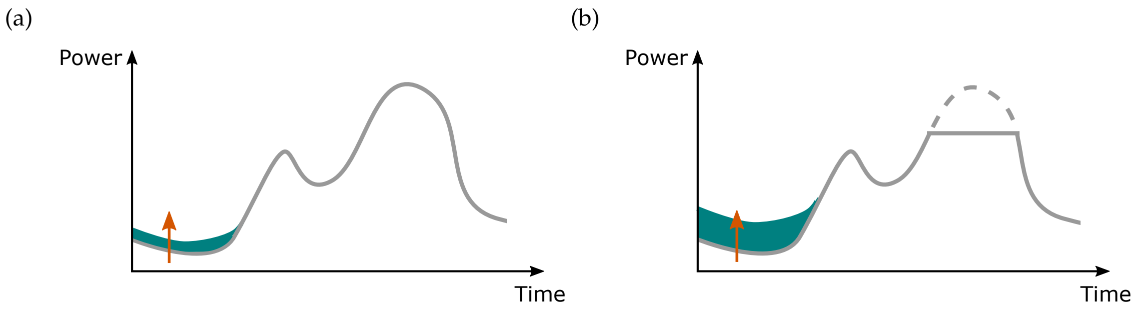

Figure 3.5: Possible congestion alleviation strategies for EV smart charging: (a) valley filling if only unidirectional charging is available, and (b) peak shaving is V2G capability is available.

Another heuristic method is proposed in [114], where at each time-step all EVs increase their charging rate by a fixed additive amount until the maximum loading limit is exceeded. Then, a congestion signal is broadcasted and each EV decreases its consumption rate by a multiplicative factor. In perpetuity, all participants converge to a utilisation pattern. Similar methods are proposed in [115–117] where decentralised valley filling methods are proposed based on a central signal broadcasted by the DSO. Additionally to various heuristic methods, optimisation techniques are commonly found in the literature both for valley filling and peak shaving. A centralised approach is presented in [118] where the optimisation is formulated for peak shaving in the following 24-h period. Here, the distribution grid constraints are not embedded in the optimisation formulation itself, but an *a posteriori* constraint check is conducted for balanced grid conditions. Similarly, the centralised method proposed in [119] ensures enough energy for the predicted EV trips while respecting the grid constraints with an *a posteriori* check for unbalanced systems. On the contrary, distribution grid contraints are included in the centralised method presented in [120], but only for balanced systems.

In addition to congestion prevention, EVs can also be directly scheduled to provide loss reduction, which indirectly provides congestion prevention since losses are dependant on the current flows. The objective can generally be formulated as:

$$\min f_{loss} = \sum_{t=1}^{T} \sum_{l=1}^{N_{lines}} R_l \cdot I_{l,t}^2 \tag{3.3}$$

where T is the number of observed time instances, N_{lines} is the number of distribution grid lines with the resistance R_l, and $I_{l,t}$ is the current through line l at the time instance t.

An example of such a strategy is presented in [107] where EVs are sorted in a priority list based on their impact on power losses. On the other hand, [121] explores the relationship between three optimal charging schedules for achieving the loss reduction, namely minimising the losses described in equation (3.3), maximising the load factor, and minimising the load variance. According to the authors, all coordinated algorithms provide similar results in terms of energy losses on a wide range of tested systems, but the analysis is again conducted only for balanced distribution grids, meaning that the unbalance impact on losses is completely disregarded.

Whereas the previously described strategies focus on EV coordination for directly addressing the loading issues, various strategies are proposed for an indirect congestion prevention. More precisely, since EV owners must allow active power modulation, their main motivation for participating in such schemes is minimising the EV charging cost. Typically, such strategies depend on the corresponding electricity market and focus on the day-ahead scheduling to charge in times of low electricity prices. This can indirectly lead to distribution grid benefits as well since low electricity prices usually coincide with the periods of low consumption. For such day-ahead scheduling, most of the identified literature uses the optimal power flow formulation in order to minimise the cost according to equation (3.4).

$$f = \sum_{t=1}^{T} \Big[\sum_{EV=1}^{N_{EV}} \Big(Cost_t^{EVch} - Profit_t^{EVdch} \Big) \Big] = \sum_{t=1}^{T} \Big[\sum_{EV=1}^{N_{EV}} \Big(c_t^{EVch} \cdot P_t^{EVch} - c_t^{EVdch} \cdot P_t^{EVdch} \Big) \Big] \tag{3.4}$$

where $Cost_t^{EVch}$ is the EV charging cost and $Profit_t^{EVdch}$ is the EV discharging profit at time instance t with discharging/charging price c_t^{EVdch}/c_t^{EVch} and discharging/charging power P_t^{EVdch}/P_t^{EVch}. Naturally, the discharging variables exist only if V2G capability is available.

A number of strategies with such objective is recognised in the literature for all control architectures. Centralised control strategies for cost minimisation are proposed in [81, 82, 122], distributed ones in [123, 124] and decentralised ones in [125, 126]. Whereas these strategies focus only on active power modulation, the additional EV reactive power control is included in [127]. However, even though the listed methods are proven to be effective for congestion prevention, all of them completely omit the local distribution grid constraints, so the obtained EV charging schedule may not be feasible in the corresponding distribution grid. On the contrary, a centralised day-ahead strategy which takes the distribution grid constraints into account is proposed in [128]. Here, it is assumed that the DSO has bilateral contracts for managing all available resources, including EVs, so the objective function is formulated as minimising the DSO's operational cost. The formulation includes the full AC power flow with non-linear equations, but the method is developed only for balanced systems. Similarly, [129] proposes a centralised method for EV scheduling with the full AC power flow formulation, but again the method is applicable only to balanced systems. On the other hand, the unbalanced grid constaints have been taken into account in [130]. This work proposes a centralised methods based on linear programming to maximise the vehicle charging power while satisfying the distribution grid constraints. Linear programming decreases the complexity and consequently the computational time, but since the full AC power flow equations are linearised around the operation point, the quality of the estimated operation point impacts the approximation error.

As pointed out in [131], most of the EV scheduling methods are single-objective and combining several objective functions has scarcely been touched upon. If EV users are willing to participate in the EV day-ahead scheduling, it is highly likely they are motivated by minimising the charging cost. Then, this becomes the aggregator's main concern and must be included in the day-ahead scheduling formulation. On the other hand, the local DSO would like to schedule EVs in order to avoid loading issues and minimise its operation cost, so combining economic concerns of both the EV aggregator and the DSO becomes of utter importance. Still, it is observed that proposed EV scheduling strategies mostly focus only on one of the two objectives. Moreover, most of them disregard the potential EV reactive power support and typically they ignore the unbalanced distribution grid constraints. Driven by this fact, developing a method which combines all of the mentioned aspects is the focus of Chapter 5.

3.2 Key aspects for enabling EV distribution grid services

Whereas the technical value to the system is evident for different EV smart charging strategies, integrating EV distribution grid services into the European regulatory context is not straightforward, so the organisational perspective must be analysed in addition to the operational one. In a liberalised environment, local distribution grid support can be acquired either through mandatory grid codes or through trading flexibility services. As previously described, there are different control strategies which can be used for EV flexibility procurement, either on individual basis or for coordinating many EVs. Regardless of the chosen strategy, some common prerequisites must be fulfilled to enable the local EV flexibility services, both from the technical and the non-technical perspective.

Enabling EV flexibility procurement on local basis requires a dedicated framework which includes three layers [132]: (1) *the techno-institutional layer*, which defines what resources are controlled and by whom, (2) *the economic layer*, which defines the trading organisation and the remuneration schemes, and (3) *the operational layer*, which defines how the resources are controlled. When dealing with EV flexibility provision for emerging DSO services, key prerequisites must be identified as guidelines for large-scale procurement, regardless if the remunerated services are obtained through bilateral contracts or a local flexibility market. Whereas the remainder of this thesis will focus on the operational layer and the technical assessment of proposed control strategies, here the focus is put on analysing the techno-institutional and the economic layers, with emphasis on recognising barriers for active EV involvement and providing recommendations for overcoming them.

3.2.1 Technical prerequisites for enabling EV services to DSOs

First of all, in order for an EV to provide flexibility services to the DSO, clear and generic flexibility products must be defined, similarly to the ancillary services defined for the TSO. As previously shown in Figure 2.7, each EV flexibility service has five theoretical attributes which must be addressed when establishing the distribution grid products. In addition to the theoretical ones, practical attributes arise due to resource imperfections, as shown in Figure 3.6, and such must also be taken into account.

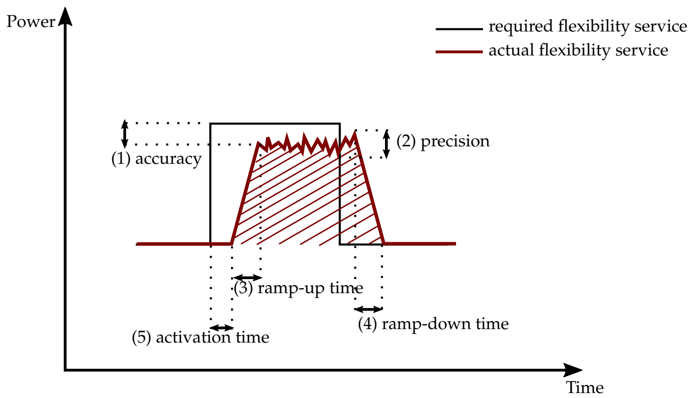

Figure 3.6: The practical attributes of a flexibility service.

Based on the individual EV capability, the flexibility can be grouped by the aggregator and offered to the DSO. To make such management possible, generic requirements must be defined with respect to the described attributes, including:

(1) *Direction*: The information if an EV can provide only unidirectional or bidirectional power flow must be known as well as the information on reactive power capabilities. These properties are obtained through contracts with the EV owners. The DSO requests and the EV offers a flexibility service of a certain power direction.

(2) *Power capacity*: Limitations on available capabilities are required such as the nominal rating of the charging equipment and the active/reactive power capability. The required/offered power capacity must be defined for each flexibility request/offer.

(3) *Duration*: The period within which flexibility is acquired must be defined in the flexibility request/offer. Then, the maximum energy which can be requested/provided in the contracting period is implicitly contained through the required power capacity and the duration.

(4) *Location*: Location of the flexible EV can be defined either as the node of coupling or as the corresponding superior substation depending on the required service. For example, exact EV location is of little importance if EV is providing congestion prevention as long as it is supplied through the congested transformer, whereas the voltage regulation service is highly dependent on the point of common coupling.

(5) *Starting time and maximum activation time*: The period between receiving the required set-point and activating the required flexibility must be determined. More precisely, the DSO defines the maximum acceptable activation time in the flexibility request, while the EV aggregator defines the maximum activation time of its resources in the flexibility offer.

(6) *Activation frequency and means*: Estimating the activation frequency, i.e., how many times can a service be activated within the contracting period is needed for estimating the contract value. Moreover, the way the service is activated should be clearly defined, e.g., if it is a direct load control or a price-based control.

(7) *Ramp-up/ramp-down time*: The acceptable and/or desirable upwards rate-of-change duration between the activation time and full service provision must be defined. Similarly, the acceptable and/or desirable downwards rate-of-change duration for service deactivation must be determined.

(8) *Accuracy*: The acceptable difference between the required and the delivered response must be defined, e.g., the acceptable response band.

(9) *Precision*: The acceptable variation of the delivered response must be defined, i.e., the amount of variation that exists in the delivered response for the same required value.

In combination with the maximum activation time and the ramping time, the accuracy and the precision can be used to define the service quality. Then, more accurate service providers would be more attractive to contract since they would be more reliable for the DSO. For enabling EV distribution services, thorough investigation of practical EV attributes is a key prerequisite. Establishing standardised tests for evaluating the internal EV parameters would enable benchmarking various vehicles to each other and provide EV aggregators as well as DSOs with the knowledge of EV technical capabilities.

In addition to the listed technical specifications for each flexibility service, when talking about EV flexibility procurement, the practical implementation must guarantee interoperability between different equipment and involved stakeholders. Specific terms and general requirements need to be defined through international standards to ensure safety, security and reliability of both the physical electric system and the communication layer. The mapping of the most important contemporary standards for supporting EV distribution grid services is depicted in Figure 3.7.

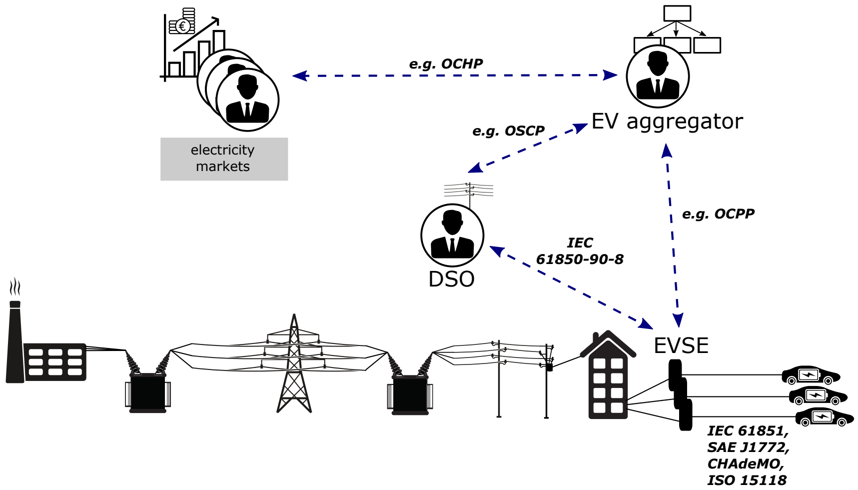

Figure 3.7: Relevant EV standards and protocols with respect to EV distribution grid services. Adapted from [133].

Nowadays, the vast majority of contemporary EVs are compliant with IEC 61851 or SAE J1772 according to which the EV charging current can be limited between the minimum charging current of 6 A and the maximum one, which is the EVSE rated current (10 A, 16 A, 32 A, etc.), in discrete 1 A steps. This is done by changing the duty cycle of the Pulse Width Modulation signal on the EVSE communication line called the Control Pilot line, as seen in Figure 3.8 for normal operating conditions. The EV must respond to the duty cycle change by reducing the charging current and guaranteeing it will not surpass the set limit. Such capability of limiting the current is seen as the first step in enabling EV distribution grid services. As opposed to the low level communication described in IEC 61851, a newer standard ISO/IEC 15118 [134] specifies the communication between the EV and the EVSE on a higher level. The standard covers information exchange between all actors involved in the electrical energy supply process to the EV, taking into account data encryption for both confidentiality and data integrity purposes. This standard is highly relevant for EV flexibility procurement, yet it is not widely supported by the contemporary EV equipment since

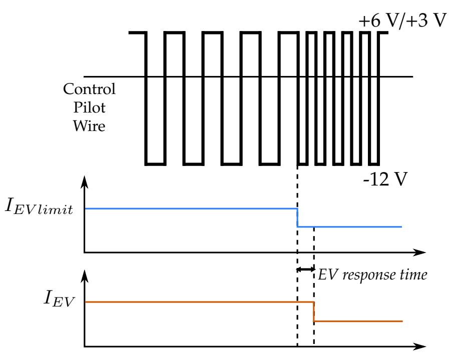

Figure 3.8: Controlling the EV charging limit under normal conditions according to IEC 61851.

it is still under development. Similarly, the scope of the standard IEC TR 61850-90-8 is to describe the communication link between EVSEs and power system operators as well as to harmonize information flow models independent of the underlying hardware and software protocols, but the standard is expected to be included in the second edition of IEC 61850-7-420 and is still not widely supported. Additionally, three open application protocols are relevant for EV flexibility procurement due to the lack of international standards: the Open Charge Point Protocol (OCPP) [135] which is developed for the communication between the EVSE and the EV aggregator; the Open Clearing House Protocol (OCHP) [136] which enables communication between the EV service provider and the clearing house system; and the Open Smart Charging Protocol (OSCP) [137] which is used for communication between the EV aggregator and the DSO. As EV flexibility provision is not a common practice, the lack of international standards for supporting it is not surprising. However, harmonisation of communication standards and protocols between all actors participating in EV flexibility procurement is the key prerequisite for ensuring the interoperability between various equipment, and successful provision of EV distribution grid services.

In addition to harmonised communication standards, several other technical prerequisites must be fulfilled for enabling EV flexibility services to the DSO. These are:

- *EV supply equipment*: The use of EVSEs with sufficient computational and communication capabilities is the key for enabling advanced flexibility services as it allows controlled EV charging, either autonomously or in a coordinated fashion.
- *Identification*: Unique ID number must be assigned to the individual EV, or alternatively to the EVSE, based on which service procurement and settlement can be made. This is the responsibility of the EV aggregator.
- *Grid observability*: Mass roll-out of smart meters is the main facilitator for contracting EV flexibility services since the accurate measurement of consumption patterns is crucial for an effective billing [138]. All installed meters should be certified by the corresponding DSO or an independent third party to ensure their compatibility with the pre-defined verification protocols. Requirements on the specific measurement parameters, such as sampling rate and accuracy, must be standardised to ensure interoperability. The sampling rate must be chosen as a trade-off between the accuracy and information speed on one hand, and the installation and data management cost on the other.
- *User information*: EV user must be willing to provide basic EV information such as the maximum battery capacity and initial SOC when plugged-in. These information should also be made accessible by the EV manufacturers, which is, e.g., currently not the case for the SOC data which is encrypted. Furthermore, at least the plug-in time must be recorded by the aggregator for assessing the provided flexibility in the settlement period.

Besides the technical prerequisites, the non-technical prerequisites are recognised as a greater challenge due to large diversity of distribution systems and regulatory frameworks across Europe. An overview of the most important prerequisites is given in the following subsection.

3.2.2 Non-technical prerequisites for enabling EV services to DSOs

Unless certain EV flexibility service is made mandatory through grid codes, a number of non-technical issues must be investigated by the relevant stakeholders to make it a tradable commodity.

Identifying and fulfilling the organisational and regulatory prerequisites is crucial to ensure that the future distribution system effectively deals with the EV integration. In the context where active distribution grid management schemes are still to be developed, it is important to recognise the prerequisites for active EV involvement in the early stage of the development. In general, local flexibility trading design can mirror the wholesale electricity market in the temporal, contractual and price-clearing dimensions, but it has a specific spatial component due to the local grid conditions. As pointed out in [139], it is still unclear who should initiate the development of local DSO markets or if the trading should be on bilateral basis due to locational restrictions. However, it is mainly agreed that a dedicated flexibility trading platform is needed to invoke the resource flexibility [140], as via such interface DSOs could require and service providers, including EV aggregators, could offer flexibility..

The open flexibility platform would enable trading of several flexibility services through different markets with their own rules or, if local flexibility markets are not established, it could be used for contracting services on bilateral basis. A possible organisation of such a flexibility framework is given in Figure 3.9. Here, the EV aggregator is not an electricity supplier to the end-customers, but only a flexibility supplier which enables EV owners to provide flexibility. In reality, the aggregator can simultaneously be both the supplier and the flexibility provider [141], but such dual-role may lead to abuse of power since the supplier could manipulate the load forecasting data to increase the need for flexibility. In any case, the contractual and the operational relations among the aggregator and other entities must be defined as well as the information to be exchanged between them.

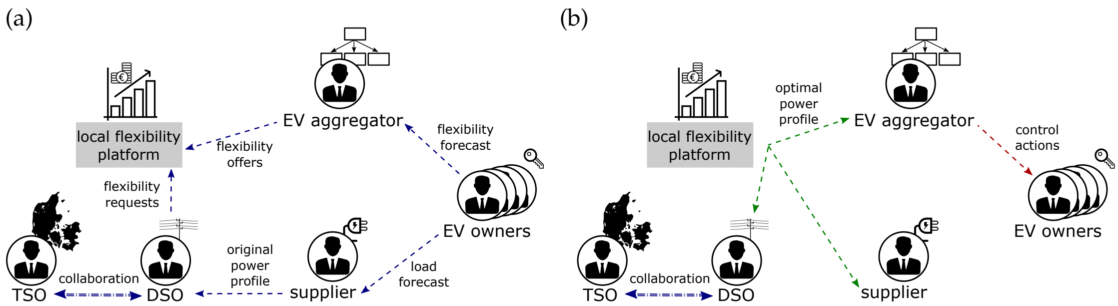

Figure 3.9: Possible local flexibility framework for the day-ahead trading of EV distribution grid services: (a) before, and (b) after the clearing process. The TSO-DSO collaboration is indicated without a detailed elaboration, as the focus is put on the local level. Adapted from [142, 143].

If a dedicated flexibility platform is available, trading of EV flexibility for local DSO services can be divided in five phases:

(1) *Contracting*: In this phase, the contractual relations between the aggregator and other participants are established. For example, the bilateral contracts between the aggregator and EV owners are signed to establish the maximum flexibility capacity and the means of activation (dynamic pricing or direct control).

(2) *Forecasting and planning*: The supplier forecasts the demand of their customers including the EV consumption, as depicted in step (1) in Figure 3.10. At the same time, EV aggregator estimates the available flexibility from the controllable resources.

(3) *Grid constraint checking*: The DSO determines whether the energy forecast by the supplier can be distributed without any grid violations. If it cannot, the DSO requests flexibility through the flexibility platform together with providing the information on the available grid capacity, as shown in step (2) in Figure 3.10. Simultaneously, EV aggregator offers the estimated flexibility through the platform, as depicted in step (3) in Figure 3.10.

(4) *Scheduling and operation*: EV scheduling can be split in two mechanisms: ahead-markets and real-time dispatch. First, the local flexibility operator, who operates the flexibility platform, obtains the EV day-ahead schedule based on the received flexibility requests and offers, as shown in step (4) in Figure 3.10. The actual resources are dispatched in real-time according to the optimal plan from the day-ahead scheduling. Should the day-ahead scheduling fail to resolve grid issues and unexpected deviations occurred, real-time flexibility dispatch could be applied in which the DSO would make autonomous decisions for load adjustment. Such real-time dispatching can be either voluntary if the DSO negotiates with aggregators on bilateral-basis to procure additional flexibility, or compulsory if the DSO unilaterally makes decisions to resolve grid issues, but incurs a penalty for it.

(5) *Settlement*: In this phase, the delivered flexibility is validated through metering data and any sold flexibility is settled and remunerated. The settlement comprises of paying for the contracted flexibility which was not delivered, i.e., the capacity payment as well as paying for the one which was delivered, i.e., the energy payment. The aggregator pays the user for the offered flexibility either through a fixed fee or as a percentage of the revenue from the actually activated flexibility.

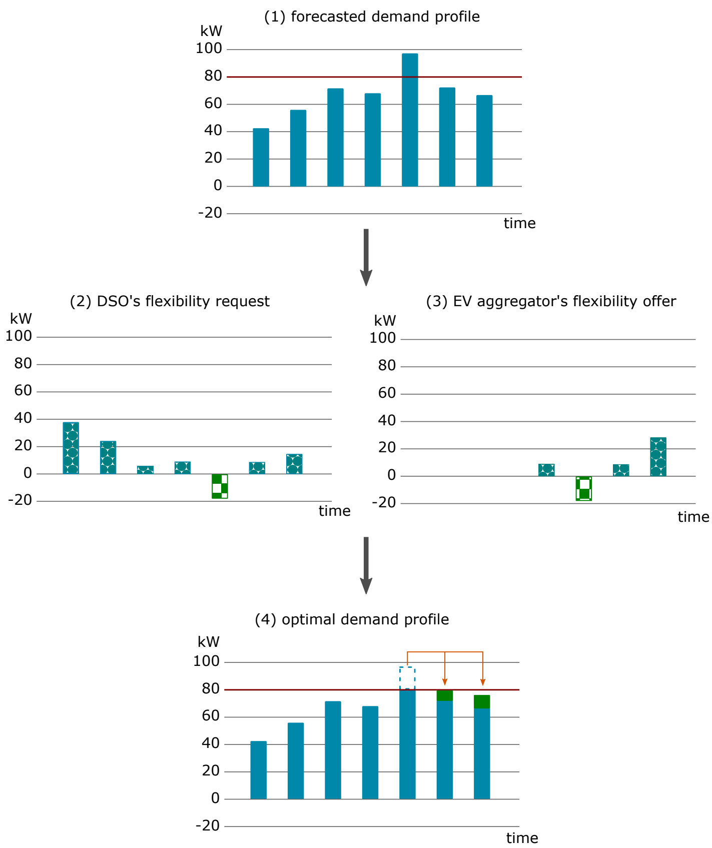

Figure 3.10: Example of flexibility trading in case of congestion management. Adapted from [142].

Since trading of EV flexibility at the distribution level is nowadays non-existent in all European countries, the key non-technical aspects to be addressed when establishing such local platforms include:

- *Flexibility platform administration and operation*: Who is to operate and administrate the flexibility platform is debated and it is conceptually possible to have separate entities for the distribution system operation and the distribution system flexibility operation. Some claim that assigning a dual role to the future DSO is more beneficial as the DSO is aware of the grid status and the operational conditions [144]. However, this can also lead to market manipulations depending on the regulatory environment, so the introduction of an independent entity may be needed in case local markets are introduced. Regardless, the flexibility operator, which is defined by the regulator, must manage and operate the flexibility platform in the day-ahead and intra-day phase by accumulating the bids, and obtaining optimal resource schedules.

- *Operational and planning authority*: The DSO must have the operational authority to ensure the short-term reliability of the respective distribution system by acquiring flexibility services to deal with contingencies. In addition to operational authority, the DSO must have planning authority for the efficient grid expansion. More specifically, the DSO must assess requirements for grid adequacy, and propose network upgrades in an open, fair and transparent manner. All stakeholders should be aware of the projected network changes and regulatory actions must challenge the DSO investment plans.

- *Independence and fair access*: Flexibility operator must be independent of any participant or resource owner to operate flexibility trading in a fair and an impartial manner. Flexibility operator should not own any flexibility assets in the corresponding distribution area to avoid conflict of interest. The access to the flexibility platform must be open and fair for all interested participants.

- *Transparency*: Participants must have access to financial information such as the cleared prices and other financial figures, whereas the bidding process, if existing, should be blind. The flexibility framework must be transparent in terms of data exchange among different parties, rules on the clearing process, operating costs, and system operation procedures. Clarity is needed on criteria how to become a participant with the corresponding pre-qualification process, respective rights and obligations as well as criteria for terminating the participation.

- *Minimum bid*: The power consumption at the distribution level is of much lower values than at the transmission level, so even one EV can be a valuable asset for a certain distribution feeder. The minimum bid requirement for flexibility trading should reflect this fact and be in the kilowatt range to facilitate distribution grid services. Some literature even proposes bidless markets where any resource can respond to the real-time signals at any time [145].

- *Settlement period*: The settlement period must not be smaller than the smart-meter sampling rate. For a successful EV integration, the lower the rate is, the more EV users would be willing to wait for the flexibility provision period to finish. From the DSO perspective, high sampling rates are not a necessity, but could be of additional value if EVs were to provide flexibility services to the TSO as well.

- *Flexibility price*: The price for each flexibility service should be determined. This process presents a challenge as it is not easy to assess the value of demand shifting and potential impact on the user comfort, making it difficult to assign a monetary value for providing flexibility. In any case, the settled price must be lower than the cost of grid reinforcement.

- *Consumption baseline*: Flexibility only exists because we can estimate what the load profile would look like if flexibility was not activated. After all, only the actual load profile can be measured and the unperturbed one never really existed. If a common baseline is not accepted by all involved participants, many settlement disputes will arise. Therefore, the baseline must be defined by an independent actor who has no interest in flexibility.

- *Collaboration between the TSO and the DSO*: Interaction between the DSO and the TSO must be ensured, particularly if distribution grid services trigger the need for system-wide services. Two possible ways to improve this relationship are *cooperation* and *coordination*. The former implies a mutual agreement for a set of use-cases, with clear roles and defined priorities for each of them. Cooperation is necessary to define mandatory assistance procedures, and cascading principles between the operators. The later one relies on the flexibility platform with a proper set of market rules to avoid double bidding and coordinate the use of flexible resources on different markets, e.g., for frequency regulation and congestion management. For instance, if EV aggregators lose money when making counter-effective offers, they could inherently enhance the coordination.

- *Privacy*: Through analytics and predictive profiling, a wealth of information can be distilled from the usage data generated by the smart energy systems. Therefore, all data on energy consumption should be treated as personal data subject to data protection and confidentiality between the involved parties.

Furthermore, since DSOs are natural monopolies, the support of regulatory frameworks is essential, so identifying and overcoming the regulatory barriers is crucial to enable local EV flexibility services. Even though the DSO regulatory framework differs from country to country, some common factors can be clearly identified. The regulatory support must cover the procurement of such services as well as the respective metering and data management aspects. First of all, to procure any kind of flexibility, these actions must be allowed by the respective regulation, which includes the regulation for introducing independent EV aggregators as well as for DSOs contracting flexibility services. The DSO should be free to consider both the traditional reinforcement means and the flexibility based solutions, or a combination of the two. Even if regulations do not encourage flexibility procurement, they must not forbid it.

Secondly, the regulatory framework must define clear DSO roles related to the active system management and recognise the potential cost for flexibility procurement. Ideally, the regulation should provide explicit support via incentives for acquiring flexibility services. The remuneration schemes should not include only cost estimations for the capital expenditures, but the innovation in distribution networks should be stimulated by including the investment costs of new technologies. The remuneration formulas should contain incentives to lower energy losses and improve the quality of supply with bonuses and penalties charged according to the established performance targets. In addition, the regulatory period should incentivise the long-term innovation with a smooth transition between the regulatory periods.

Additionally, the regulated electricity tariffs must be designed in order to ensure the full cost-recovery for the DSO's allowed expenses while encouraging a more efficient grid use. As network upgrades will still be needed, the predictable and appropriate regulatory regime must be supported by sufficient incentives for the necessary network reinforcement. The electricity tariff should include at least two components: a capacity and an energy component with the right balance between them. The capacity component would cover the necessary grid reinforcement cost, whereas the energy component could vary to reflect the local network conditions. Additionally, the tariffs should be revised more often to reflect the contemporary technology status. This would provide a strong incentive for DSOs to make efficiency gains and ensure they do not over-invest to avoid grid issues.

Finally, regulations must ensure that data sharing is free of charge for all eligible players and that processes for data exchange are defined with clear responsibility for data management. Installing the meters and managing the data imposes extra costs, and recovering these expenses must be ensured by the regulation. Data exchange is especially vital to ensure DSO-TSO collaboration.

3.3 Recommendations for supporting active EV involvement in distribution grids

As recognised before, enabling EV distribution grid services requires a coordinated participation of the full energy value chain. However, most European countries still suffer from a critical gap between the political sustainability plans and the implemented regulatory frameworks for local flexibility procurement. The current status can be assessed from four aspects: (1) enabling consumer participation and aggregation, (2) standardised measurement and verification requirements, (3) payment structures, and (4) appropriate programme requirements for distribution grid services (flexibility products, minimum bid, penalty for non-delivery, etc.). To provide insight into contemporary conditions for supporting EV flexibility services at the distribution level, Table 3.2 and Table 3.3 summarize the situation in several European countries with respect to smart metering and several regulatory aspects.

Based on the afore recognised technical and non-technical prerequisites as well as the current regulatory and infrastructure status, a series of recommendations is provided as guidelines to a future flexible distribution system where EVs become proactive participants at the distribution level. These recommendations are as follows:

Table 3.2: Current status for several European countries with respect to smart metering [146].

Country	Wide-scale roll-out by 2020[a]	Sampling rate	Data management responsible
Belgium	○	○	DSO
Denmark	●	15 min/1 h[b]	DSO
France	●	30 min	DSO
Germany	◐	15 min	meter operator/DSO
Ireland	●	30 min	DSO
Italy	●	10 min	DSO
Netherlands	●	15 min	DSO
Spain	●	○	DSO
UK	●	15 min	supplier

[a] ○ = the criteria is not fulfilled, ◐ = the criteria is fulfilled to some extent, ● = the criteria is fulfilled
[b] 1 h for smart meters installed until 2011, 15 min for the meters installed after 2011

Table 3.3: Current status for several European countries with respect to DSO regulation [147–149].

Country	Aggregation enabled by regulation [a]	DSO service requirements defined[a]	Network tariff structure [b]	DSO regulatory period (years)	Mechanisms for stimulating innovation[a]
Belgium	◐	○	€ + €/kWh	4	○
Denmark	◐	○	(€)[c] + €/kWh	3	◐
France	●	○	€ + €/kW + €/kWh	4	○
Germany	◐	○	€ + €/kWh	5	○
Ireland	◐	○	€ + €/kWh	5	◐
Italy	○	○	€ + €/kW + €/kWh	4	◐
Netherlands	◐	○	€ + €/kW + (€/kVArh)[c]	3	○
Spain	○	○	€/kW + €/kWh	6	○
UK	◐	○	€ + €/kWh	8	◐

[a] ○ = the criteria is not fulfilled, ◐ = the criteria is fulfilled to some extent, ● = the criteria is fulfilled
[b] fixed charge (€); capacity charge (€/kW); energy charge (€/kWh); reactive energy charge (€/kVArh)
[c] possible

- *Smart metering*: Most of the countries have plans for wide-scale roll-out of smart meters supported by the regulatory framework. Yet, standards are needed to ensure the interoperability as well as the basic functionalities, e.g., the universal sampling rate and the acceptable accuracy. The same applies to advanced metering infrastructure which must be available for individual EVs to allow verification of flexibility delivery. From the EV integration perspective, the standardised sampling rate should not be higher than 5 minutes to be aligned with the trading settlement period, which is described later on. Moreover, if the meters installed in the EVSEs could serve for flexibility settlement, the overall system complexity would decrease. However, in order to make such a system viable, clear verification and pre-qualification protocols must be defined for the EVSE measurement equipment in addition to the responsible parties for carrying out the validation and the data management.

- *EV identification*: Standardised way of assigning an identifier to the individual EV must be defined. This ID must be unique to ensure that the proper EV is procured and remunerated for the delivered flexibility. EV identification should be carried out by an aggregator and the data must be kept private.

- *DSO regulation revision*: All current regulations which forbid the DSO to procure flexibility should be removed and regulations need to be revised with respect to two key areas. On one hand, the set of new tasks for the DSO related to the active system management must be defined, including data management and flexibility operation responsibilities. On the other hand, it is necessary to revise the current incentives for performing the traditional DSO tasks, including the remuneration and tariff structures. The remuneration schemes should incentivise the long-term innovation and the reduction of operational expenditures, whereas the tariffs should include both the capacity charge component and the dynamic energy component. Such tariff system would also encourage EV user participation in flexibility schemes as EV is a significant load which would increase the peak power, making them more likely to allow EV control. Moreover, the regulatory period should be prolonged with a smooth transition between the periods, so that regulatory uncertainty is reduced when investing in new technologies, therefore incentivising DSOs to reduce the cost in the long-run.

- *Local flexibility platform*: Local flexibility framework should be established with an open flexibility platform to enable trading of flexibility services. The regulatory body should clearly define the roles and responsibilities for each of the involved parties as well as who is to operate and clear the developed platform. The flexibility operator should be independent of any EV owner and provide an open and fair access to all interested participants with transparent information flows.

- *Flexibility products*: Clear and generic flexibility products must be defined which are applicable to any EV. Contractual arrangements should be simple, transparent and fair to allow all willing EV owners to participate in such schemes. Each flexibility product must have clear conditions for procurement and defined technical requirements including: the direction, the required power capacity, the duration, the location, the starting time and the maximum acceptable activation time, the estimated activation frequency with the corresponding activation mean as well as the acceptable ramp-up/down time, accuracy and precision.

- *Minimum bid*: If flexibility trading is introduced, lowering the requirements for minimum participation would allow easier entry of many players to the local flexibility platform. The minimum bid should be in the kilowatt range and preferably the lowest possible. This would allow both the DSO and the EV aggregator to be more pliable in their flexibility requests and offers.

- *Settlement frequency*: The settlement frequency of the local trading process must correspond to the measurement interval, i.e., the settlement period should not be lower than the data sampling rate. In [145], a 5-min settlement period has been recognised as a trade-off between the related metering and communication cost, and the system performance. Such settlement period would not impose a high inconvenience for the owner in case the EV is unavailable during the contracted period, and the user has to wait until flexibility provision is terminated. However, higher settlement period may discourage the user to participate in flexibility trading as it can influence his comfort.

- *TSO-DSO priority*: First, a clear priority list between the TSO and the DSO must be defined for normal operation and various emergency situations, especially when procuring flexibility services at the distribution level inadequately interacts with the transmission system needs. Secondly, open and interoperable standards should be defined for the TSO-DSO interfaces in place with clear data exchange rules. Finally, the local flexibility platform must be transparent and provide the TSO with the possibility of requesting certain service deactivation.

- *Baseline*: Standardised measurement methodology for flexibility must be defined, and a common baseline must be agreed upon. In case of EVs, the baseline could be constructed more easily than for other flexible resources by estimating the load demand if uncontrolled charging is applied. For this, three parameters should be known in addition to the maximum battery capacity: the maximum charging power, and the recorded initial SOC and plug-in time. The baseline can be defined as the case where EV charges at the maximum rate from the plug-in time until it is completely full.

- *Flexibility price*: The price should be transparent and communicated in advance, but how it should be defined is not straightforward. Since it should be lower than the reinforcement cost in any case, the first step are new regulations to impose transparent service remuneration of all current DSO services. With this transparency effort, economic calculations can be performed to compare the efficiency between the "fit-and-forget" approach and "proactive solutions" as well as provide basis for calculating the flexibility price. Regardless, the maximum price C_{max} that the DSO is willing to pay for reserving the flexibility service could be defined as follows [150]:

$$C_{max} = \Big(C_{reinforcement} - N_{activation} \cdot \lambda_{activation} - C_{transaction}\Big) \cdot (1 - u)$$

where $C_{reinforcement}$ is the present value of the deferred cost for grid reinforcement, $N_{activation}$ is the expected number of service activations, $\lambda_{activation}$ is the activation price determined in the contract, $C_{transaction}$ is the cost of transaction, and u is the uncertainty premium which reflects the DSOs risk preferences. The activation price $\lambda_{activation}$ is dependent both on the capacity and the duration of the required service, and reflects the aggregator's operational cost which is determined for each flexibility offer. The uncertainty premium u directly rewards the more reliable resources, since the DSO can decrease the premium for the resources which are considered to be less risky. Moreover, as flexibility trading develops and many participants get involved, the transactions costs are expected to decrease.

- *Consumer protection*: User privacy must be ensured by regulations and all the collected data must be treated as confidential by the responsible party managing it. If users themselves are willing to share some privacy-sensitive data with other parties, they should be allowed to do so. Moreover, EV users must be properly informed and provided with the tools to understand complex contracts to which they can be exposed. It is necessary to develop EV interfaces which are user-friendly and provide insight into the signed contracts as well as the scheduled EV operation.

- *EV supply equipment*: Whereas there is already commercially available equipment which allows the controlled EV charging, including the communication and computational capabilities in the contemporary EVSEs is not a common practice as it imposes an additional cost. If such capabilities would be included from the beginning of the infrastructure roll-out, the additional cost of retrofitting the older EVSEs once EV smart charging becomes a common practice would be avoided. In order to make this process viable, the deployment of infrastructure with embedded intelligence should be supported and promoted via standards and regulations in the near-future.

- *Communication standards*: Harmonised standards are needed to define protocols between all participants in the flexibility trading. The standardised protocols are especially needed between the EV aggregator and the DSO, the aggregator and the flexibility platform, as well as between the aggregator and the controllable EVSEs.

One must bear in mind that this list is not exhaustive, and many other barriers exist. For example, it is important to define how local flexibility trading would interact with the wholesale electricity market and the parties involved in those trading processes [142]. However, without addressing the listed recommendations, it will not be possible to unleash the full potential of procuring EV flexibility for distribution grid services. Since the transition to such a proactive system should be evolutionary, the phases for the listed recommendations as well as the intermediate steps needed for fulfilling them are presented via the roadmap depicted in Figure 3.11.

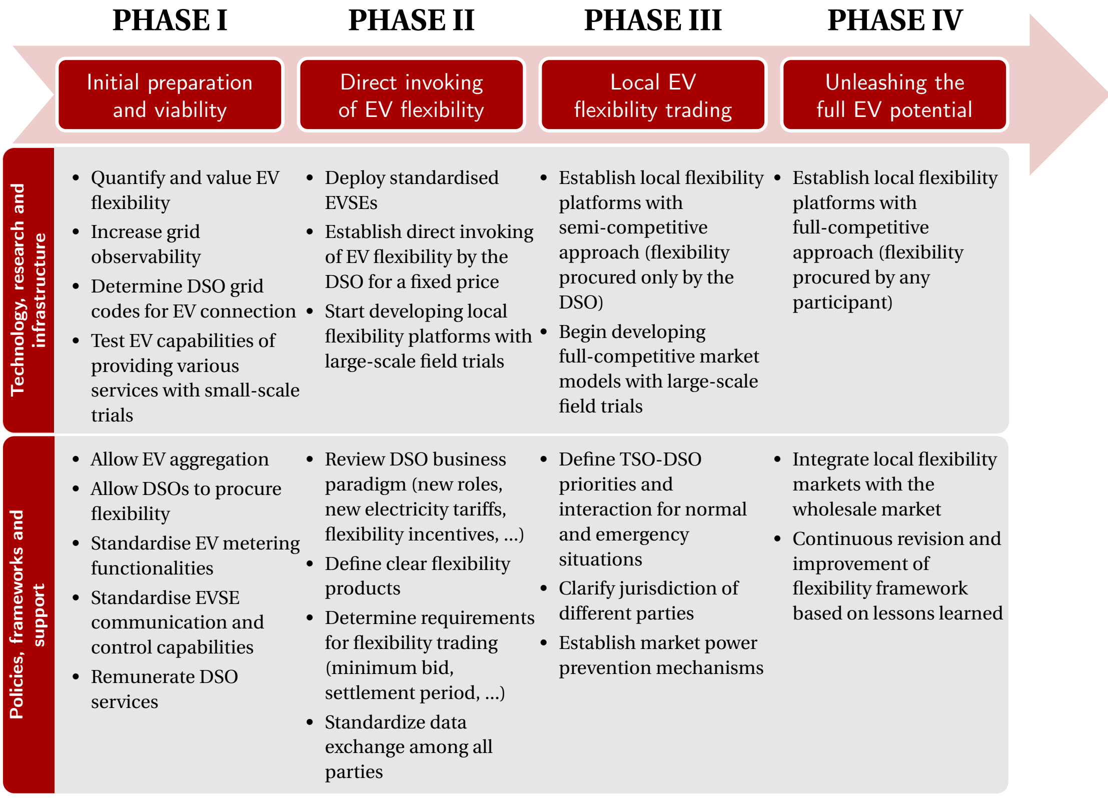

Figure 3.11: Roadmap with key recommendations for supporting active EV involvement in distribution grids.

3.4 Summary

Based on the presented state of the art regarding the EV distribution grid services, several open research questions have been recognised and such will be addressed in the remainder of the thesis. First of all, it has been observed that EV reactive power control holds great potential for real-time voltage support in an autonomous fashion. Therefore, the potential benefits and drawbacks of such a capability are analysed in Chapter 4. Secondly, it has been seen that most of EV scheduling strategies which use active power modulation in a coordinated fashion are single-objective, whereas combining both the EV aggregator's and the DSO's economic concerns is widely disregarded. Hence, this topic has been addressed in Chapter 5 where a multi-objective optimisation model is proposed for EV day-ahead scheduling in flexible unbalanced distribution grids. Thirdly, it has been recognised that the vast majority of literature remained on simulation studies, whereas experimental testing has been neglected. If EVs are to be treated as "black boxes" when providing flexibility services, their internal parameters must be carefully addressed. The experimental validation is the subject of Chapter 6, where both laboratory and field tests are conducted to assess practical issues arising with EV smart charging.

Moreover, the technical and the non-technical prerequisites for enabling EV flexibility procurement at the distribution level have been presented. It was observed that non-technical prerequisites present a greater challenge than the technical ones due to large diversity of distribution systems and respective regulatory frameworks across Europe. The identified organisational and regulatory barriers with the corresponding recommendations are summarized in Table 3.4.

Table 3.4: Main recommendations for supporting active EV involvement in distribution grids.

Smart metering	Wide-scale deployment of smart meters. Standardised functionalities to ensure interoperability. Sampling frequency in accordance with flexibility trading settlement period (maximum 5-min). Clear pre-qualification and validation protocols.
DSO regulation	Remove regulation which forbids aggregation and flexibility procurement. Incentivise long-term innovation (longer regulatory period, incentives for new technologies, profit, etc.). Revise tariffs to include both the capacity and the energy charge. Define new DSO tasks (active grid operation and data management). Remunerate current DSO services to provide basis for comparing different solutions and estimating the flexibility price.
Flexibility trading	Establish an open, transparent and fair flexibility trading platform with the corresponding roles. Define clear and generic flexibility products. Define technical requirements which must be included in flexibility requests/offers (power capacity, duration, direction, location, accuracy, precision, etc.). Define the minimum bid in the kilowatt range, and the settlement period of maximum 5 minutes to encourage EV owner participation. Define common EV baseline (uncontrolled charging), and the corresponding measurement methodology. Introduce capacity and energy payments, and a premium for rewarding the more reliable resources.
TSO-DSO collaboration	Define standards for TSO-DSO interface and data exchange. Define clear priorities between TSO and DSO for normal operation and emergency situations. Make local flexibility trading platform transparent to the TSO.
Consumer	Determine regulations for ensuring data protection. Allow sharing of privacy-sensitive data if user is willing to do so. Develop interface for providing insight into signed contracts and EV schedules. Define standards for providing an unique ID for flexibility procurement and remuneration.
EV/EVSE technology	Define standards and regulation for deploying EVSEs with embedded intelligence. Harmonise communication protocols between the EV aggregator and other participants. Determine standardised tests for evaluating internal EV parameters (accuracy, response time, etc.).

It is important to note that the provided recommendations are not exhaustive, since providing all-inclusive recommendations, which are applicable to all European countries, is practically impossible. However, the presented recommendations must be addressed in the near-future if one is to enable EV flexibility procurement for distribution system operators. Due to the system complexity and diversity across different European countries, other non-listed organisational and regulatory barriers also arise, both on the pan-European level and on the individual country basis. Moreover, political interference creates regulatory uncertainty and unique local environment may detrimentally affect the regulatory stability. Periodically comparing and contrasting various regulations across Europe is a useful source for identifying the barriers and the best-case solutions, and should become a common practice for all stakeholders involved in the EV value chain. Only then could the regulations be properly revised to ensure the EV technical and economic competitiveness when providing distribution grid services.

CHAPTER 4

EV provision of local voltage support

In this chapter, the main results concerning the first research topic of EV reactive power support are summarized. The results have been published in separate papers Pub. C, Pub. D and Pub. E which are included as appendices. First, the reasoning for reactive power support is given, which is then applied to EV voltage support in this thesis. After describing the proposed control, the main results are presented, followed by a summary with a discussion.

4.1 Background

As described in Chapter 2, it is largely agreed that EVs impose high voltage drops in distribution grids since they are considerably larger units compared to conventional residential appliances. Taking into account that the DSO must ensure the grid's compliance with the standard EN 50160, grid reinforcement is inevitable unless EVs provide local support for mitigating the self-inflicted voltage issues. As recognised in Chapter 3, voltage regulation can be accomplished via active power modulation which implies that EV owners are willing to participate in such schemes, but also via EV reactive power support.

Even though the X/R ratio for LV distribution grids is typically between 0.2 and 2 [151], which is much lower than for high voltage grids where X/R is between 6 and 9 [152], the reactive power contribution to voltage variations at the LV level should not be ignored. Generally, as seen in Figure 4.1 and from equation (4.1), offsetting the reactive current I_i from the voltage source U_1 has an impact on the voltage magnitude U_2 at the end of the line with the impedance $R + jX$. Naturally, the higher the X/R ratio is, the more impact does the reactive power support have, which can also be deducted from equation (3.1).

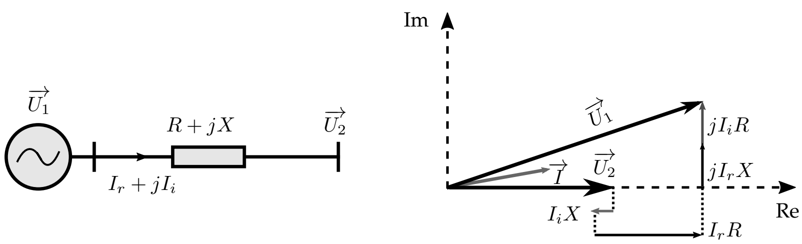

Figure 4.1: Impact of active and reactive power on the voltage magnitude.

$$| U_2 |= \sqrt{| U_1 |^2 - | I_i R + I_r X |^2} - | I_r R | + | I_i X | \tag{4.1}$$

Nowadays, there are already comercially available PV inverters which can provide inductive reactive power support by using the excess PV inverter capacity, which is even requested by several European grid codes, e.g., in Germany [153] and Italy [154]. Similarly, the inherent EV power electronics can be enabled to perform more advanced charging strategies with limited modifications to the current technology.

The EV charger typically includes a two stage topology with a cascaded AC/DC converter, which rectifies the AC current drawn from the grid, and a DC/DC converter, which connects the DC bus to the battery pack. Nowadays, the most common EV chargers are unidirectional chargers designed to operate close to the unity power factor with an interleaved AC/DC boost rectifier, as shown in Figure 4.2a. In such a topology, a diode bridge (diodes D1-D4) rectifies the AC input voltage to DC, while the DC current amplitude is controlled through the switching behaviour of the boost section. By controlling the rectified current to be in phase with the amplitude of the AC grid voltage, a unity power factor is achieved. However, for power levels above approximately 3.5 kW, the efficiency of such converters significantly degrades [155], so a full-bridge active rectifier, shown in Figure 4.2b, is typically implemented.

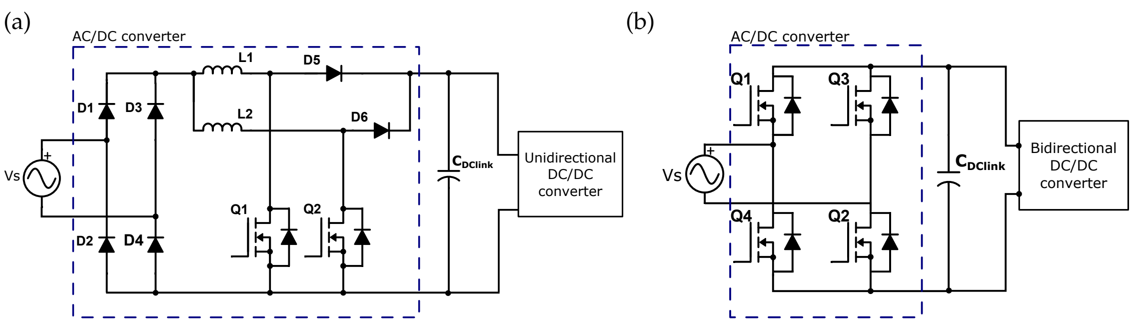

Figure 4.2: (a) Interleaved AC/DC boost converter for unidirectional charging, and (b) full bridge AC/DC converter for uni- or bidirectional charging. Adapted from: [155].

One advantage of the full-bridge topology is that it can be extended to more advanced charging strategies. Specifically, the rectifier can introduce a certain phase angle between the charging current and the grid voltage, thereby making it able to exchange reactive power with the grid. If a bidirectional DC/DC converter is installed, the full-bridge rectifier can also allow bidirectional power flow by creating a 180° current phase angle, resulting in a full 4-quadrant converter. Even though EV chargers with such a capability are not commercially available, the proof of concept has been experimentally established. In [156], a single-phase EV charger which can modulate both the active and the reactive power is tested. It is shown that the charger maintains the externally requested power at the point of common connection, while the battery is not affected by the reactive power operation, neither in terms of its lifetime nor the available SOC.

Using the potential EV reactive power capability, combined active and reactive power control strategies for minimising voltage deviations are investigated in [157, 158]. These approaches are shown to be effective in balanced distribution grids, but they remain on centralised strategies which require communication infrastructure for information exchange between various units. However, until sufficient communication infrastructure is available, reactive power capability can be utilised in an autonomous fashion, especially considering that voltage is a local characteristic. Hence, decentralised control emerges as an intuitive solution for providing real-time voltage support whilst requiring the minimum communication capabilities. Ref. [151] investigates a decentralised EV reactive power support and shows that the capacitive behaviour has a beneficial grid impact in unbalanced grid conditions. Yet, this approach assumes a fixed power factor regardless of the vehicle connection point, which may not be good enough in case the EV is connected towards the end of the feeder. On the other hand, [159] investigates an EV reactive power controller based on the local three-phase voltage measurement, which implicitly takes into consideration the EV connection point. However, EVs in residential areas are typically single-phase connected, so the three-phase voltage measurement is not available. Moreover, if a three-phase connection is available, such an approach may not be sufficient in case of highly unbalanced networks, as the heavily loaded phases would require more support which is not reflected in the three-phase voltage measurement.

In this chapter, an autonomous EV reactive power control (RPC) with a single-phase voltage dependency is investigated as well as its benefits and potential drawbacks. The analysis is conducted both for balanced and unbalanced grid conditions in Pub. C and Pub. E, respectively, with the main results presented in 4.4.1 and 4.4.3. Additionally, if the EV owner also allows active power modulation for providing other services, e.g., frequency regulation, the reactive power control can be used to simultaneously support the distribution grid. This topic has been addressed in Pub. D with the main results presented in 4.4.2.

4.2 Phase-wise enhanced EV reactive power control

For a 4-quadrant AC/DC converter, as seen in Figure 4.3, the nominal EV converter size S_{conv} and the EV active power (P_{EV}) determine the reactive power bounds ($\pm Q_{reg}$) within which the reactive power can be modulated (Q^*). The complex power at the point of common connection is then denoted as S_{PCC}. The EV reactive power support can be either inductive or capacitive depending on the set external signal, both while vehicle is charging or when operating in V2G mode. Contrary to the fixed power factor approach [151] where the converter is enabled to provide constant capacitive reactive power for a certain active power as shown in Figure 4.3a, enhancing

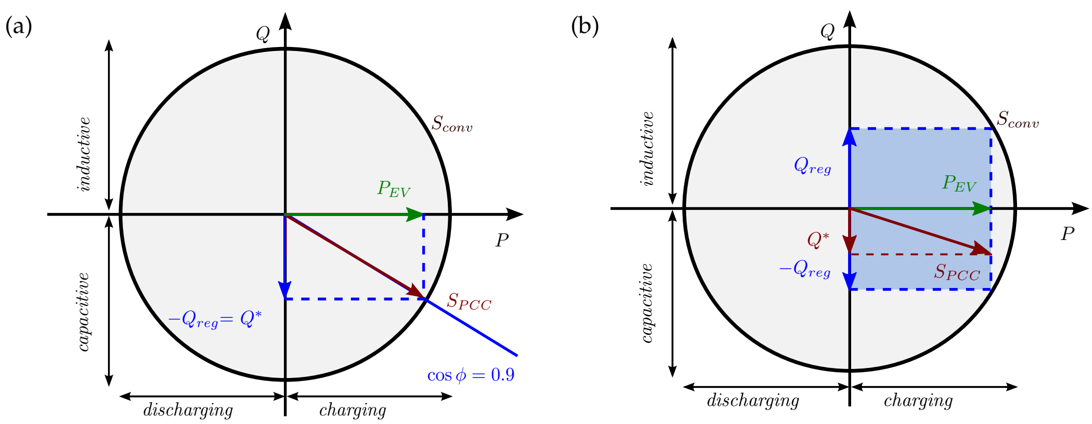

Figure 4.3: 4-quadrant EV converter operating range, during the EV charging process, for (a) constant power factor concept, and (b) the proposed voltage enhanced support with a dynamic power factor.

the converter with the phase-to-neutral voltage dependency leads to a wider operational range, as seen in Figure 4.3b. Thus, EVs can partially mitigate the self-induced voltage issues as well as the deviations caused by other renewable resources and residential loads, depending on the real-time grid conditions. More precisely, an autonomous controller can be implemented as an on-board device to dynamically change the reactive power set-point depending on the voltage conditions at the point of common connection, as depicted in Figure 4.4a. If an off-board EV charger is available, the RPC control can be included in the embedded intelligence of such chargers as well, as presented in Figure 4.4b. The benefit of such a phase-wise dependent RPC is that it can be used for real-time voltage support in the vast amount of current EV chargers as a relatively cheap solution in the near-term future. Indeed, there is no need for any external communication since the controller monitors the phase-to-neutral voltage conditions and calculates the reactive power set-point based on the voltage measurement, instantaneous active power and the predefined droop characteristic. Implementing a voltage dependency also means that the control is fair and does not penalise the users connected towards the end of the feeder where voltages are usually lower. On the contrary, more support is provided if the measured voltage is further from the nominal value.

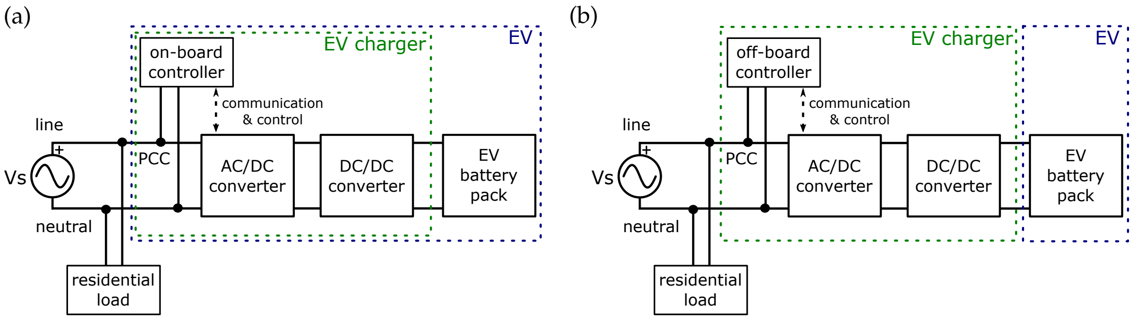

Figure 4.4: Schematic of the proposed reactive power controller connection in case of (a) single-phase on-board EV charger, and (b) single-phase off-board EV charger.

Here, the focus is on analysing the possible EV reactive power support which is independent of active power modulation. Hence, the converter must be oversized to provide reactive power in addition to the maximum active power charging rate, without the need for prioritising between the two. For example, in order to obtain a 0.9 power factor, the apparent power rating should be approximately 110% of the active power rating. For the typical 3.7 kW active power rating, an apparent power rating of 4.1 kVA is enough to provide reactive power support up to 50% of the active power consumption. The implemented droop control characteristic used for further analysis is a function of the EV active power rate and the phase-to-neutral voltage at the EV connection point, as seen in Figure 4.5. The characteristic is depicted for the charging process, whereas a similar one with the opposite values is used for V2G operation mode if available. The maximum capacitive and inductive reactive power provision occur at $0.9U_n$ and $1.1U_n$, respectively, according to the Danish technical regulation for generation facilities with rated current 16 A per phase or lower [160] as well as the European standard EN 50160. Considering that not all RPC requirements are defined in these regulations, the droop characteristic has been modified according to the Italian technical standard CEI 0-21 [154] since both countries belong to the same synchronous region, so harmonization of regulations is expected in the future. Hence, it is assumed that EV converter is sized to modulate the reactive power within $\pm 0.5\ p.u.$ additionally to the EV active power, corresponding to $\approx \cos\phi = 0.9$ $(ind./cap.)$. The dead-band where there is no reactive power provision has been arbitrarily set to ± 0.01 $p.u.$, whereas the remaining droop values have been obtained by linear interpolation.

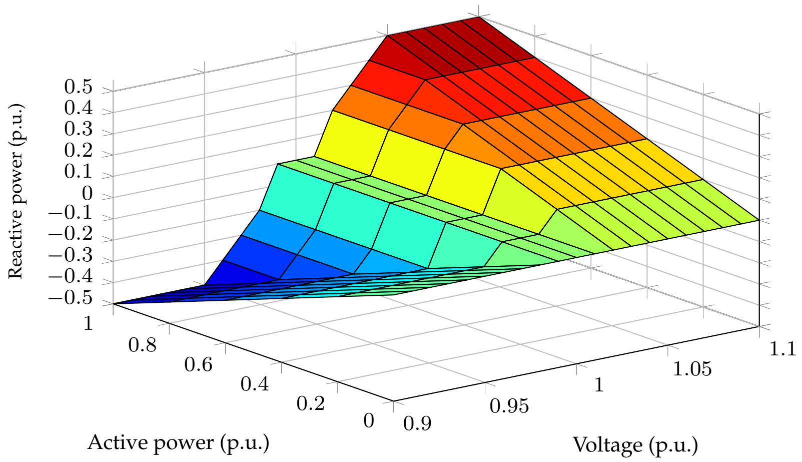

Figure 4.5: Implemented reactive power control capability of the EV converter.

4.3 Study case

The described EV reactive power control is tested and studied on the previously described typical Danish semi-urban low-voltage feeder which is modelled based on the data provided by the responsible DSO. To recall, it is a 400 V radially run distribution grid with 4 feeders in total connected to the 10 kV medium-voltage network through a 400 kVA distribution transformer. Its grid parameters such as X/R ratio resemble those of other low-voltage grids, e.g., to the CIGRE European low-voltage benchmark network [152]. Due to the lack of data for each individual house, only one feeder is modelled in details, whereas the remaining three are represented as a single aggregated load connected to the LV transformer side. There are 43 residential houses under the analysed feeder which are three-phase connected with a common neutral conductor grounded only at the transformer substation. Further details about the analysed feeder can be found in Appendix B.

Individual residential consumption and production profiles are based on real-metered data from March 2012 to March 2013 with an hourly sampling rate, from which two characteristic weeks are chosen for further analysis:

(1) a spring week in mid-May 2012 with low consumption and high PV production, and

(2) a winter week in January 2013 with high consumption and almost no PV production.

The consumption values are based on the measured three-phase power flows with no insight into individual phase fractions. Therefore, for balanced grid analysis, the consumption distribution per phase is 33%:33%:33%, whereas it has been assumed that phase a is heavily loaded in unbalanced conditions with the overall load distribution 50%:25%:25% among the phases. Table 4.1 summarizes the total consumption and production values for the observed weeks.

Table 4.1: Consumption and production overview for the observed weeks

Season	Transformer weekly consumption (kWh)	Feeder weekly consumption (kWh)	Average daily household consumption (kWh)	Transformer weekly production (kWh)	Feeder weekly production (kWh)	Average daily household production (kWh)
spring	10176	2883	7.9/10.6[a]	3404	3096	17.0[b]
winter	25416	12251	14.2/56.4[a]	38	32	0.2[b]

[a] lower value stands for area A and greater for area B
[b] stands for area B

An EV is added to every household in the observed feeder resulting in a 100% local penetration rate which represents one of the worst case scenarios for the DSO. However, looking at the transformer level, the penetration rate is 25% since all feeders have approximately the same amount of households and no EVs are added to the remaining three feeders. If there were additional EVs present in other feeders, the voltage at the LV side of the transformer would decrease resulting in an increased need for voltage support in the observed feeder as well.

Each EV is connected through a typical Mode 2 charging infrastructure with a single-phase 16 A connection, i.e., P_{EV}=3.7 kW under U_n=230 V as described in Chapter 2. The EV charging pattern is taken from the Test-an-EV program [51] and corresponds to an average "dumb-charging" profile, as shown in Figure 4.6a. The charging process lasts for 5 hours with the starting time randomly distributed between 18:45 and 19:15. Additionally, for the purposes of analysing concurrent provision of frequency regulation via active power modulation and simultaneous local voltage support via reactive power control, it is assumed that the TSO requires EV active power injection as seen in Figure 4.6b. This can be interpreted as one of the worst case scenarios since the frequency provision time coincides with high PV production and already high grid voltages.

The simulations are made in Matlab Simulink SimPowerSystems with a variable time step (maximum 1-min), while the household consumption and production profiles are constant on an

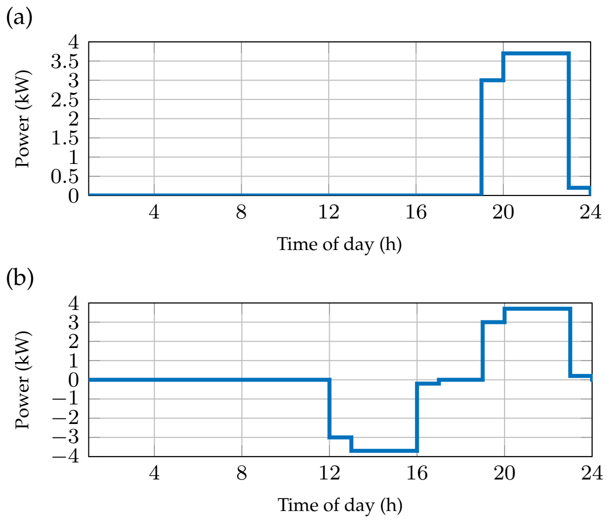

Figure 4.6: Implemented daily EV pattern for (a) reactive power control analyses, and (b) reactive power control and frequency regulation analysis.

hourly basis. Section 4.4 compares relevant network parameters for the distinctive scenarios as listed in Table 4.2. More precisely, subsection 4.4.1 presents the impact on voltage and current magnitudes as well as on system losses in balanced grid conditions, whereas subsection 4.4.2 reports the same parameters in case of concurrent provision of frequency regulation. On the other hand, subsection 4.4.3 extends this analysis to unbalanced grid conditions and additionally reports the impact on several unbalance indicators described in Appendix A. It is important to note that PVs are also equipped with RPC similar to the EV one, so they can contribute to voltage regulation by injecting inductive reactive power whenever production differs from zero. In most of the scenarios, this capability is always active as the main focus is on the EV contribution.

Table 4.2: Overview of conducted scenarios for EV reactive power control analyses.

Scenario	Covered in subsection	Grid conditions	Season	RPC by PVs	RPC by EVs	Frequency regulation by EVs
IV-Ia	4.4.1	balanced	spring	off	off	off
IV-Ib	4.4.1	balanced	spring	on	on	off
IV-Ic	4.4.1	balanced	winter	off	off	off
IV-Id	4.4.1	balanced	winter	on	on	off
IV-IIa	4.4.2	balanced	spring	on	off	on
IV-IIb	4.4.2	balanced	spring	on	on	on
IV-IIIa	4.4.3	unbalanced	spring	on	off	off
IV-IIIb	4.4.3	unbalanced	spring	on	on	off
IV-IIIc	4.4.3	unbalanced	winter	on	off	off
IV-IIId	4.4.3	unbalanced	winter	on	on	off

4.4 Results

All evaluated parameters are presented for several selected nodes of the observed feeder, i.e., transformer LV side (node 301), the beginning of the observed feeder (node 601A) and the end points of each area (node 604 for area A, and node 613 for area B). For balanced grid conditions, only results for phase a are presented since it is assumed that the consumption is equally divided among the phases as well as that PVs and EVs are evenly distributed across the grid resulting in equivalent conditions on all phases. For unbalanced grid conditions, the results for each individual phase are reported. Moreover, it is worth mentioning that most of the results are presented via boxplots - a descriptive statistical method which graphically depicts data through its quartiles by indicating the degree of dispersion and the outliers located within ± 1.5 of the extreme quartiles.

4.4.1 EV provision of reactive power support in balanced grid conditions

The impact of the proposed EV RPC on voltage magnitudes in balanced grid conditions is presented in Figure 4.7 for scenarios IV-Ia to IV-Id. It is obvious how the reactive power support positively impacts the voltage, especially in winter scenarios where it seems to be necessary to maintain the minimum voltage within the $\pm 10\% U_n$ requirements. Additionally, when looking at the spring scenarios, slight voltage improvements can also be seen for overvoltages. As aforementioned, PVs also provide reactive power support resulting in decreased overvoltages in the spring scenarios, whereas the same support is not available in the winter scenarios as there is no PV production.

To complement Figure 4.7, Figure 4.8 depicts the power profile at the substation level for the observed spring week, with and without any reactive power support from PVs and EVs. Here,

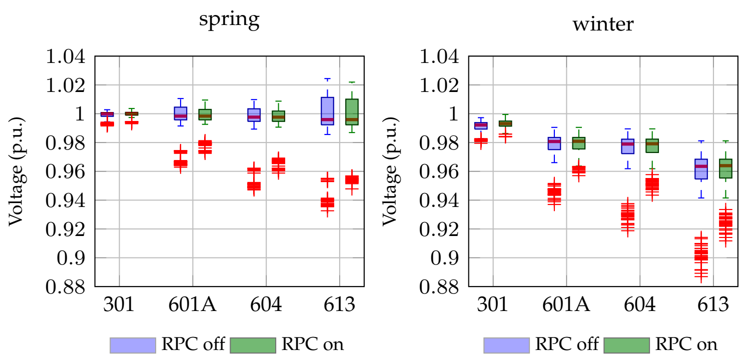

Figure 4.7: Comparison of voltage magnitudes at selected junction points in balanced grid conditions with and without PV and EV reactive power control for spring scenarios IV-Ia and IV-Ib, and winter scenarios IV-Ic and IV-Id.

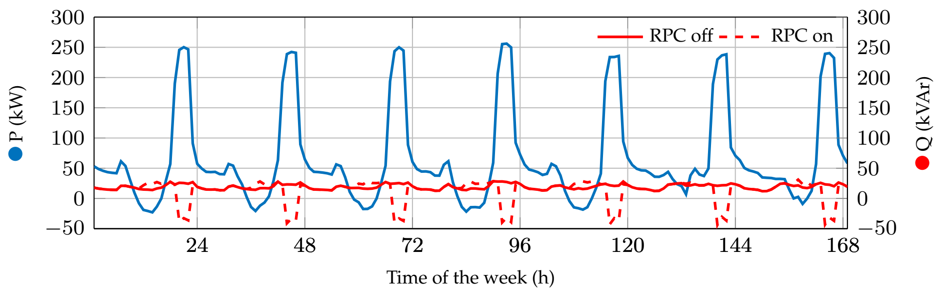

Figure 4.8: Three-phase power profiles at the substation level in balanced grid conditions for the observed spring scenarios IV-Ia and IV-Ib.

Table 4.3: Maximum currents and active power losses for the conducted scenarios in balanced grid conditions.

Scenario	Season	$I_{a_{max}}$ (A)	Active losses (kWh)	Relative active losses (%)
IV-Ia	spring	371	247	1.95
IV-Ib	spring	372	257	2.01
IV-Ic	winter	611	702	2.28
IV-Id	winter	591	690	2.26

two distinctive periods can be observed. The first one consists of time intervals with high PV production when there is a reverse power flow to the medium-voltage grid and PVs inject inductive reactive power to provide overvoltage support. The second one is the evening peak hour with a relatively high total consumption due to EV charging coinciding with the peak residential demand, when EVs provide local support to increase the undervoltages.

However, even though the EV RPC has a beneficial impact on voltages, the increase in reactive power leads to potential excessive loading and increased energy losses, which may arise as a major drawback of such a control. To address this issue, Table 4.3 reports the maximum currents and active power losses for the conducted scenarios. Presented values clearly show that neither the losses nor the maximum current notably increase with the activation of EV reactive power support. On the contrary, it can be observed that RPC activation leads to reductions in the maximum current as well as the losses. The reason behind is that EVs first compensate the existing inductive reactive power coming from other residential loads, followed by a further injection of capacitive reactive power. Capacitive reactive power is provided until the measured voltages are within the set limits or the maximum reactive power is reached. Therefore, it can be concluded that EVs improve the local voltage conditions without notably affecting the overall currents and losses. This behaviour is also observed for the spring scenarios, but the compensation effect if of much lower extent since the residential consumption and, consequently, the inductive reactive power are lower.

4.4.2 Concurrent EV provision of frequency regulation and reactive power support in balanced grid conditions

The main argument for utilising RPC for local grid support is the fact that, given the appropriate equipment sizing, it does not influence the battery SOC while still providing benefits for the distribution grid. However, if EV users are willing to allow active power modulation for additional grid services, reactive power could be provided concurrently for local grid support. Figure 4.9 depicts the voltage conditions during the observed spring week when the EV active power is used in the middle of the day for frequency regulation, while the reactive power is simultaneously used for local voltage support. As it can be seen, even though the voltages are within the $\pm 10\% U_n$ requirements without the RPC, voltage dispersion is reduced after RPC activation. This behaviour is observed both for the overvoltage period when the V2G operation mode coincides with local PV injection, as well as for the undervoltage period when the vehicles are charging.

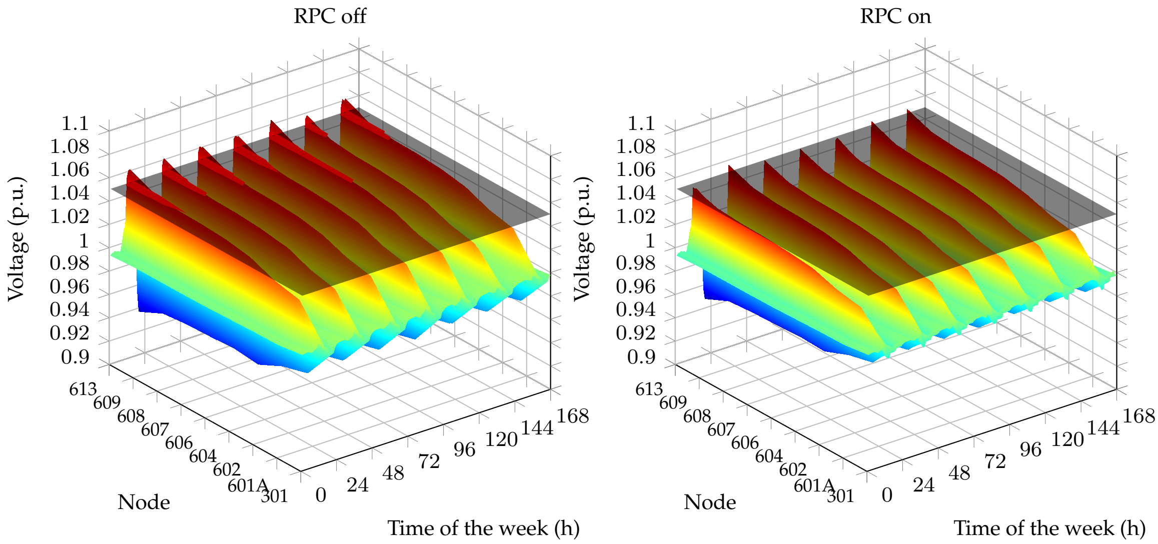

Figure 4.9: Comparison of voltage magnitudes across the observed feeder for spring scenarios IV-IIIa and IV-IIIb. EVs are providing frequency regulation **without** and **with** simultaneous reactive power support in balanced grid conditions.

To provide a closer look into different EV behaviours, Figure 4.10 shows the active and reactive power profiles of three vehicles connected to three different nodes. As seen, all vehicles have the same active power profile as it is assumed that the TSO requires the same frequency response regardless of the EV connection point, which is followed by the "dumb-charging" pattern in the peak hours. Contrary to the active power profile, it is easily noticeable that reactive power profiles differ depending on the EV connection point. The vehicle connected at the end of the line (node

613) provides more reactive power support as the voltage deviations are higher, resulting in a greater need for voltage support. On the other hand, vehicles located close to the transformer station provide less reactive power due to better voltage conditions. Hence, it can be concluded that the required frequency regulation can be provided to the TSO with a decreased impact on the local distribution system.

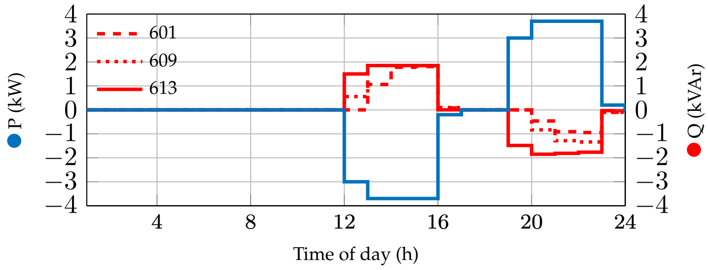

Figure 4.10: Active and reactive power profiles for three selected EVs in spring scenario IV-IIIb when EVs provide frequency regulation with simultaneous reactive power support in balanced grid conditions.

4.4.3 EV provision of reactive power support in unbalanced grid conditions

Contrary to the previous subsections where the RPC impact has been analysed in balanced grid conditions, this section focuses on the impact on the single-phases since distribution grids are usually operating in unbalanced conditions. Here, similar voltage behaviour has been observed as for the balanced conditions, both in the spring and in the winter scenarios. Hence, the 10 minute rms phase-to-neutral voltage values are presented only for winter scenarios IV-IIIc and IV-IIId in Figure 4.11 as voltage violations are observed to be more critical in the winter period, whereas the summary of voltage improvements for all scenarios is given in Table 4.4. It is clear that both the minimum voltage magnitudes U_{min} and the voltage dispersion σ_U improve after activating the EV reactive power control. However, since RPC is phase-to-neutral voltage dependent, the highest influence can be seen on the most heavily loaded phase a where the vehicles provide more support. Consequently, this also influences the voltage unbalances as reported further on.

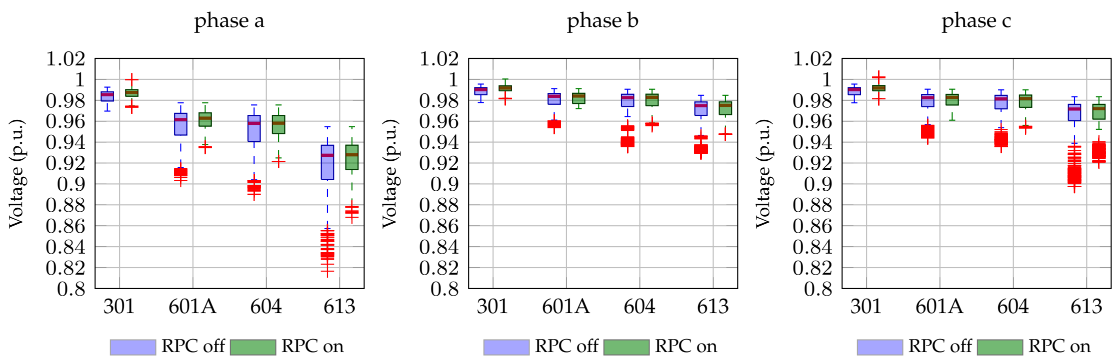

Figure 4.11: Phase-to-neutral voltage magnitudes at selected junction points for the winter scenarios without (IV-IIIc) and with (IV-IIId) EV reactive power support in unbalanced grid conditions.

Table 4.4: Phase-to-neutral voltage improvements after RPC activation in unbalanced conditions.

Season	Compared scenarios	Node	ΔU_{min} (%)			$\Delta\sigma_U$ (%)		
			a	b	c	a	b	c
spring	IV-IIIa and IV-IIIb	301	0.6	0.5	0.4	-49	-56	-36
		601A	3.1	2.1	1.6	-46	-34	-32
		604	3.1	2.9	2.1	-41	-30	-29
		613	5.6	2.7	2.1	-39	-16	-19
winter	IV-IIIc and IV-IIId	301	0.4	0.4	0.4	-3	-9	-1
		601A	3.5	1.9	1.8	-47	-51	-44
		604	3.5	2.1	1.9	-45	-43	-41
		613	6.3	1.9	2.6	-44	-37	-31

On the other hand, since the simulations are run with a variable time step, short-term oscillations have been noticed in certain circumstances due to simultaneous reactions of the RPC controllers. As the controllers are autonomous, they do not account for the voltage deviations made by other units which can therefore lead to overcompensation. Contrary to the balanced grid conditions where all phases are supported equally, in the unbalanced conditions the phase a controller improves the corresponding voltage and simultaneously influences the remaining phase-to-neutral voltages due to the moving of the neutral point. At a certain point when the voltages come close one to another, reactive power oscillations occur leading to voltage instability in all conducted scenarios. Hence, to diversify the EV response, but still keep the controllers' autonomy and simplicity, random delays up to 6 seconds have been implemented in the controllers.

Reactive power profile of a single vehicle connected to phase c with the respective voltage magnitude can be seen for one working day of the observed spring and winter week with 100% EV penetration in Figure 4.12a and Figure 4.12b respectively, and for one spring day with 50% EV penetration rate in Figure 4.12c. First of all, it can be seen that random delays are successful in removing the oscillations in the winter period, but they are not enough for avoiding them completely in the spring case when the phase-to-neutral voltages are much closer one to another. Secondly, the oscillations from the EV reactive power provision are completely eliminated in the spring case with a lower EV penetration rate. Since there is less EVs, there are less synchronisation issues and the avalanche effect of simultaneous reaction is avoided. Finally, the voltage instability is not unique to the EV charging period, but it also appears in the middle of the day due to high amount of PVs with inductive reactive power capability. Similar syncronisation issues have been discussed for the decentralised active power controllers studied in [109]. One of potential solutions for overcoming such oscillations could be implementing an adaptive droop slope which is dependent on the specific grid parameters, the EV penetration rate and the EV connection distance from the transformer substation. This has not been thoroughly investigated and is left as a potential topic for future work.

Since the proposed EV RPC has different voltage impacts depending on the EV connection point, it as also important to analyse the overall impact on the voltage unbalances[1]. The voltage unbalance factor VUF_- has been calculated as the ratio between the negative and the positive voltage sequence, according to the standard EN 50160 definition given in equation (A.2). It is worth recalling that the acceptable VUF_- limit equals to 2%. However, the zero voltage sequence has a significant impact in the three-phase four-wire systems and should not be neglected, as is the case

[1] All used voltage unbalance factors with the corresponding definitions are described in more detail in Appendix A

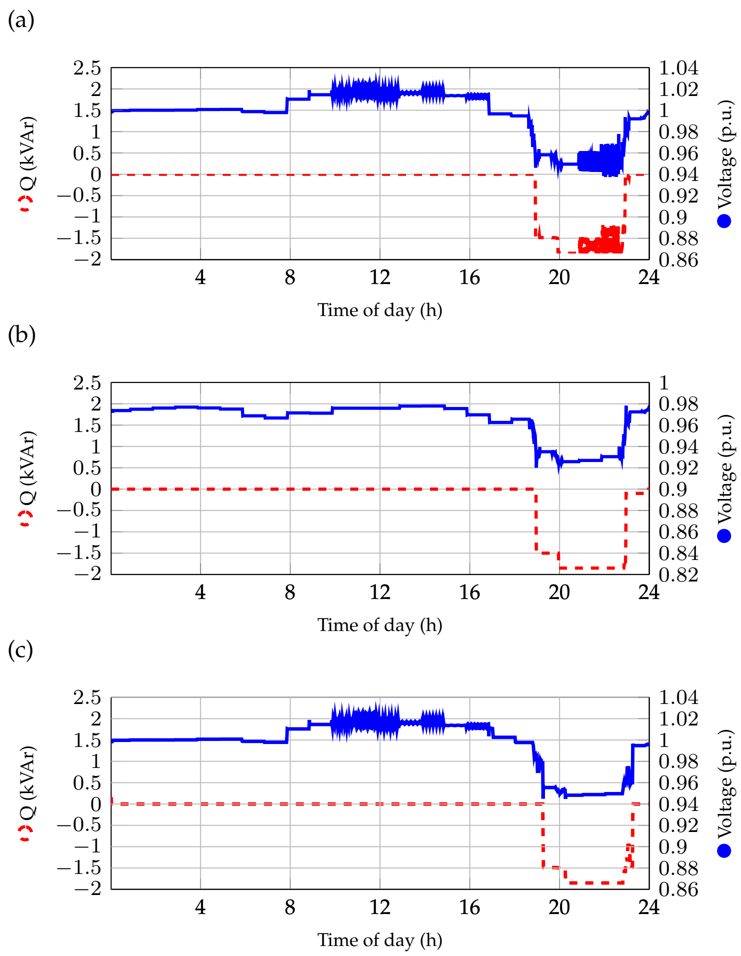

Figure 4.12: Example of reactive power provision by a vehicle connected to phase c at node 613 with the corresponding phase-to-neutral voltage for (a) a spring day with 100% EV penetration, (b) a winter day with 100% EV penetration, and (c) a spring day with 50% EV penetration.

in the VUF_{-} definition. Thus, the voltage unbalance factors VUF_0 and VUF_{rms} are additionally reported as defined in equation (A.3) and equation (A.4). Table 4.5 summarises the RPC impact on the most critical node, i.e., node 613 at the end of the observed feeder. Presented values show that VUF_{-} increases in the spring week after RPC activation since the direct voltage component decreases while the inverse one remains the same. As observed, the positive impact of EV reactive power control on VUF_0 and consequently on VUF_{rms} is quite high for all conducted scenarios, leading to the conclusion that RPC contributes to overall unbalance reduction, both in magnitude and in duration.

Table 4.5: Voltage unbalance factors at node 613 for conducted scenarios in unbalanced grid conditions.

Scenario	Season	$\mathbf{VUF_{-max}}$ (%)	$\mathbf{VUF_{-} > 2\%}$ (h)	$\mathbf{VUF_{0max}}$ (%)	$\mathbf{VUF_{rms_{max}}}$ (%)
IV-IIIa	spring	1.55	0	4.2	4.4
IV-IIIb	spring	1.87	0	3.5	3.7
IV-IIIc	winter	2.13	1.2	7.9	8.1
IV-IIId	winter	1.99	0	5.6	5.8

Similarly to the balanced grid conditions, it is important to analyse the potential increased loading and losses in the unbalanced conditions as well. Table 4.6 compares the maximum current values and the active losses, as well as the zero sequence current unbalance factor CUF_0 for all conducted scenarios. It is evident from the presented values that active losses throughout the spring scenarios do not notably increase, whereas they even decrease in the winter scenarios similarly as in previously analysed balanced grid conditions. On the other hand, the maximum currents are significantly lower in all scenarios due to the local EV support, especially in the winter period. Additionally, the proposed control has a positive effect on reducing the current unbalance factor in all conducted scenarios, meaning that it contributes to overall unbalance mitigation due to uneven reactive power provision to different phases. Even if EVs are not introducing additional unbalances, their RPC capability can help alleviate the unbalances coming from other residential units.

Table 4.6: Maximum currents, current unbalance factor and active power losses for the conducted scenarios in unbalanced grid conditions.

Scenario	Season	$I_{a_{max}}$ (A)	$I_{b_{max}}$ (A)	$I_{c_{max}}$ (A)	$I_{n_{max}}$ (A)	CUF_{0max} (%)	Active losses (kWh)	Relative active losses (%)
IV-IIIa	spring	454	335	339	124	24.8	440	3.47
IV-IIIb	spring	434	332	338	105	17.4	444	3.52
IV-IIIc	winter	698	539	552	139	26.5	1008	3.57
IV-IIId	winter	658	519	530	98	20.4	972	3.47

4.5 Summary

The voltage dependent EV reactive power control, which can be easily implemented with the existing EV electronics, has been investigated in this chapter. Such control can provide real-time local voltage support regardless of the EV location and phase connection and without the need for estimating the mobility patterns. It has been observed that such control provides voltage improvements without noticeably affecting the losses and therefore DSO operational cost. In addition, since EVs provide unequal reactive power to different phases due to their voltage dependency, RPC partially mitigates the unbalances caused by other residential loads.

From the DSO point of view, the investigated reactive power capability is advantageous as it supports the grid in real-time and allows deferring infrastructure investments needed for ensuring the power quality. Since the proposed control is autonomous, there is no operational transparency over the controller, making it difficult to trade such a service, but the proposed method can be applied for mandatory voltage support. Moreover, the reactive power flexibility increases as the EV number raises, therefore making it an effective mean for increasing the hosting capacity in case of uncontrolled EV charging. On the other hand, from the EV owner point of view, reactive power modulation has no impact on the charging behaviour and battery state of charge, given that the equipment is properly sized. The control is fair and does not penalise the users connected towards the end of the feeder. On the contrary, the lower the measured voltage is, the more support is provided to the grid.

Despite its beneficial grid impact, it is important to note how EV reactive power capability is still not commercially available since it imposes an additional cost for the manufacturer due to converter over-sizing. The manufactures are reluctant to implement such capability as there are currently no grid codes requiring it, so the cost for them is unjustified. Hence, given the considered advantages, it is recommended that EV reactive power capability is included in the future grid compliance regulations, similarly to the current requirements for conventional power plants or PVs in countries with high penetration rates.

Considering that RPC efficacy depends on the underlying grid, it is up to the stakeholders to determine the most suitable requirements which could be widely applicable. Leveraging the reactive power control for voltage regulation is dependent on the X/R ratio, cable lengths, MV grid strength and the transformer's parameters, which must be taken into account when defining the requirements. For instance, [161] assessed the reactive power impact for various LV grid parameters in balanced conditions, and concluded that X/R ratio has a marginal impact on the RPC benefits, but the absolute R and X values have a significant contribution to the efficacy. It has also been concluded that reactive power has a greater impact for weaker LV grids and smaller transformers with $S_n < 200$ kVA. Therefore, in strong grids with relatively short feeders, EV RPC capability may not have a substantial impact on the voltage conditions unless many EVs are connected to the system, and, in the worst case scenario, the capability would be used only for local reactive power compensation. On the other hand, in weaker grids with long feeders, RPC capability from only several vehicles could be crucial for integrating higher EV amounts without additional grid reinforcement even if the X/R ratio is relatively small.

To explore the full potential of EV reactive power control for various LV grid parameters, it is also important to include the impact of various degrees of unbalances. Here, it has been observed that droop requirements need to be carefully chosen as synchronisation issues among autonomous controllers occur in certain circumstances. Such issues could be overcome by implementing an adaptive droop slope which limits the maximum reactive power provision depending on the specific grid's parameters and EV penetration rate, which is recognised as a topic for future research work.

The question remains if the cost of implementing such a control with respect to oversizing the equipment is worthwhile. For a limited oversizing up to $cos\phi = 0.95$, the increase in power and current does not require an upgrade of the charging infrastructure since it is still within the safety margins. For instance, for Mode 3 with $P_n = 3.3$ kW, a 20 A fuse must be used anyway. On the other hand, according to [162], the cost of oversizing the converter for adding reactive power capability up to $cos\phi = 0.8$ on a 3.3 kW charger equals to 13.75 $/kVAR. Nowadays, without the existence of a voltage market and explicit remuneration for voltage regulation, it is difficult to assign value to EV reactive power control. The comparison with traditional DSO means, e.g., implementation of capacitor banks, is highly dependent on the analysed grid making it difficult to generalize the economic value. This remains an interesting topic for future work, especially with the evolvement of new distribution grid markets where the method for valuing such a service should be determined.

Chapter 5

Combining local and system-wide aspects in EV scheduling

In this chapter, the focus is put on how to combine the EV aggregator's concerns with the local distribution grid concerns. A multi-objective optimisation method is presented for EV day-ahead scheduling in flexible unbalanced distribution grids. This method combines two partially competing objectives: minimising the EV charging cost on one hand, which presents the system-wide aspect as the EV aggregator participates in the wholesale market, and minimising the DSO's loss cost on the other, which represents the local conditions. In addition, the impact of the additional EV reactive power support on the obtained optimal solution is investigated, both when EVs are the only flexible resource and when combined with other demand response. The content of Pub. F is included in this chapter.

5.1 On the importance of multi-objective EV scheduling

As described in Chapter 2, subsection 2.4.1, EV aggregator is needed as an intermediary to fill the gap between the DSO and EV owners, and provide the EV flexibility to the DSO. Until local flexibility platforms are established and service trading is enabled, it is anticipated that the DSO will acquire a new role of a flexibility operator by entering into bilateral agreements with flexibility providers for a fixed price [19]. Then, the DSO could directly invoke the available flexibility to obtain the optimal day-ahead resource management. However, what is considered to be an optimal schedule may differ considerably among the stakeholders whose wishes are often competing. The importance of each can only be assessed by the stakeholders themselves, so optimising the EV schedule requires weighing not only the importance of each stakeholders' wishes, but also the alternatives.

For illustrative purposes, Figure 5.1 presents the Borup transformer profile for a Monte Carlo[1] analysis where 1000 simulations are run with up to 20 EVs randomly connected across the grid. Assuming that EV owners have a contract with the aggregator and allow their EV to be controlled as long as it is fully charged before the estimated departure time, the aggregator would like to minimise the charging cost with respect to the forecasted electricity price. The results for the case when EVs are scheduled according to this objective are shown in Figure 5.1a from which it is obvious how the aggregator aims at charging the EVs in the least expensive hours during the night which may result in additional consumption peaks for high EV concentrations. On the other

[1]Monte Carlo method is a broad class of algorithms which rely on repetitive random sampling to obtain numerical results. Here, the randomly generated variables are the amount of EVs with the respective connection point, estimated plug-in/plug-out time and the initial SOC.

hand, the DSO has access to information on network topology and equipment specifications in addition to the consumption forecasts, and would like to schedule the EVs so that the operating cost is minimised. Figure 5.1b shows the case where the objective function is minimising the loss cost, resulting in a more spread-out EV consumption during the night. Comparing Figure 5.1a and Figure 5.1b, it can be observed that the two objectives are partially in conflict, so a collaborative framework is needed to include the economic interests of both stakeholders.

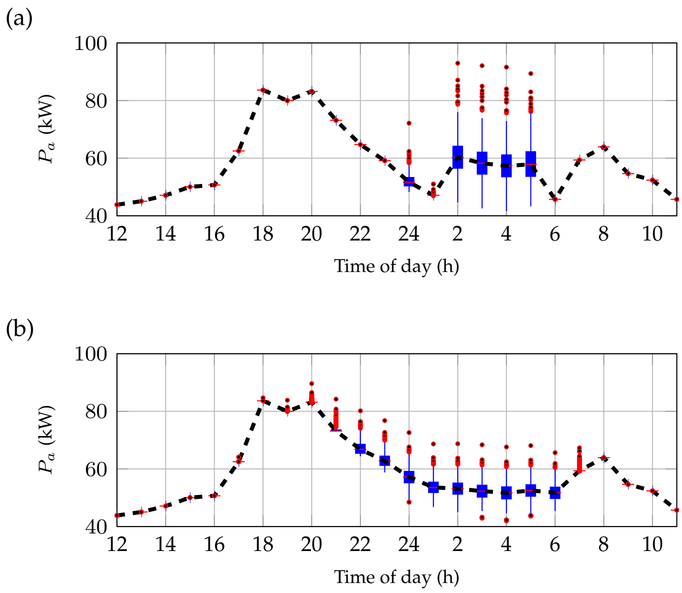

Figure 5.1: Transformer loading on phase a for Monte Carlo analysis of 1000 runs with up to 20 EVs randomly connected, in case of (a) minimising the EV charging cost, and (b) minimising the DSO loss cost.

As recognised in Chapter 3, even though the EV smart charging problem is well studied and numerous approaches are proposed with respect to the EV day-ahead scheduling, combining several objective functions has scarcely been touched upon. Ref. [163] proposes a centralised multi-objective method which minimises the total distribution grid operational cost and the CO_2 emissions. Similarly, [164] proposes a centralised multi-objective formulation for minimising the operation cost and voltage deviations at the same time. However, both of the proposed methods are applicable only to balanced grids and they disregard the potential EV reactive power support which can have impact on the obtained day-ahead schedule.

It is recognised that many existing EV day-ahead scheduling methods suffer from one or more of the following drawbacks: (1) lack of distribution grid constraints, (2) optimal power flow formulation only for balanced conditions, (3) no EV reactive power flexibility, and (4) no multi-objective formulation for collaborative EV scheduling. Driven by this fact, developing a method which combines all these aspects is the focus of this chapter. First of all, the multi-objective formulation combines two partially competing objectives, namely the EV aggregator's charging cost and the DSO's loss cost to assess the trade-off with respect to the EV scheduling. Secondly, the formulation includes the impact of unbalances on the individual EV schedule by incorporating the unbalanced optimal power flow. Finally, similarly to Chapter 4, it is assumed that EV converters are enabled to provide reactive power support additionally to the active power charging rate. However, contrary to the autonomous control investigated in the previous chapter, here EVs respond to an external reactive power set-point. The impact of introducing such reactive power control is analysed both on the technical grid parameters and on the stakeholders' costs. The main results are presented in section 5.4, whereas the reader is referred to Pub. F for more details.

5.2 Multi-objective framework for EV day-ahead scheduling

In this section, the proposed multi-objective methodology is described. First, the formulation for the unbalanced optimal power flow is given, followed by the EV modelling with the corresponding constraints. Then, the respective objective functions are presented, with the method for obtaining a range of optimal solutions. Finally, the choice of the best compromise solution is explained.

Before describing the methodology itself, it is important to state the working assumptions of the proposed formulation. These are as follows:

- All EVs are under the jurisdiction of a single EV aggregator who entered into agreement with individual EV owners. Therefore, it is familiar with their connection points, and uses forecasting techniques for predicting their arrival and departure time.
- EVs are equipped with smart metering technology with direct access to the EV state of charge, and they can be remotely controlled by receiving the active/reactive power set point. Even though, as discussed in Chapter 3, the majority of contemporary commercial EVs do not allow access to the EV SOC, this assumption becomes a necessity if EVs are to be utilised for advanced flexibility services. Nowadays, there are various initiatives to include the access to SOC data in the requirements defined by international standards. For instance, SOC is already available in the CHAdeMO standard and IEC 15118 defines the SOC data to be optional, so it can be expected that such information will become mandatory in the near future.
- Grid operator has access to the following information: network size, network topology as well as cable and transformer specification. So far, due to passive distribution grid operation, many DSOs lack the knowledge of the underlying distribution grid parameters since it has not been necessary. However, in order to properly integrate distributed resources and perform active grid management, DSOs will have to increase the grid observability as well as to become familiar with the underlying topology.
- EV battery efficiency is modelled as an input parameter, which is assumed to be estimated by empirical data and known by the aggregator. It is possible to introduce a more detailed battery model to represent EV efficiency as a function of cell temperature, battery state-of-health, environmental conditions as well as the rate of charge. However, extensive experimental tests are necessary to characterize such function properly, which has been beyond the scope of the work described here. Moreover, for unidirectional charging rates lower than the nominal one, as utilised here, thermal and cycling stress and consequently battery degradation are not substantial [165–167]. Hence, battery ageing cost associated to the charging power modulation has been omitted.

5.2.1 Unbalanced distribution grid constraints

As distribution grids are operating in unbalanced conditions and EVs are usually single-phase connected, the unbalanced optimal power flow is essential in order to account for the constraints of the phase to which the EV is connected. Here, the formulated full AC optimal power flow is based on [168] and implemented as a single non-linear program which can be solved by commercial non-linear solvers such as CONOPT or IPOPT. Within the formulation, the calculated active and reactive power for phase a of branch ij at time t are given in equation (5.1) and equation (5.2), respectively. Similar equations can be extracted for the remaining two phases as given in equation (5.3) and equation (5.4) for phase b, and in equation (5.5) and equation (5.6) for phase c.

$$P^{a}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{a}_{i,t}||Y^{a\phi-n}_{ij}||V^{\phi}_{i,t}| \cos(\theta^{a\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{a}_{i,t}) - |V^{a}_{i,t}||Y^{a\phi-n}_{ij}||V^{\phi}_{j,t}| \cos(\theta^{a\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{a}_{i,t}) \Big) \tag{5.1}$$

$$Q^{a}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{a}_{i,t}||Y^{a\phi-n}_{ij}||V^{\phi}_{j,t}| \sin(\theta^{a\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{a}_{i,t}) - |V^{a}_{i,t}||Y^{a\phi-n}_{ij}||V^{\phi}_{i,t}| \sin(\theta^{a\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{a}_{i,t}) \Big) \tag{5.2}$$

where $|V^{\phi}_{i,t}|$ and $\delta^{\phi}_{i,t}$ are voltage magnitude and voltage angle of phase ϕ at bus i at time t, respectively; $|V^{\phi}_{j,t}|$ and $\delta^{\phi}_{j,t}$ are voltage magnitude and voltage angle of phase ϕ at bus j at time t, respectively; $\theta^{a\phi}_{ij}$ represents the admittance angle between phase a at bus i and phase ϕ at bus j of branch ij, whereas $|Y^{a\phi-n}_{ij}|$ represents the admittance magnitude including the effect of the neutral ground wire between phase a at bus i and phase ϕ at bus j of branch ij.

$$P^{b}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{b}_{i,t}||Y^{b\phi-n}_{ij}||V^{\phi}_{i,t}| \cos(\theta^{b\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{b}_{i,t}) - |V^{b}_{i,t}||Y^{b\phi-n}_{ij}||V^{\phi}_{j,t}| \cos(\theta^{b\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{b}_{i,t}) \Big) \tag{5.3}$$

$$Q^{b}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{b}_{i,t}||Y^{b\phi-n}_{ij}||V^{\phi}_{j,t}| \sin(\theta^{b\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{b}_{i,t}) - |V^{b}_{i,t}||Y^{b\phi-n}_{ij}||V^{\phi}_{i,t}| \sin(\theta^{b\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{b}_{i,t}) \Big) \tag{5.4}$$

$$P^{c}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{c}_{i,t}||Y^{c\phi-n}_{ij}||V^{\phi}_{i,t}| \cos(\theta^{c\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{c}_{i,t}) - |V^{c}_{i,t}||Y^{c\phi-n}_{ij}||V^{\phi}_{j,t}| \cos(\theta^{c\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{c}_{i,t}) \Big) \tag{5.5}$$

$$Q^{c}_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^{c}_{i,t}||Y^{c\phi-n}_{ij}||V^{\phi}_{j,t}| \sin(\theta^{c\phi}_{ij} + \delta^{\phi}_{j,t} - \delta^{c}_{i,t}) - |V^{c}_{i,t}||Y^{c\phi-n}_{ij}||V^{\phi}_{i,t}| \sin(\theta^{c\phi}_{ij} + \delta^{\phi}_{i,t} - \delta^{c}_{i,t}) \Big) \tag{5.6}$$

Moreover, the power mismatch equations for each bus, which describe the relationship between the specified and the calculated power injections, are given in equation (5.7) and equation (5.8).

$$\sum_{\substack{j=1\\ j\neq i}}^{N_j} P^{\phi}_{ij,t} = \sum_{G=1}^{N_G} P^{\phi G}_{i,t} - \sum_{D=1}^{N_D} P^{\phi Dnew}_{i,t} - \sum_{EV=1}^{N_{EV}} P^{\phi EV}_{i,t} \tag{5.7}$$

$$\sum_{\substack{j=1\\ j\neq i}}^{N_j} Q^{\phi}_{ij,t} = \sum_{G=1}^{N_G} Q^{\phi G}_{i,t} - \sum_{D=1}^{N_D} Q^{\phi Dnew}_{i,t} - \sum_{EV=1}^{N_{EV}} Q^{\phi EV}_{i,t} \tag{5.8}$$

where $P/Q^{\phi G}_{i,t}$ represents active/reactive power of a generating unit connected to bus i on phase ϕ, $P/Q^{\phi Dnew}_{i,t}$ represents variable active/reactive power demand connected to bus i on phase

ϕ, $P/Q_{i,t}^{\phi EV}$ represents active/reactive power of EV connected to bus i on phase ϕ, and $P/Q_{ij,t}^{\phi}$ represents the active/reactive power of branch ij connected to node i and phase ϕ.

In addition to the power flow and power mismatch equations, residential consumption must be modelled. In order to use appliance models in power system simulations, a composite demand model can be used as a representation of the aggregated response. The demand is then represented as a combination of constant impedance load, constant current load and constant power load, which is also known as the ZIP model [169]. For the presented formulation, the voltage dependency of the residential demand is described in equation (5.9).

$$P_{i,t}^{\phi D} = P_{0,i}^{\phi D} \cdot |V_{i,t}^{\phi}|^{\kappa} \tag{5.9}$$

where $P_{0,i}^{\phi D}$ represents the load's nominal active power, whereas κ equals to zero for constant power loads, to one for constant current loads, and to two for constant impedance loads.

Furthermore, the residential loads are assumed to be somewhat flexible, and can be controlled via the direct demand response program. Hence, the load can vary within the observed period as described by equation (5.10), equation (5.11) and equation (5.12).

$$\sum_{t=1}^{T} P_{i,t}^{\phi Dnew} \cdot |V_{i,t}^{\phi}|^{\kappa} = \sum_{t=1}^{T} P_{0,i}^{\phi D} \cdot |V_{i,t}^{\phi}|^{\kappa} \tag{5.10}$$

$$(1-\xi_i)P_{0,i}^{\phi D} \leq P_{i,t}^{\phi Dnew} \leq (1+\xi_i)P_{0,i}^{\phi D} \tag{5.11}$$

$$Q_{i,t}^{\phi Dnew} = \tan(\arccos(\varphi_{i,t}^{\phi D})) \cdot P_{i,t}^{\phi Dnew} \cdot |V_{i,t}^{\phi}|^{\kappa} \tag{5.12}$$

where ξ_i is the demand flexibility parameter for bus i, which describes the amount of flexible load (between 0 and 1 inclusive), and $\varphi_{i,t}^{\phi D}$ is the residential power factor.

In addition to the power flow equations, the unbalanced distribution grid constraints need to be formulated, specifically the voltage and line limits. Voltage constraints for each bus are specified according to equation (5.13), whereas the power flow constraints for each branch are given by equation (5.14). These ensure that the obtained power flow solution is feasible within the specified operational constraints of the respective distribution grid since any solution outside the set constraint will be treated as unfeasible.

$$V_{i,t,min}^{\phi} \leq |V_{i,t}^{\phi}| \leq V_{i,t,max}^{\phi} \tag{5.13}$$

$$(P_{ij,t}^{\phi})^2 + (Q_{ij,t}^{\phi})^2 \leq (S_{ij,max}^{\phi})^2 \tag{5.14}$$

where $S_{ij,max}^{\phi}$ is the maximum apparent power capacity of branch ij. In case cable limits are given in terms of ampacity, equation (5.14) can be reformulated to equation (5.15), where $I_{ij,t,Re}^{a/b/c}$ and $I_{ij,t,Im}^{a/b/c}$ are given by equation (5.16) and equation (5.17), respectively. To avoid an increase in problem complexity, i.e., in dimensions to be solved in each iteration, current constraints can be actively applied only after the capacity is exceeded.

$$(I_{ij,t,Re}^{\phi})^2 + (I_{ij,t,Im}^{\phi})^2 \leq (I_{ij,max}^{\phi})^2 \tag{5.15}$$

$$I_{ij,t,Re}^{a/b/c} = \sum_{\phi=a,b,c} \Big(|V_{i,t}^{\phi}||Y_{ij}^{a/b/c-\phi-n}| \cos(\delta_{i,t}^{\phi} + \theta_{ij}^{a/b/c-\phi}) - |V_{j,t}^{\phi}||Y_{ij}^{a/b/c-\phi-n}| \cos(\delta_{j,t}^{\phi} + \theta_{ij}^{a/b/c-\phi}) \Big) \tag{5.16}$$

$$I_{ij,t,Im}^{a/b/c} = \sum_{\phi=a,b,c} \Big(|V_{i,t}^{\phi}||Y_{ij}^{a/b/c-\phi-n}| \sin(\delta_{i,t}^{\phi} + \theta_{ij}^{a/b/c-\phi}) - |V_{j,t}^{\phi}||Y_{ij}^{a/b/c-\phi-n}| \sin(\delta_{j,t}^{\phi} + \theta_{ij}^{a/b/c-\phi}) \Big) \tag{5.17}$$

5.2.2 EV modelling

Several EV characteristics need to be formulated to include EVs in the optimal scheduling formulation. First, equation (5.18) describes the EV SOC which is dependent on the SOC in the previous time step $SOC^{\phi EV}_{i,t-1}$, the EV active charging power $P^{\phi EV}_{i,t}$ and the EV charging efficiency $\eta^{\phi EV}_{ch,i}$. The battery size constraint is defined by equation (5.19) where $SOC^{\phi EV}_{0,i}$ represents the initial SOC unique for each vehicle depending on the previous driving conditions, while SOC^{EV}_{max} represents the nominal size of the battery dependant on the EV model. Furthermore, a conservative approach has been adopted, meaning that the vehicle must be fully charged one hour before the estimated departure time as described in equation (5.20). This ensures that the vehicle is fully available for primary transportation purposes even if the EV owner decides to leave before the estimated departure time. In addition, it has to be noted that the vehicle is always available for emergency situations since there is no V2G capability, so the battery will never be discharged below the initial SOC value. Moreover, EVs are modelled as a constant current load [170], meaning that $\kappa = 1$, as represented by equation (5.21).

$$SOC^{\phi EV}_{i,t} = SOC^{\phi EV}_{i,t-1} + P^{\phi EV}_{i,t} \cdot \Delta t \cdot \eta^{\phi EV}_{ch,i} \tag{5.18}$$

$$SOC^{\phi EV}_{0,i} \leq SOC^{\phi EV}_{i,t} \leq SOC^{EV}_{max} \tag{5.19}$$

$$SOC^{\phi EV}_{i,t|t=t_{end}-1} = SOC^{EV}_{max} \tag{5.20}$$

$$P^{\phi EV}_{i,t} = P^{\phi EV}_{0,i,t} \cdot |V^{\phi}_{i,t}| \tag{5.21}$$

In addition to EV battery constraints, EVSE constraints must be defined in terms of active and reactive power limits which are given in equation (5.22) and equation (5.23), respectively. It is assumed that the power factor can be dynamically modulated as described in equation (5.24), and that $k^{\phi EV}_{i,t}$ is fixed for each EVSE. For example, $k^{\phi EV}_{i,t} = 1/3$ means that an EVSE is capable of modulating the power factor up to 0.95 $(ind./cap.)$. The reactive power set-point is not autonomously calculated based on the predefined droop characteristics as it was the case in Chapter 4, but it is externally set by a centralised controller which calculates both the EV active and reactive power.

$$0 \leq P^{\phi EV}_{0,i,t} \leq P^{EV}_{max} \tag{5.22}$$

$$Q^{EV}_{min} \leq Q^{\phi EV}_{i,t} \leq Q^{EV}_{max} \tag{5.23}$$

$$-k^{\phi EV}_{i,t} \cdot P^{\phi EV}_{i,t} \leq Q^{\phi EV}_{i,t} \leq k^{\phi EV}_{i,t} \cdot P^{\phi EV}_{i,t} \tag{5.24}$$

It is assumed that EV aggregator gathers historical data and can accurately estimate probability distributions of EV arrival and departure times as well as the initial SOC. Thus, these values are input parameters for the proposed model. It should be noted that the choice of the probability distribution does not influence the formulation of the optimisation model.

5.2.3 Objective functions

As previously described, the method combines two partially competing objectives with respect to EV scheduling. In general, it is not possible to optimise both objectives at once and improvement of one objective leads to worsening of the other. Assuming that $F(X)$ is the vector of objective functions, whereas $H(X)$ and $G(X)$ represent equality and inequality constraints, respectively, the bi-objective minimisation problem can be formulated as described in equation (5.25).

$$\begin{aligned} \text{minimise} \quad & f(X) = [f_1(X), f_2(X)] \\ \text{subject to:} \quad & \{G(X) = 0, H(X) \leq 0\} \\ & X = [x_1, ..., x_m] \end{aligned} \tag{5.25}$$

It is said that the solution X_1 dominates X_2 if and only if X_1 is no worse than X_2 in all objectives and X_1 is strictly better than X_2 in at least one objective, i.e., if and only if equation (5.26) is fulfilled. Any solution which is not dominated by any other belongs to the so-called Pareto optimal front which contains all possible solutions of the bi-objective optimisation. As seen in Figure 5.2, the Pareto front is contained in the objective space which is divided in feasible and infeasible regions defined by the equality and inequality constraints.

$$\begin{aligned} f_k(X_1) \leq f_k(X_2), \forall k \in \{1, 2\} \\ f_{k'}(X_1) < f_{k'}(X_2), \exists k' \in \{1, 2\} \end{aligned} \tag{5.26}$$

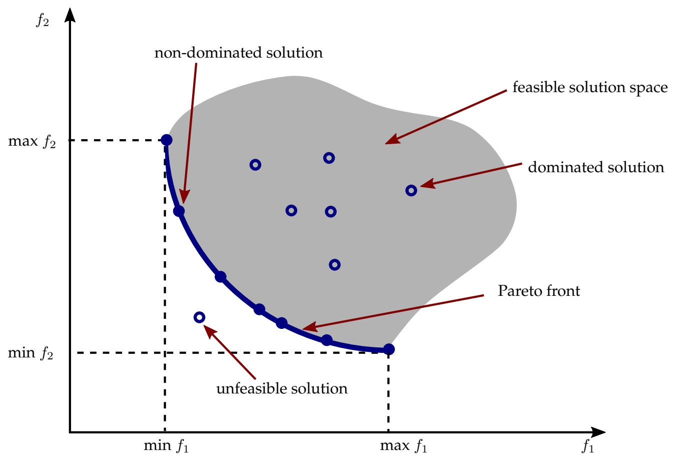

Figure 5.2: Pareto front of a bi-objective optimisation problem.

In this method, the first objective function is minimising the total loss cost as formulated in equation (5.27). The second objective function is minimising the EV aggregator's charging cost as formulated in equation (5.28).

$$\min \ f_1 = \sum_{t=1}^{T} \sum_{l=1}^{N_l} \sum_{\phi=a,b,c} P_{l,t}^{\phi loss} \cdot \Delta t \cdot \lambda_t = \sum_{t=1}^{T} \sum_{i}^{N_i} \sum_{j}^{N_j} \sum_{\phi=a,b,c} (P_{ij,t}^{\phi} + P_{ji,t}^{\phi}) \cdot \Delta t \cdot \lambda_t \tag{5.27}$$

$$\min \ f_2 = \sum_{t=1}^{T} \sum_{EV=1}^{N_{EV}} \sum_{\phi=a,b,c} P_{i,t}^{\phi EV} \cdot \Delta t \cdot \lambda_t \tag{5.28}$$

where $P_{l,t}^{\phi loss}$ are the losses on phase ϕ of line l, $P_{i,t}^{\phi EV}$ is the EV charging rate, and λ_t is the corresponding electricity price at time t.

For obtaining the Pareto front of the bi-objective optimisation, the two most common approaches are the weighted sum method and the ϵ-constraint method [171]. The weighted-sum method transforms the two objectives into an aggregated single-objective function by multiplying each of them with an *a priori* specified weighting factor and summing all up. On the other hand, the ϵ-constraint method involves minimising the primary objective function while expressing the other one in the form of inequality constraints. Here, the ϵ-constraint method is used due to several advantages, e.g., it can be used for both convex and non-convex Pareto optimal sets, it does not require scaling of the objective functions which can influence the results, and it needs less iterations for the front discovery compared to the weighted-sum method where several weight combinations can result in the same solution. Hence, equation (5.25) can be reformulated as described in equation (5.29).

$$\begin{aligned} \text{minimise} \quad & f_1(X) \\ \text{subject to:} \quad & \{G(X) = 0, H(X) \leq 0\} \\ & f_2(X) \leq \epsilon \\ & X = [x_1, ..., x_m] \end{aligned} \tag{5.29}$$

where ϵ varies from the maximum value to the minimum value of f_2.

5.2.4 Best compromise solution

One of the benefits of a multi-objective approach is that it provides a range of possible solutions which allows to obtain a priority list of EV schedules according to the decision maker. Therefore, once the Pareto optimal front is obtained, the final operating schedule needs to be chosen. Here, a fuzzy satisfying set theory is used to choose the best compromise solution. For each solution X_n in the Pareto front with N_S solutions and N_O objectives, a linear function $\mu_k(X_n)$ is defined as described in equation (5.30). This function shows the level of which X_n belongs to the set that minimises the objective function f_k. For example, in the Pareto solution where f_1 is minimised, the linear function μ_1 will equal to one meaning that the DSO is completely satisfied with the solution, whereas μ_2 will equal to zero meaning that the EV aggregator is completely dissatisfied with the solution.

$$\forall k \in \{1,2\} \; \mu_k(X_n) = \begin{cases} 0, & f_k(X_n) \geq f_{kmax} \\ \dfrac{f_k(X_n) - f_{kmax}}{f_{kmin} - f_{kmax}}, & f_{kmin} \leq f_k(X_n) \leq f_{kmax} \\ 1, & f_k(X_n) \leq f_{kmin} \end{cases} \tag{5.30}$$

where f_{kmin} is the minimum and f_{kmax} is the value of objective f_k.

The best compromise solution is determined by the decision maker who needs to balance the satisfaction of both stakeholders. A conservative decision maker tries to minimise the maximum dissatisfaction of both entities, which can be described by equation (5.31).

$$\min_{N_S} \left(\max_{k=1}^{N_O} (\mu_k(X_n)) \right) \tag{5.31}$$

5.3 Study case

The same Borup LV grid which has been used in Chapter 4 is also used for testing the proposed multi-objective model, with the following conditions:

- A winter 24-h period is chosen from 15/01/2013 12:00 until 16/01/2013 11:00 in order to include the night time when EVs are typically connected with the corresponding electricity price taken from the NordPool Spot day-ahead electricity market.

- It is assumed that the price as well as the consumption can be forecasted with a reasonable accuracy, so the error associated with the forecast is disregarded.
- The consumption unbalance distribution is assumed to be $a : b : c = 40\% : 30\% : 30\%$ and the demand response parameter is fixed for all nodes to $\xi_i = 10\%$ meaning that 10% of the residential load is flexible if demand response is available.
- There are 15 EVs randomly connected across the observed feeder resulting in 35% penetration rate. The normal probability distribution used for rendering the arrival/departure time as well as the initial SOC is taken from the Test-an-EV program [51].
- All EVs are assumed to be a Nissan Leaf with $SOC_{max}^{EV} = 24\ kWh$, $\eta_{ch,i}^{\phi EV} = 80\%$ [172] and a single-phase Level 2 connection of maximum $16\ A$, i.e., $P_n^{EV} = 3.7kW$. Moreover, all EVs are capable of providing reactive power modulation with $Q_n^{EV} = \pm\frac{1}{3}P_n^{EV}$ in addition to the active power modulation [151], i.e., $S_n = 3.9kVA$.

The main results of the scenarios listed in Table 5.1 are presented in section 5.4, whereas the reader is referred to Pub. F for more details. The simulations are done using GAMS software with CONOPT solver on a notebook with a 2.6-GHz Intel(R) Core(TM) i7-5600U CPU and 8 GB of RAM, taking in average 6-20 seconds for solving one optimisation problem depending on the scenario. The stop criteria for the optimisation is given as the CONOPT's default tolerance value of 10^{-7}. It is worth noting that the formulated problem is highly non-convex and for such the solver converges to a local optimum which is not necessarily the global one.

Table 5.1: Overview of conducted scenarios.

Scenario	EV flexibility	Demand response	Plot label
V-I	-	-	uncontrolled
V-IIa	P	-	P
V-IIb	PQ	-	PQ
V-IIIa	P	±10%	P+DR
V-IIIb	PQ	±10%	PQ+DR

5.4 Results

The comparison of the obtained Pareto optimal fronts for all conducted scenarios is given in Figure 5.3a, from which it is obvious that introducing any kind of EV flexibility is more beneficial than uncontrolled EV charging which coincides with the most expensive peak hours. The more detailed view for scenarios V-IIa to V-IIIb is shown in Figure 5.3b, with the best compromise solutions emphasised in red. It can be seen that there is a small, but non-trivial trade-off between the loss cost minimisation and the EV charging cost minimisation.

Introducing EV reactive power flexibility has a beneficial impact on the grid, both when interconnected with other residential demand response and when not. However, it can be noticed how the maximum EV cost increases with the additional system flexibility. One of the reasons behind it is the EV reactive power support which influences the losses, but is only available if EVs are charging. Hence, the minimum loss cost is obtained if part of the charging process is shifted to more expensive hours when there is a greater need for reactive power support.

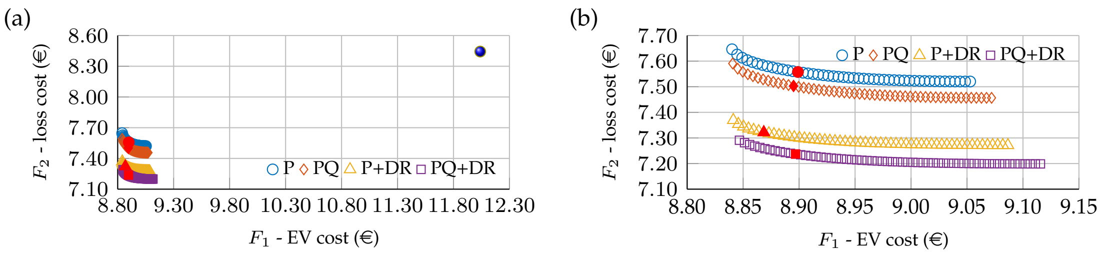

Figure 5.3: (a) Comparison of obtained Pareto fronts for scenarios V-IIa to V-IIIb with the uncontrolled charging, and (b) more detailed view of obtained Pareto fronts.

Table 5.2: Reduction in the objective functions' values for the best compromise solutions compared to the uncontrolled charging.

Scenario	Total losses (kWh)	Δ EV charging cost (%)	Δ loss cost (%)
V-I	161.2943	-	-
V-IIa	150.5874	-26.08	-10.49
V-IIb	149.1654	-26.11	-11.14
V-IIIa	150.2265	-26.33	-13.28
V-IIIb	148.0795	-26.10	-14.29

Furthermore, as seen from the relative values of the best compromise solutions shown in Table 5.2, introducing EV reactive power flexibility does not have a significant impact on the EV charging cost, whereas it has a beneficial influence on the DSO loss cost. Interestingly, even though the absolute losses increase in certain scenarios, the loss cost decreases, since the consumption is shifted to the less expensive hours. Hence, minimising the grid loss cost, as formulated in this method, is more advantageous than minimising the losses themselves.

Figure 5.4 reports the active and reactive power interaction between the observed feeder and the MV grid at the substation level. First of all, when looking at the active power profiles, similar behaviour is observed for all phases. The EV charging has been shifted to the off-peak time in all conducted scenarios, with the additional residential consumption moved to the same hours in cases where demand response is available. On the other hand, EV reactive power support is observed to be different on each phase. It is clear that the reactive power import from the MV grid is lower in scenarios with EV reactive power flexibility as the EVs provide local support. The exception is phase b due to the specific EV behaviour explained further on.

Individual EV active and reactive power profiles for the best compromise solution of scenario V-IIIb are given in Figure 5.5. It can be easily seen that individual EV schedules differ depending on the connection point, both for the active and for the reactive power. As expected and seen in Figure 5.5a, EVs are charging during the night since the electricity price is lower, resulting in indirect peak shaving and a decreased need for grid reinforcement. However, what is more interesting to observe are the reactive power profiles depicted in Figure 5.5b. Even though one would expect only capacitive EV behaviour, inductive behaviour is observed for several EVs connected in area A on phase b. The reason behind are relatively high unbalances in the corresponding area which negatively impact the losses. Therefore, several EVs behave inductively to bring the voltages closer together, reduce the unbalances and consequently also the loss cost. These results also emphasise the importance of using the unbalanced optimal power flow, as such optimal schedule would be impossible to obtain with the balanced grid formulation.

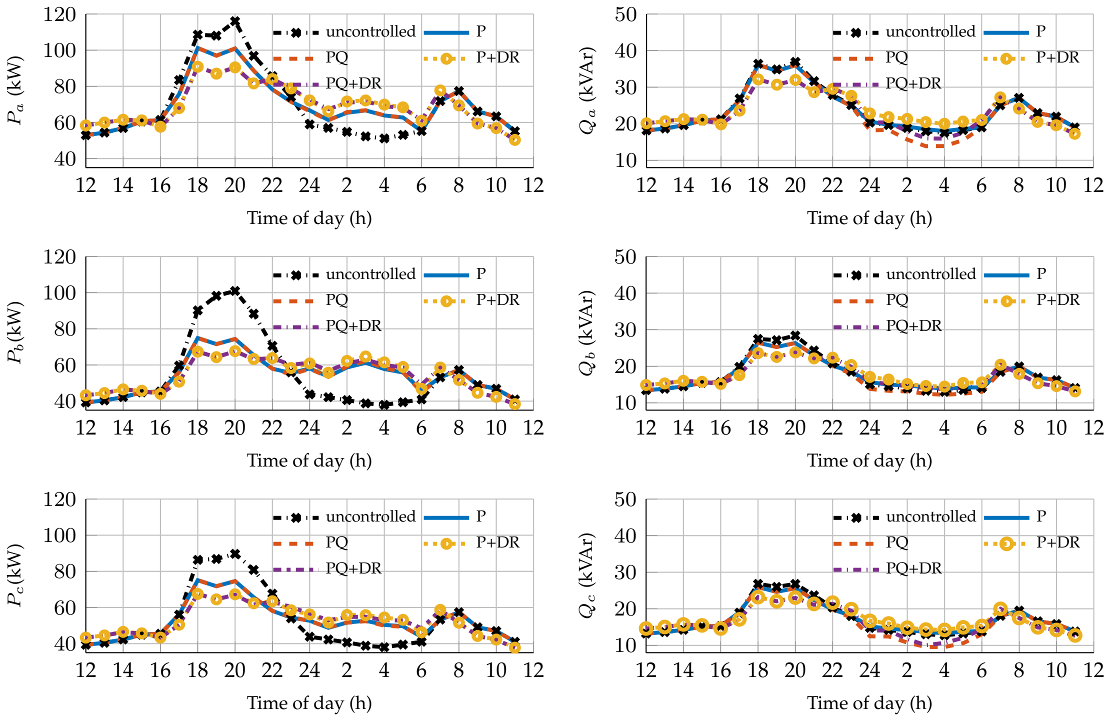

Figure 5.4: Active and reactive power profiles of each phase at the substation level for the best compromise solutions of conducted scenarios.

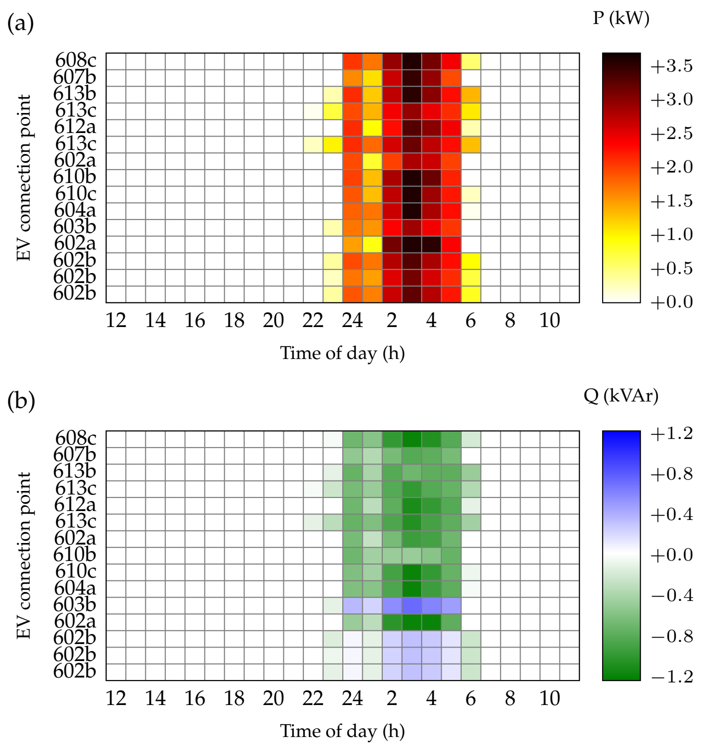

Figure 5.5: (a) Active and (b) reactive power profiles for EVs in the winter scenario with demand response (scenario V-IIIb).

There are several assumptions which influence the final EV schedule, so sensitivity analysis is conducted for the chosen parameters. First of all, the impact of the maximum EV charging rate on the Pareto front is presented in Figure 5.6a. It can be seen how the minimum lost cost does not change as it is never in the DSO's interest to charge at the maximum rate. However, from the aggregator's point of view, the higher the charging power is, the lower the minimum charging cost can be since EVs can charge more in the low electricity price hours. Hence, the DSO is willing to pay more since the alternative worst-case scenario is more severe, so the best compromise solution is moved upwards. Secondly, as seen in Figure 5.6b, the better the EV charging efficiency is, the greater the benefits for both entities are, so the Pareto front moves towards the utopia point. Finally, the impact of the residential demand response amount is given in Figure 5.6c. Interestingly, the more system flexibility is introduced, the more the maximum EV charging cost increases. Nevertheless, for a fixed EV charging cost, the loss cost are reduced as more demand response is introduced.

Furthermore, sensitivity analysis is also conducted for the probability distribution of the EV arrival/departure time. According to [173], EV arrival time can be approximated with the generalised extreme value distribution $GEV(\mu, \sigma, \zeta)$ whose cumulative distribution function (CDF) is described in equation (5.32), whereas the departure time can be approximated with the Weibull distribution $Weibull(\alpha, \beta)$ whose CDF is described in equation (5.33). The comparison between using these distributions and the previously used normal distribution is given in Table 5.3. It can be observed that the best compromise solution does not change notably, since EVs mainly charge during the night when they are available regardless of the used distribution. The differences arise due to several EVs which are estimated to departure earlier and are, naturally, rescheduled to charge earlier as well. This results in a lower EV charging cost due to lower electricity prices, but a higher loss cost due to the total consumption increase in these hours.

$$F_{GEV}(x; \mu, \sigma, \zeta) = e^{-(1+\zeta\frac{x-\mu}{\sigma})^{(-1/\zeta)}} \tag{5.32}$$

$$F_{Weibull}(x; \alpha, \beta) = 1 - e^{-(x/\alpha)^{\beta}} \tag{5.33}$$

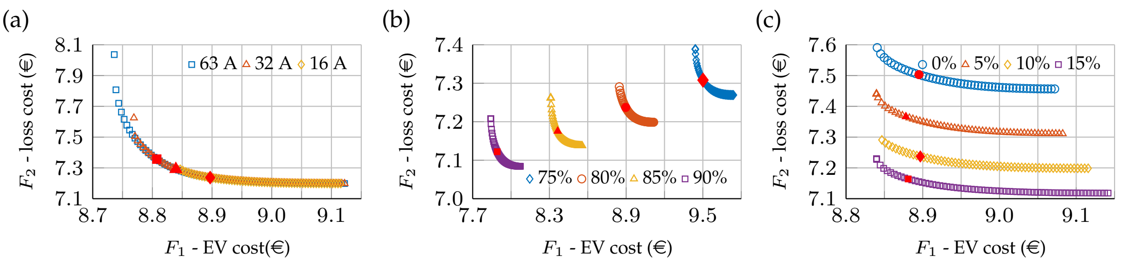

Figure 5.6: Impact of (a) maximum EV charging rate, (b) EV charging efficiency, and (c) demand flexibility on Pareto optimal front in scenario V-IIIb.

Table 5.3: Impact of EV arrival/departure time probability distribution on the best compromise solution in scenario V-IIIb.

Arrival time distribution	Departure time distribution	EV charging cost (€)	Loss cost (€)
$t^{\phi EV}_{start,i} \sim \mathcal{N}(19.16, 0.66)$	$t^{\phi EV}_{end,i} \sim \mathcal{N}(7.83, 0.48)$	8.8976	7.2367
$t^{\phi EV}_{start,i} \sim GEV(17.3, 0.85, -0.06)$	$t^{\phi EV}_{end,i} \sim Weibull(7.67, 21.83)$	8.8839	7.2442

5.5 Summary

This chapter described the importance of combining both the DSO's and the EV aggregator's economic concerns when obtaining the EV day-ahead schedule. It has been seen that the optimal EV schedule may differ considerably among the stakeholders, so the final solution requires weighing not only the wishes of each of them, but also the alternatives. Therefore, a bi-objective optimisation model has been proposed to combine the economic concerns of both entities, namely minimising the loss cost and minimising the EV charging cost.

It has been shown that the method successfully obtains a Pareto front with evidence there is a relatively small (in this study case), but non-negligible trade-off between the two objectives. The fuzzy set approach has been used to determine the best compromise solution since it weights each solution compared to the alternatives and balances the satisfaction of both entities. In addition, the importance of including unbalanced grid conditions has been noted as individual EV schedules greatly differ depending on their connection point and local conditions. Moreover, the impact of additional EV reactive power support has been analysed, both on the grid conditions and on the obtained costs. It has been observed that such support provides benefits for the DSO without significantly affecting the EV aggregator's cost.

One must bear in mind how it is assumed that the DSO and the EV aggregator are willing to share information to obtain the best-compromise solution. More specifically, the DSO functions as a flexibility operator which receives data about EV availability and has the authority to obtain the best-compromise solution for the involved parties. However, the economic model of such a system is highly dependent on the regulatory environment as well as on future roles of the local flexibility operator. If EV aggregator has no incentive or obligation to help the active distribution grid management, it will not do so. More precisely, the aggregator will schedule the EVs based solely on their own economic concerns, while disregarding the potential drawbacks for the local grid. The DSO would then need to formulate a price signal which would reflect the local concerns and represent the loss cost at each phase and node, and based on which the aggregator would modify the schedule independently. Whereas such nodal pricing schemes have been extensively explored for congestion prevention purposes, formulating nodal prices for loss cost becomes non-trivial for unbalanced distribution systems and has not been extensively analysed. More specifically, in order to derive such a price, it would first be necessary to calculate the loss sensitivity of each phase at each node to specific nodal load, while also accounting for the nodal load at the remaining two phases. For instance, [174] presents a nodal pricing method where marginal loss coefficients are calculated to indicate incremental loss deviations due to nodal power injections, but the method is derived only for balanced systems. On the other hand, [175] presents an approximate method for calculating loss sensitivity factors in unbalanced systems, yet it assumes that the mutual impact between the phases is negligible, which is often not the case. For the model proposed in this chapter, formulating loss prices would mean that the price utilised in the objective function f_1 for loss cost minimisation would not be the spot market price, but the local nodal loss price. The model could then be extended and split into two stages. The first one would include deriving the nodal loss prices via loss sensitivity coefficients and power flow equations. The second stage would include the multi-objective optimisation where nodal loss prices are forwarded to the aggregator, and the best-compromise schedule is found based on the spot market price and the derived loss cost. Since the aggregator does not have information about the underlying grid, EV schedules would be send back to the DSO who could reformulate the prices if the schedule violates local network constraints. The process would be repeated until a feasible solution is obtained. However, due to the difficulty of formulating loss sensitivity coefficients for unbalanced systems, it may be more beneficial to embed the power flow equations in the scheduling problem itself, as formulated here. This means that the flexibility operator must act as a mediator with the authority to obtain the best-compromise schedule. Even though technical benefits of such collaborative scheduling have been shown here, additional regulations are needed to enhance the collaboration among the participating stakeholders.

Furthermore, the presented methodology is based on several assumptions which can be addressed in future work. First, the error associated to the electricity price forecast has been disregarded, so the method could be extended to include the price uncertainty via, e.g., robust optimisation techniques. Secondly, EV aggregator is assumed to be a price taker who does not impact the wholesale electricity price with its EV schedule. This is currently the case, but as EVs become widely adopted, the aggregator may have a large market share and potentially influence the electricity price. It is also assumed that EV owners are not interested in how and when the vehicles are charged as long as they are fully available by the estimated departure time. This remains true as long as the aggregator chooses to remunerate all EV owners in the same manner, e.g., EV owners pay a fixed charging price which is somewhat lower than the residential electricity tariff, and in return the aggregator can manipulate the charging process for its own benefit. In case EV owners are remunerated differently, e.g., by forming nodal prices and remunerating EVs accordingly, competitiveness among EV owners would be introduced since they would all like to charge as fast as possible when local nodal prices are low. Then, the objective function should be extended to compensate for the unfairness issues coming from the underlying electrical grid and specific EV connection point. A proportionally fair approach from telecommunication systems can be applied to EV scheduling to ensure that the available capacity is allocated in a fair manner and the welfare of controllable resources is maximised [176]. Moreover, altering the EV charging process may have detrimental impacts on the battery life-cycle since battery degradation depends on the operating and storing conditions [177], which have not been included in the presented model. To include the potential battery ageing and avoid strategies which excessively detriment the battery, the objectives presented in Section 5.2 could be extended to include battery ageing cost. Even though several papers indicate that the dominant battery degradation is not dependent on the charging rate for low power values [165–167], extensive empirical characterisation tests are needed to derive the values for capacity fade for different combinations of initial/final SOC at various charging rates, and consequently the battery ageing cost. Finally, the presented method assumes that the connection points of controllable EVs are randomly distributed. The model could be extended for distribution grid planning purposes to determine the optimal phase to which the EV should be connected within each household.

Chapter 6

Experimental validation of multiple EV flexibility services

The main results of Pub. G and Pub. H, which focus on validating the feasibility of series-produced EVs to provide flexibility services, are provided in this chapter. First, the importance of experimental work with contemporary EV technology is discussed after which the developed smart charging controller is presented. Finally, the main results of experimental trials are shown, followed by a discussion and a summary with the recognised recommendations.

6.1 On the importance of experimental validation

As described in Chapter 2 and Chapter 3, EVs can provide different ancillary services to the power system which is shown through a variety of theoretical studies. However, a distinction between the EV current set-point and the actual EV current must be made. The EV current set-point is the one allocated to the individual EV through the used control strategy. On the other hand, the internal EV charging control system may choose not to draw the set current due to battery-dependent constraints including the state of health, the temperature, etc. Most of the recognised literature remained on simulation-based studies, whereas the experimental validation has rarely been touched upon. In general, when dealing with flexibility services, the literature addresses only the EV current set-point, assumes an ideal EV response to it, and ignores the potential latencies as well as the response inaccuracies. However, these issues may be crucial since each service has specific requirements which must be fulfilled by the providing device.

The importance of the hardware-in-the-loop tests for evaluating the ancillary service provision of power-electronic-interfaced units is discussed in [178]. The authors interconnect a small physical inverter with an emulated system to investigate the coordination of ancillary services with the existing infrastructure. It is shown that pure digital simulation approaches cannot reproduce the true system behaviour in all circumstances and testing real hardware is crucial. The same reasoning can be extended to testing the EV capabilities since they are also power-electronic-interfaced.

Experimental testing of the proposed frequency controllers is presented in [98, 179]. However, therein, the EV is represented by a custom-made set of Li-Ion batteries whose behaviour differs from that of commercial EVs. In the future smart grid system, the EV potential mostly lies in the commercial vehicles primarily being used for transportation purposes and secondly for system support. The system operators will deal with EVs as a "black box" whose internal characteristics cannot be changed and consequently have to be carefully analysed in order to guarantee system stability and reliability. Hence, an extensive experimental activity is required to demonstrate the technical feasibility of different EV control strategies with the currently available technology. Moreover, the assessment of realistic errors, which could then be used for further theoretical studies, is needed.

This chapter focuses on validating the developed smart charging controller for providing multiple flexibility services with a commercially available EV, as well as identifying potential issues which may arise when dealing with the practical implementation. This topic is addressed in Pub. G with the main results presented in section 6.3. Furthermore, extending the controller to coordination of several EVs for a specific application of improving the power quality in distribution grids is discussed in Pub. H with the main results presented in section 6.4.

6.2 Developed smart charging controller

In order to validate the technical feasibility of contemporary EVs to provide different services, a universal smart charging controller is developed, which is applicable to any EV compliant with standards IEC 61851 and SAE J1772. This controller can be used for performing both centralised control strategies by the EV aggregator, such as congestion management or primary frequency control, or as a decentralised controller implemented directly in the EVSE, e.g., for local voltage support. The following subsection presents the developed controller applicable to a single EV, whereas the changes necessary for coordinating multiple EVs are presented in section 6.4.

6.2.1 Control logic

The control logic is based on a well-established droop control scheme commonly used in the power system domain due to its simplicity, making it a viable solution for EV flexibility provision as well. As shown in a number of studies [95, 96, 100], EVs equipped with a simple droop controller can provide frequency regulation and maintain the system frequency, whereas several studies have shown that such control can also be extended for distribution grid support in terms of voltage and congestion regulation [110, 180].

The developed controller is depicted in Figure 6.1 and the necessary input parameters for the construction of the ideal droop characteristic are explained in the following:

(1) the *type of service* which defines the droop characteristic sign ($sign(k)$) and the input measurement to which the EV is responding (I_{meas}, U_{meas} or f_{meas}),

(2) the *minimum* I_{EVmin} and the *maximum EV charging current* I_{EVmax}, and

(3) the *minimum* $threshold_{min}$ and the *maximum* $threshold_{max}$ for the chosen service which define the range within which the EV must provide flexibility for system support.

The controller's output signal $I_{EVlimit}$ represents the charging current above which the EV must not charge and can be interpreted as the EV charging set-point. However, the effective droop characteristic cannot be linear as the ideal theoretical one due to several practical limitations.

As described in section 3.2.1, contemporary standards define that EVs must be able to limit their charging rate between the minimum charging current of 6 A and the maximum EVSE rated current. These values are used by default in the controller unless specified otherwise. The same standards also require that EV charging rate is limited in discrete 1 A steps, whereas the response

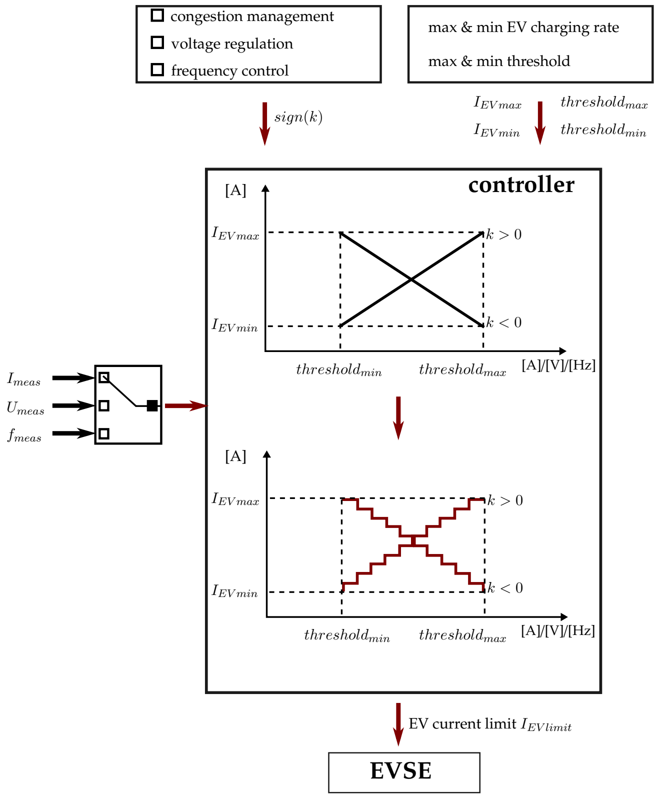

Figure 6.1: Schematic overview of controller's input parameters for droop characteristics construction.

to intermediate currents is not guaranteed. Hence, the effective EV droop characteristic cannot be linear like the ideal theoretical one and it becomes stepwise due to the described practical limitations. Secondly, the standard defines I_{EVmin} to be minimum 6 A due to the EV's internal technical requirements. Thus, if a lower current is desired, the EV can either charge at 6 A or be switched off. Finally, I_{EVmax} equals to the maximum EVSE charging rate, but can also be arbitrarily defined within the controller if other practical reasons arise, e.g., residential fuse ratings. Therefore, for the tested smart grid applications, I_{EVmin} and I_{EVmax} specify the band within which the $I_{EVlimit}$ can be controlled as follows:

$$\begin{aligned} I_{EVmin} \leq I_{EVlimit} \leq I_{EVmax} \\ I_{EVlimit} \in \mathbb{N} \end{aligned} \tag{6.1}$$

This means there are only 11 current steps available for a typical 16 A single-phase connected EV (i.e., 6 A, 7 A, ..., 16 A).

Depending on the chosen service, the developed controller responds to measurement data coming either from a central entity, a transformer substation or a local measurement device within the EVSE, as described in more detail in 6.2.2. It is up to the system operator to determine the most suitable thresholds for each of the services, and to define the range $threshold_{min} - threshold_{max}$ within which the EV provides flexibility. These thresholds can be either constant or dynamically changed depending on grid conditions if an adaptive droop characteristic is required or if the droop characteristic needs to be periodically updated to include the SOC target. Here, the main focus has been on assessing EV technical parameters such as the response time and the accuracy, which are not influenced by the chosen thresholds. Therefore, the thresholds have been set to fixed values. Similarly as derived in [180], EV charging rate is a linear characteristic of the input measurement data which can be calculated as the multiplication between the droop gain and the difference between the measured and the nominal value (i.e., current, voltage or frequency). Thus, once the thresholds are defined, the droop slope k is calculated as:

$$k = \frac{I_{EVmin} - I_{EVmax}}{threshold_{min} - threshold_{max}} \tag{6.2}$$

Then, the EV charging current limit I_{calc} is calculated according to equation (6.3) for congestion management, equation (6.4) for voltage regulation and equation (6.5) for frequency control. Since the set EV charging limit $I_{EVlimit}$ must be an integer value due to the described practical limitations, the calculated current is rounded up.

$$I_{calc} = \lceil -k \cdot (I_{meas} - threshold_{min}) + I_{EVmax} \rceil \tag{6.3}$$

$$I_{calc} = \lceil +k \cdot (U_{meas} - threshold_{max}) + I_{EVmax} \rceil \tag{6.4}$$

$$I_{calc} = \lceil +k \cdot (f_{meas} - threshold_{max}) + I_{EVmax} \rceil \tag{6.5}$$

Finally, the EV current charging limit $I_{EVlimit}$, which is sent to the EVSE controller, is set as:

$$I_{EVlimit} = \begin{cases} I_{calc}, & I_{EVmin} \leq I_{calc} \leq I_{EVmax} \\ I_{EVmax}, & I_{calc} > I_{EVmax} \\ I_{EVmin}, & I_{calc} <_{EVmin} . \end{cases} \tag{6.6}$$

One should note that the droop control is chosen due to its simplicity which makes it cheap and applicable on a wide range of computing devices, which is often of interest due to scalability reasons. However, the controller can be extended to other control strategies such as multi-agent systems investigated in [181, 182] where the EV charging limit is calculated based on the market price, as well as for a more complex droop control strategies which include the user preferences [183]. Naturally, for a more complex control logic, the overall performance could decrease due to a longer computational time. Nevertheless, the way the EV current limit is calculated does not effect the EV responsiveness and accuracy which have been the main focus of this chapter. The experimental comparison of different control logics has been beyond the scope of the project and is recognised as a topic for future work.

6.2.2 Communication architecture

The communication architecture for the implemented controller is given in Figure 6.2 which makes it clear that the input measurement signal comes from different devices depending on the chosen service. More specifically, the voltage measurement comes via Ethernet using the MODBUS protocol from a local measurement device installed directly in the EVSE, whereas the transformer loading and the system frequency measurement come from remotely located devices via the Internet. After polling the measurement using the corresponding data poller subroutines, the control logic sends the desired EV charging rate to the EVSE controller. The EV itself is connected to the EVSE using the IEC 61851 standard, so the EVSE controller actuates the charging limit by changing the PWM signal of the Control Pilot line, as described in Chapter 3, section 3.2.1.

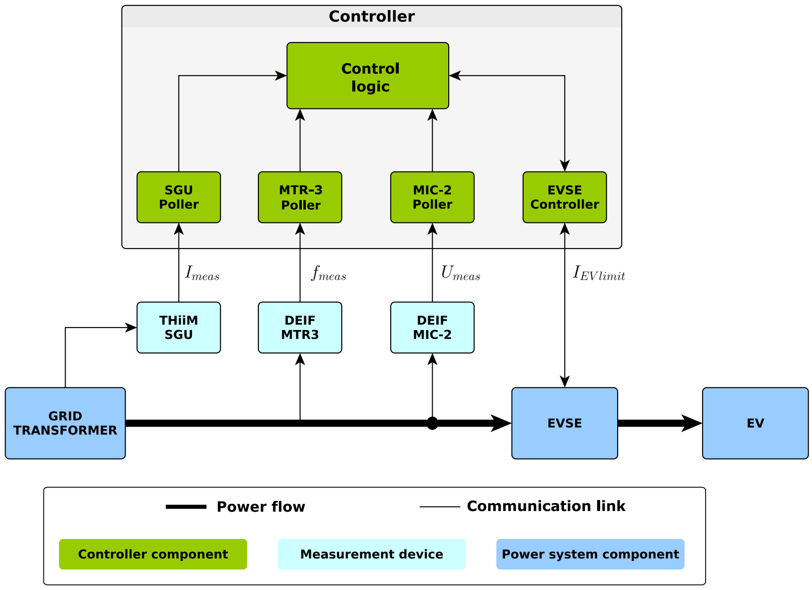

Figure 6.2: Communication architecture diagram for the tested smart charging controller.

6.3 Field test validation

The field test has been conducted in the same 400 V distribution feeder used for simulation analyses in the previous chapters which is described in Appendix B. The specific experimental setup together with the corresponding results are given in the remainder of this section.

6.3.1 Experimental setup

For the conducted field trials, the EV has been connected to a standard Schuko plug in a residential house located towards the end of the feeder at node 612, as depicted in Figure 6.3. The following components have been used in the experimental setup:

- series-produced EV (Nissan Leaf from 2015) with 24 kWh Li-Ion battery and a single-phase 16 A (230 V) connection,
- EVSE with a PhoenixContact EVSE controller for limiting the EV charging current,
- ThiiM Smart Grid Unit (SGU) located at the transformer substation for loading measurement with 0.1 A accuracy and 30-s sampling rate,
- DEIF MIC-2 for local voltage measurement and EV current measurement with 0.2% accuracy and 1-s sampling rate,
- DEIF MTR-3 located at Risø Campus of Technical University of Denmark for frequency measurement with 10 mHz accuracy and 1-s sampling rate, and
- a notebook with Internet connection for receiving the measurements and running the control logic.

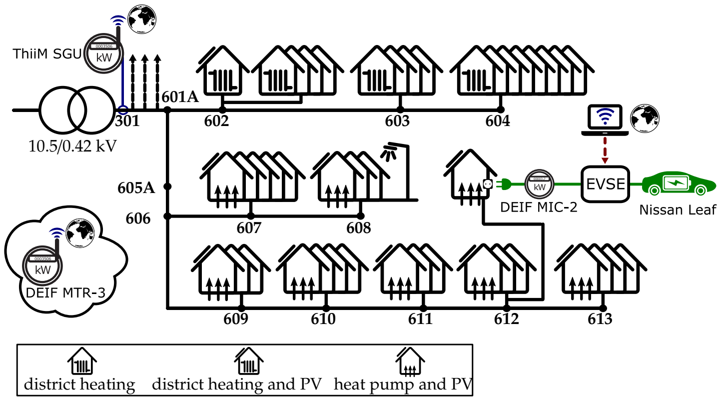

Figure 6.3: Schematic overview of the conducted field trials and the corresponding grid topology.

EV provision of three flexibility services has been tested, namely:

(1) *congestion management* with the set thresholds $I_{min} = 90$ A and $I_{max} = 120$ A ,

(2) *local voltage support* with the set thresholds $U_{min} = 0.96\ U_n$ and $U_{max} = 0.98\ U_n$, and

(3) *frequency-controlled normal (FCN) operation reserve*[1] with the set thresholds $f_{min} = 49.9$ Hz and $f_{max} = 50.1$ Hz.

As aforementioned, the chosen thresholds do not impact the assessment of EV technical parameters. Here, the specific thresholds have been arbitrarily chosen based on the grid circumstances at the time of the field trial, except for the FCN operation reserve whose thresholds correspond to the grid codes. The constructed ideal and the effective EV droop characteristics can be seen in Figure 6.4.

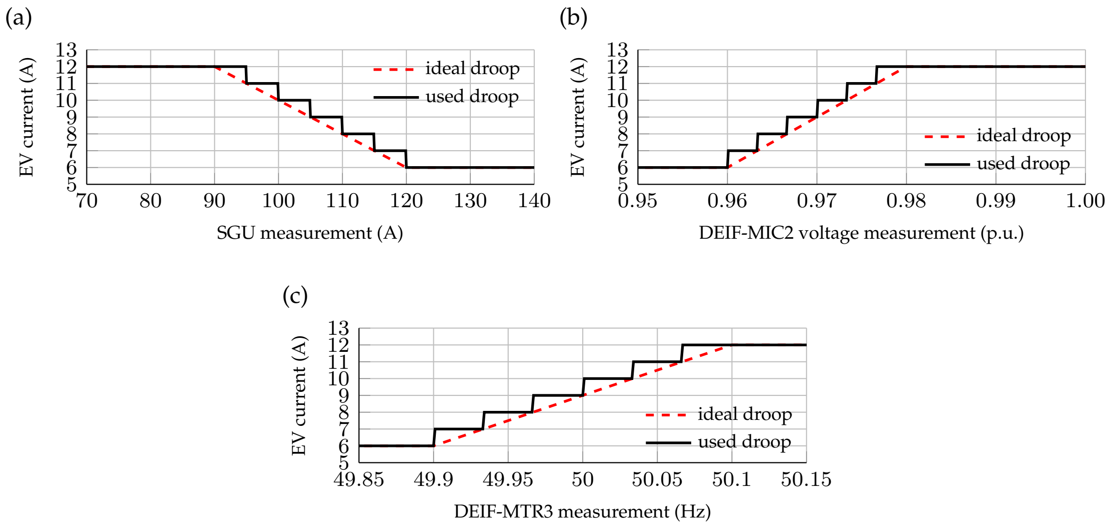

Figure 6.4: Implemented droop characteristics for the field validation in case of: (a) transformer congestion management, (b) local phase-to-neutral voltage support, and (c) frequency-controlled normal operation reserve.

[1] Primary frequency control in the Nordic syncronous region is split into two reserves: frequency-controlled normal (FCN) operation reserve and frequency-controlled disturbance (FCD) reserve as described in Chapter 2.

6.3.2 Evaluation criteria

The technical feasibility and the performance are evaluated by assessing four distinctive error indicators as listed in Table 6.1. The evaluated control delay includes the EV charging limit computation time, the communication delay between the control logic and the EVSE controller as well as the time needed for the change of the PWM signal including all the respective measurement delays. On the other hand, the EV response time includes only the time the EV needs to change the charging current after the PWM signal has been changed by the EVSE controller, including the respective measurement delay.

Table 6.1: Evaluated error indicators in the EV field trials.

Compared signals	Observed aspect	Parameter name
$\{I/U/f\}_{meas}$ & $I_{EVlimit}$	time difference	*control delay*
$I_{EVlimit}$ & I_{EV}	time difference	*EV response time*
$\{I/U/f\}_{meas}$ & I_{EV}	time difference	*overall delay*
$I_{EVlimit}$ & I_{EV}	magnitude difference	*EV accuracy*

The aim of this work has been to assess the controller's overall responsiveness and accuracy compared to the ideal droop controllers commonly used in simulation studies, i.e., the ones where the EV responds with no accuracy error and with a negligible response time. The EV response time is benchmarked to the frequency-controlled disturbance (FCD) reserve where 50% of the response must be provided within 5 seconds and the remaining 50% within additional 25 seconds. These specifications have been taken into account since the tested FCN service requirements only define that all reserve must be supplied within 150 seconds as described in Table 1.1. Currently, there are no requirements for the distribution grid services as they do not exist in practise. However, one must bear in mind that if an EV satisfies the FCD reserve requirements, it would also satisfy the future distribution grid ones since the overloading and voltage issues are of much slower nature. Selected field experiment results are reported in the following subsection and the reader is referred to Pub. G for a more detailed analysis.

6.3.3 Results

The first tested ancillary service is congestion management where the EV responds to the total feeder loading of its respective phase. The relationship between the input measurement signal and the EV response is given in Figure 6.5, with the corresponding scatter plot representation given in Figure 6.6 for several overall delays.

The two current dips seen in Figure 6.5a represent skipped measurement samples which are not an unusual occurrence for measurement devices. For validating purposes of this field trial, they were not seen as an issue since they do not impact the EV response time and accuracy. However, the resilience to such occurrences should be taken into account when deploying EV smart charging technology on a larger scale. One simple possible solution for overcoming this issue would be to remain on the previous EV charging rate if the input measurement equals to zero. Moreover, it can be seen from Figure 6.5b that EV charging has an inverse proportional behaviour to the input measurement current, with an evident difference between the set EV charging limit $I_{EVlimit}$ and the measured EV current I_{EV}. The shapes of these two curves are almost identical, but there

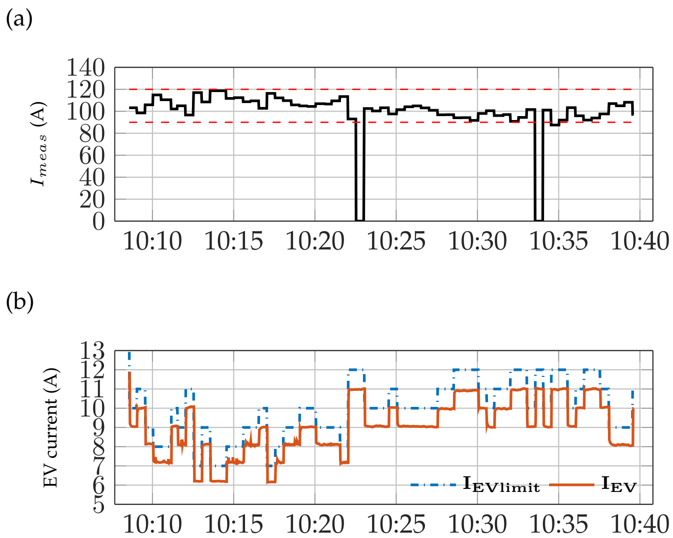

Figure 6.5: (a) Measured total feeder current at the transformer station I_{meas}, and (b) set EV charging limit $I_{EVlimit}$ and measured EV response current I_{EV} for the congestion management field trial.

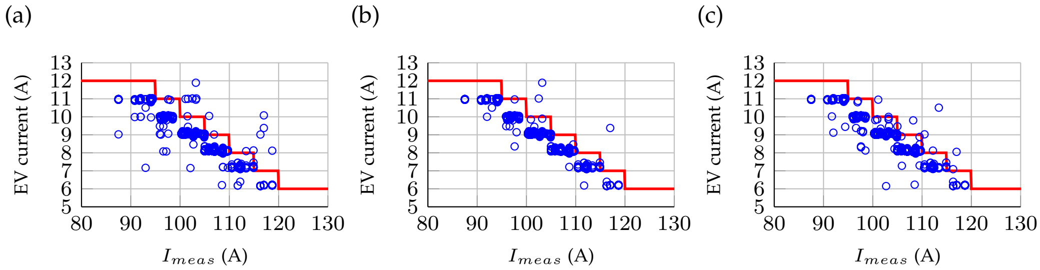

Figure 6.6: Relationship between the measured feeder current I_{meas} and the measured EV response current I_{EV} for the congestion management field trial in case of (a) 1 s overall delay, (b) 2 s overall delay, and (c) 3 s overall delay, with the used droop control characteristic emphasized in red.

is a consistent offset in their magnitudes. This "undershooting" phenomenon can also be easily recognized in Figure 6.6. Based on these observations, one can expect that the EV responsiveness is sufficient for flexibility provision, whereas the accuracy may arise as an issue, as discussed later on.

Similar EV behaviour is observed for the remaining two tested services, namely the local voltage support and the FCN reserve, whose overview is given in Figure 6.7, whereas the reader is referred to Pub. G for more details. Here, each scatter plot shows the relationship between the measured input signal and the set EV charging limit $I_{EVlimit}$ for a specific control delay, as well as the relationship between the measured input signal and the measured EV current I_{EV} for the same overall delay. Again, EV responsiveness has not been observed as an issue, whereas the accuracy is identified as a potential topic of concern.

As described in Table 6.1, the EV technical performance is evaluated by assessing the distinctive error indicators. First of all, different latencies need to be addressed as the response time is crucial for several ancillary services. It is important to note how these delays are not constant, so

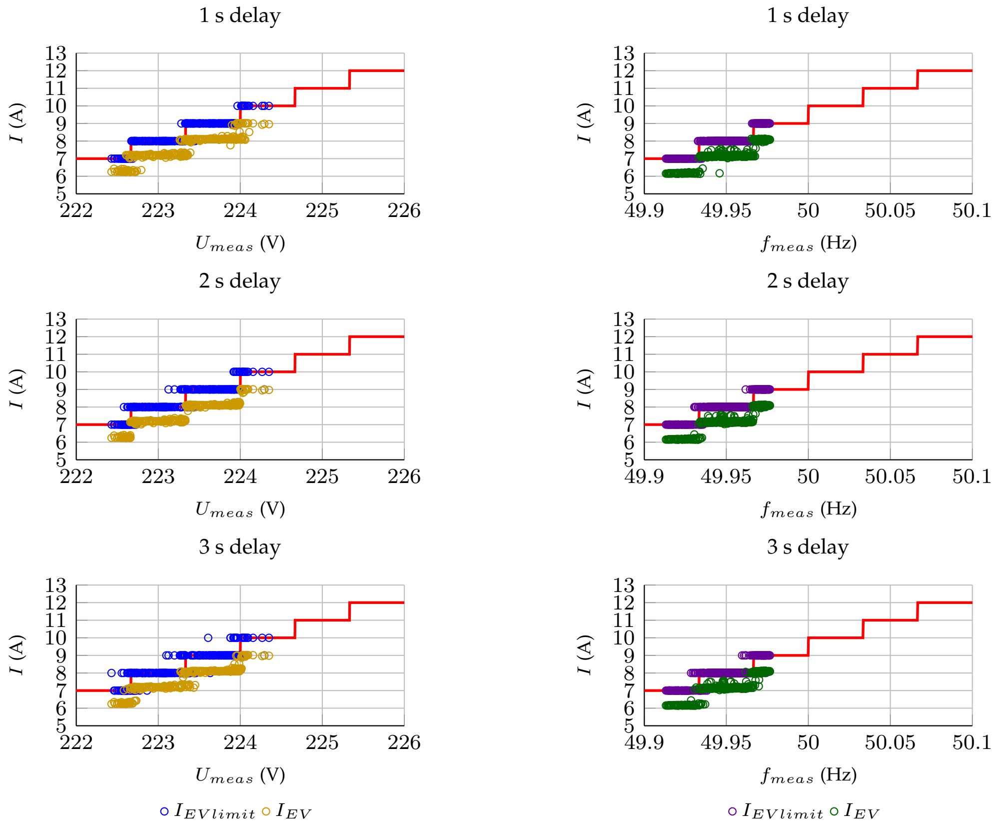

Figure 6.7: Relationship between the input measurement ($\{U/f\}_{meas}$), and the set/measured EV charging current ($I_{EVlimit}/I_{EV}$) for a specific control/overall delay in case of the voltage regulation trial (left subfigures), and the FCN reserve trial (right subfigures).

estimating the average value is not trivial. One of the commonly used methods when assessing the variable time delay in signal processing is using the cross-correlation method [184] where the peak value indicates the time difference for which the signals are best aligned. This difference is considered to be the average signal delay. In addition, the Pearson's Product-Moment (PPM) correlation coefficient [185] can be used as an indicator of this average delay value.

Calculated PPM correlations coefficient between different signals of the conducted field trials for various time delays are depicted in Figure 6.8, whereas the detailed numerical values are given in Table 6.2. More precisely, the first inset depicts the correlation between the input measurement signal $\{I/U/f\}_{meas}$ and the set EV charging limit $I_{EVlimit}$ for different control delays, the second one depicts the correlation between the set EV charging limit $I_{EVlimit}$ and the measured EV current I_{EV} for different EV response times, and the third inset depicts the correlation between the input measurement signal $\{I/U/f\}_{meas}$ and the measured EV current I_{EV} for different overall delays.

In general, the PPM correlation coefficients between various signals are higher for the congestion management trial since the input measurement sampling rate is 30 seconds. For the other two tested services, the input measurement sampling rate is only 1 second, so the difference in the PPM coefficients for different delay values is significantly more noticeable. Nevertheless, the obtained PPM correlations coefficients are the highest in all trials for a 1-s control delay, 1-s EV response time and 2-s overall delay with a comparable value for the 3-s overall delay. These findings have also been obtained via the cross-correlation method. Table 6.3 gives an overview of minimum,

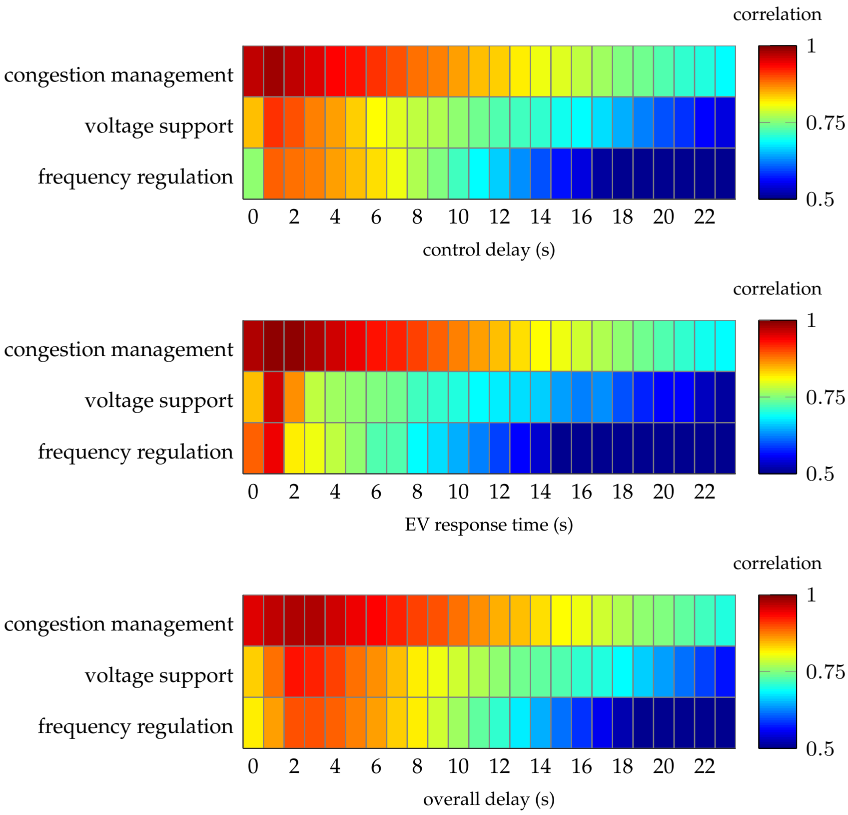

Figure 6.8: Absolute value of Pearson's product-moment correlation coefficients between $\{I/U/f\}_{meas}$ and $I_{EVlimit}$ for various control delays, between $I_{EVlimit}$ and I_{EV} for various EV response times, and between $\{I/U/f\}_{meas}$ and I_{EV} for various overall delays.

Table 6.2: PPM correlation coefficients between the input measurement, the set EV charging limit and the measured EV current for all the tested ancillary services and different Δt delays.

	Signals	$\mathbf{\Delta t = 0s}$	$\mathbf{\Delta t = 1s}$	$\mathbf{\Delta t = 2s}$	$\mathbf{\Delta t = 3s}$
congestion	I_{meas} & $I_{EVlimit}$	-0.9630	***-0.9768***	-0.9635	-0.9497
management	$I_{EVlimit}$ & I_{EV}	0.9758	***0.9913***	0.9904	0.9728
trial	I_{meas} & I_{EV}	-0.9463	-0.9616	***-0.9754***	-0.9713
voltage	U_{meas} & $I_{EVlimit}$	0.8412	***0.9119***	0.8950	0.8737
support	$I_{EVlimit}$ & I_{EV}	0.8374	***0.9557***	0.8605	0.7806
trial	U_{meas} & I_{EV}	0.8315	0.8820	***0.9261***	0.9185
FCN	f_{meas} & $I_{EVlimit}$	0.7514	***0.8879***	0.8823	0.8730
reserve	$I_{EVlimit}$ & I_{EV}	0.8893	***0.9377***	0.8191	0.7975
trial	f_{meas} & I_{EV}	0.8189	0.8574	***0.8944***	0.8909

average and maximum values of the evaluated error indicators in all conducted field experiments. It should be noted that these values may be even lower, but the measurement equipment does not allow better assessment due to the 1-s sampling rate. Regardless, the obtained values are more than satisfactory for all flexibility services unless EVs are providing very fast ones such as virtual inertia.

Another important aspect for EV service provision is the EV accuracy, i.e., the magnitude deviation between the set-point and the measured EV current. As aforementioned, a consistent "undershooting" phenomenon is observed and the deviation arises to more than 1 A, which is

Table 6.3: Summary of the evaluated error indicators for all conducted field trials.

	minimum	**average**	**maximum**
control delay	1 s	1 s	1 s
EV response time	1 s	1 s	3 s
overall delay	2 s	2 s	4 s

far beyond an ideal response. The average deviation values depending on the set EV charging current are given in Table 6.4. A possible explanation of this phenomenon is that the EV battery management system is highly dependent on the ambient temperature. In fact, as it will be reported in section 6.4, this "undershooting" phenomenon has been lower for the conducted experiments in laboratory environment than for the presented field tests performed on a winter day with temperatures below 0°C. Unfortunately, the EV battery management system is subject to manufacturer′s confidentiality, so it is not possible to exactly determine if these EV inaccuracies are of hardware or software origin.

Table 6.4: Average difference between the set charging limit and the measured EV current for the conducted field trials - "undershooting" phenomenon.

$\mathbf{I_{EVlimit}}$	6 A	7 A	8 A	9 A	10 A	11 A	12 A
average deviation	-0.21 A	-0.76 A	-0.81 A	-0.89 A	-0.95 A	-0.99 A	-1.04 A

6.4 Coordination of multiple vehicles

The developed and tested controller can be used with all EVs compliant with IEC 61851 and SAE J1772 meaning that it can be easily scaled up to large EV numbers. This section focuses on the specific application where three EVs are coordinated for the local voltage support service via active power modulation, similar to the thereotical study conducted in [110]. The needed changes in the communication architecture for such an application are described in subsection 6.4.1, the experimental setup is presented in subsection 6.4.2 and the main results are shown in subsection 6.4.3. The reader is referred to Pub. H for more details.

6.4.1 Changes in the communication architecture

Depending on the chosen service, several changes in the communication architecture need to be made for coordinating multiple EVs. Figure 6.9 compares the communication architecture for the developed controller in case of a centralised and a decentralised control strategy. As depicted in the figure, the main difference is in the information flow among different components. Naturally, in case of centralised control, a single control element concentrates all the system information and controls all EVs by sending the calculated EV charging limit to each of them. Depending on the specific control logic, the charging limit can be either identical for all EVs or different for each of them. On the contrary, for a decentralised strategy, each EV has its own control logic which independently reacts on local measurements without any system-wide coordination.

For the experimental testing described in the following subsection, a decentralised approach is adopted where each EV is equipped with its own smart charging controller. Similar to the reactive power control analysed in Chapter 4, an autonomous phase-to-neutral voltage dependent controller

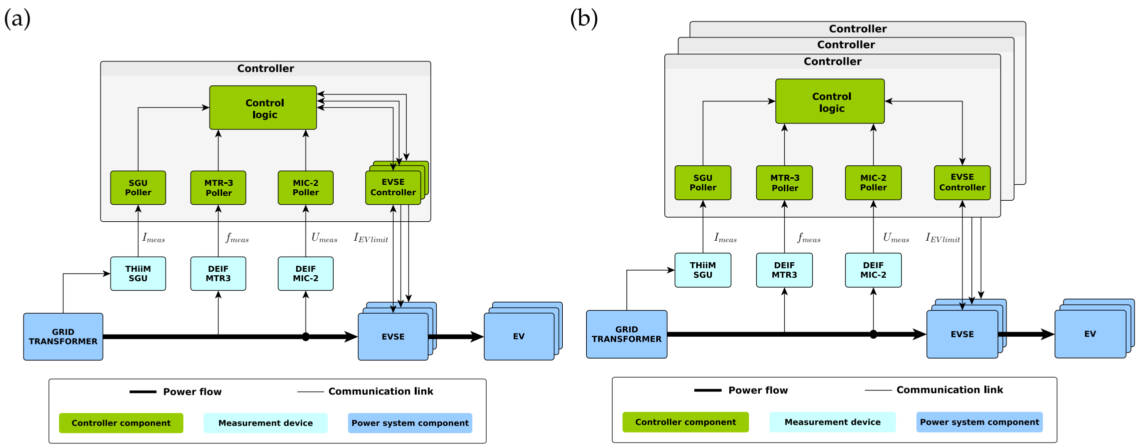

Figure 6.9: Communication architecture diagram for the tested smart charging controller for multiple EVs in case of a (a) centralised and (b) decentralised control strategy.

is used for local voltage regulation. However, here, only the active power is modulated for voltage support, since the reactive power capability is not yet available for commercial EVs. There have been no changes in the control logic itself, so a simple, yet robust droop control described in subsection 6.2.1 is used. However, the EV flexibility range and the voltage thresholds are adjusted as described in the following subsection.

6.4.2 Laboratory experimental setup

The experimental testing has been performed in SYSLAB (part of PowerLabDK at the Risø Campus of Technical University of Denmark). This is a flexible laboratory for distributed energy resources consisting of real power components with a dedicated communication infrastructure and control nodes. As seen in Figure 6.10, the complete test setup represents a typical LV feeder where the EVs are connected at the end of the feeder next to a resistive load, representing the common home charging setup. The reader is referred to Appendix B for more details on SYSLAB, and to Pub. H for a more detailed experimental setup description.

Here, it is sufficient to state the main differences between the laboratory experiment and the previously described field test validation, which are as follows:

- 3 commercially available EVs have been used, i.e., two Nissan Leafs manufactured in 2015 and one Nissan Leaf manufactured in 2011. The maximum EV charging rate I_{EVmax} is set to 16 A as there are no fuse restrictions, resulting in 11 possible current steps in total.
- 45 kW (3x15 kW) controllable resistive load is used to emulate the residential consumption by controlling the loading per phase.
- 2-blade wind turbine is connected with $P_n = 11$ kW to provide stochastic behaviour as well as the active and reactive power variations in the system.
- Three different EV droop characteristics have been tested, out of which two selected ones are presented: 5% droop with $I_{EVmin} = 6$ A as shown in Figure 6.11a and 5% droop with $I_{EVmin} = 0$ A as shown in Figure 6.11b.

Several scenarios have been conducted with the most relevant ones presented in the following subsection. Overview of the selected scenarios is given in Table 6.5.

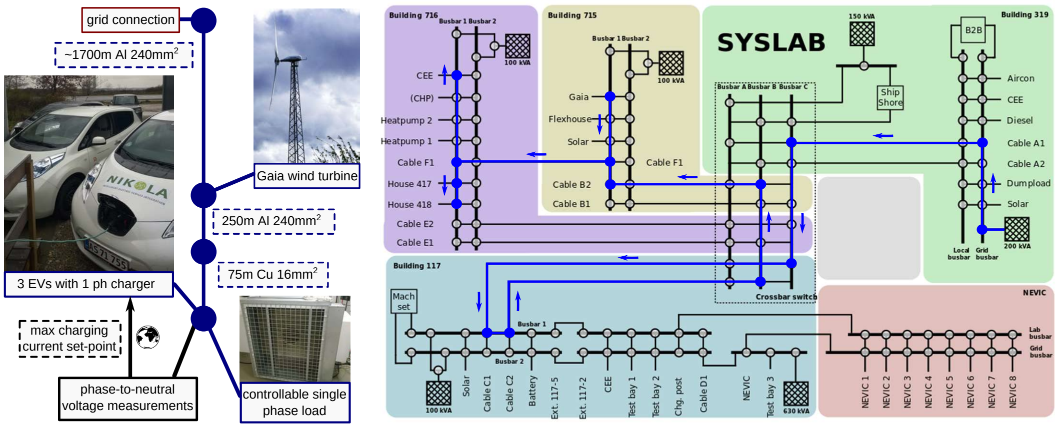

Figure 6.10: Experimental setup and overview of the Syslab PowerLabDK grid topology used for the conducted experiments.

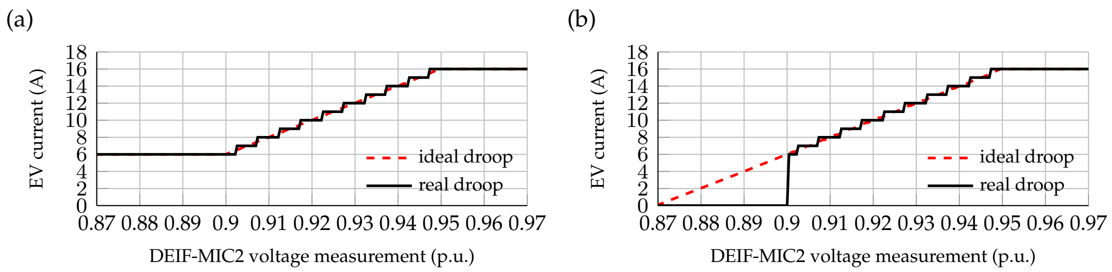

Figure 6.11: Implemented droop characteristics in case of voltage support experimental validation in the laboratory environment: (a) without EV switching off, and (b) with EV switching off.

Table 6.5: Overview of conducted scenarios for experimental validation of EVs providing local voltage support in SYSLAB PowerlabDK.

Scenario	I	II	III
Droop slope k	5%	5%	5%
I_{EVmin}	6 A	6 A	0 A
Load	3 phase	1 phase	3 phase
Maximum load current on phase a [A]	43	0	43
Maximum load current on phase b [A]	43	0	43
Maximum load current on phase c [A]	43	43	43

6.4.3 Results

In this subsection, the selected experimental results are shown and the same technical parameters described in Table 6.1 are evaluated. Figure 6.12 presents the phase-to-neutral voltages U_{meas} at the EV connection point and the respective measured EV current I_{EV} for the three selected scenarios.

In scenario I, the single-phase controllable load has been used to make consumption step increments on all three phases, resulting in all phase-to-neutral voltages similar one to another. Therefore,

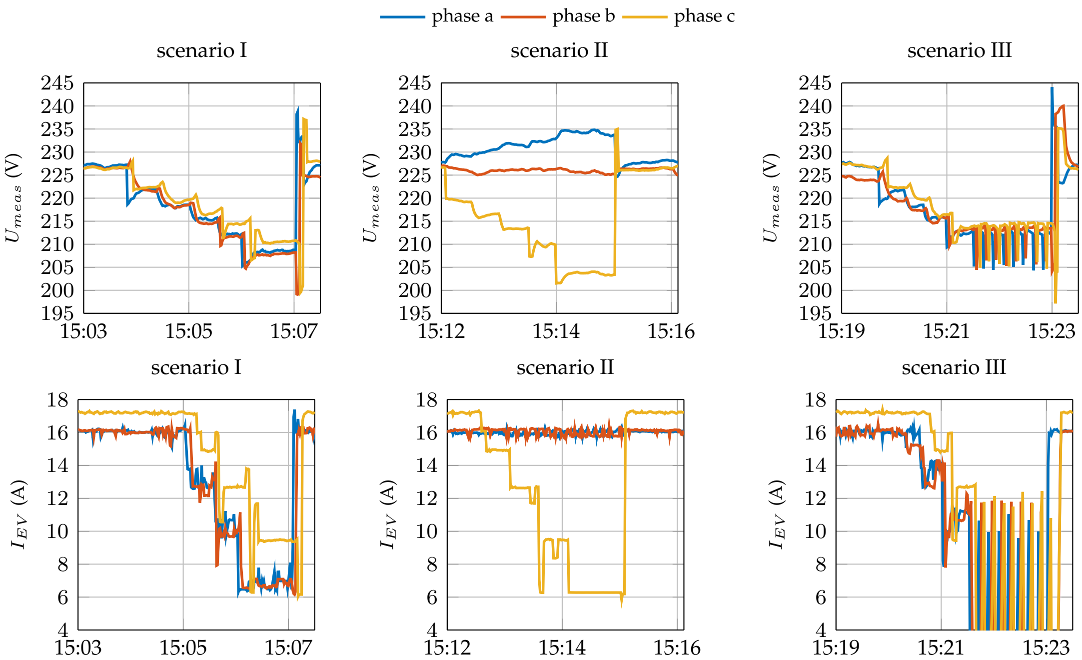

Figure 6.12: Phase-to-neutral voltages and corresponding EV charging currents for the conducted experimental testing of the voltage support service.

one can expect similar behaviour from all EVs as well. However, it can be seen how two EVs, the ones connected to phase a and b, have similar charging behaviour, whereas the behaviour of the EV connected to phase c significantly differs. The reason behind is that, even though all EVs are the same brand and model, the one connected to phase c is an older version, so its internal hardware and software components differ from the other two. As reported later on, it is observed that its response time is somewhat longer and that it often does not comply to the set charging limit $I_{EVlimit}$.

In scenario II, the single-phase controllable load has been used to make consumption step increments only on phase c resulting in different phase-to-neutral voltages between the phases and, therefore, also different EV behaviour on each phase. More precisely, the vehicles connected to phases a and b are charging with the maximum charging current as the voltage is not falling below the set thresholds, whereas the EV connected to phase c modulates the charge according to the defined droop characteristic. What is also interesting to note is that by increasing the consumption on phase c, the phase-to-neutral voltage on phase a is increased due to the floating neutral point.

The most interesting scenario is scenario III where oscillations are obvious both in the measured voltage and in the measured EV current. This scenario is identical to scenario I, except for the droop characteristic which is modified so that EVs switch off if the calculated charging limit is less than the minimum 6 A. With such a control characteristic, the system is observed to become unstable since EVs switch off when measured voltages are low, consequently leading to a voltage increase. This then leads to EVs turning on again and decreasing the voltage, eventually resulting in a persistent repetitive behaviour as long as the voltages stay close to the set 0.9 p.u. threshold. Such instability issues due to the discrete EV characteristic could be resolved by modifying the controller to detect the voltage oscillations with an additional hysteresis characteristic [186]. This has not been experimentally tested and is recognised as a field of interest for future work.

Furthermore, the overall control performance in terms of control delay and EV responsiveness is given for all three tested EVs in Table 6.6. From the presented values, it is evident that the control delay is identical for all EVs as it does not depend on the vehicle itself, but only on the controller equipment which is the same for all three vehicles. On the other hand, the EV response time is highly dependent on the vehicle as it is influenced by the internal EV hardware and software. Referring to the previously described field experiment and the EV responsiveness shown in Table 6.3, it can be seen how the same vehicle, here denoted as EV 1, has an equally fast response in the laboratory environment as well. Moreover, EV 2 which is manufactured the same year as EV 1, has a comparable response with a slightly higher average response time. On the contrary, as already seen in Figure 6.12, EV 3 has a much slower response, i.e., the average time is almost twice as long as the response time of the remaining two vehicles. Nevertheless, even the maximum measured overall delay of 7 seconds is still sufficient enough for providing all the currently required services except the very fast ones such as virtual inertial.

Table 6.6: Summary of evaluated parameters for the presented voltage support scenarios tested in laboratory environment.

	EV 1			EV 2			EV 3		
	min	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
control delay	1 s	1 s	1 s	1 s	1 s	1 s	1 s	1 s	1 s
EV response time	1 s	1 s	3 s	1 s	2 s	3 s	2 s	4 s	6 s
overall delay	2 s	2 s	4 s	2 s	3 s	4 s	3 s	5 s	7 s

Contrary to the EV responsiveness which has been similar in both the field trial and the conducted laboratory experiment, the EV accuracy in laboratory experiments greatly differs from the values obtained in the field trials. As seen in Table 6.7, different local phase-to-neutral voltage conditions lead to different EV charging limits and the corresponding EV accuracy differs for each vehicle. Secondly, whereas EV 1 was "undershooting" up to 1 A in the field trial, the difference has been much smaller for the conducted laboratory experiment and has never amounted to more than 0.52 A. Similar behaviour has also been observed for EV 2. Finally, here none of the EVs charged below the set 6 A limit as has been the case in the field trial. On the contrary, all EVs charged at an approximately 0.5 A higher current that the minimum 6 A required by IEC 61851 in order not to damage the internal equipment. However, violations are seen for other set charging limits when the "overshooting" phenomenon appears. This is especially noticeable for EV 3 which constantly charges above the set limit amounting to more than 1 A for the maximum charging limit. Again, similarly to the field experiment, it can be concluded that EV accuracy may arise as an issue when providing ancillary services, especially since the mismatch may trigger other units to provide unnecessary services, leading to an overall less efficient power system.

Table 6.7: Average difference between the set charging limit and the measured EV current for the conducted voltage support experiment in scenario I.

$\mathbf{I_{EVlimit}}$	6 A	7 A	8 A	9 A	10 A	11 A	12 A	13 A	14 A	15 A	16 A
average deviation EV 1	0.44 A	-0.22 A	-0.52 A	-	-0.11 A	-0.27 A	-	-0.22 A	-0.29 A	-	-0.01 A
average deviation EV 2	0.48 A	-0.16 A	-0.07 A	-	-0.11 A	-	0.18 A	-0.15 A	-	-	0.05 A
average deviation EV 3	0.64 A	-	-	0.36	0.01 A	0.17 A	0. 68 A	0.26 A	1.05 A	0.74 A	1.19 A

6.5 Summary

This chapter investigated the technical capability of current series-produced EVs to provide various ancillary services through several laboratory and field validations. A smart charging controller based on a droop control scheme has been developed, which is applicable to any EV compliant to IEC 61851 or SAE J1772. The experimental validation focused on assessing several charging parameters such as EV responsiveness and EV accuracy.

It has been observed that current series-produced EVs are capable of providing flexibility services, both system-wide and for the local distribution grid. The overall EV response, including all control and measurement delays, has been 3-4 seconds on average and had never amounted to more than 7 seconds. Most of the noted delay comes from the EV itself, more precisely from the internally implemented hardware and software which cannot be externally changed as it is subject to manufacturer's confidentiality. Nevertheless, the observed EV responsiveness is more than sufficient for providing almost all required power system ancillary services, as summarized in Table 6.8. On the other hand, whereas EV responsiveness has not been observed as an issue, EV accuracy might arise as a topic of concern. More precisely, the mismatch between the set charging limit and the measured EV current has greatly differed depending on the tested EV and the external conditions, amounting to more than 1 A for some experimental trials.

Table 6.8: Ability of current series-produced EVs to provide ancillary services with respect to EV responsiveness.

	Inertia response	**FCN reserve**	**FCD reserve**	**Voltage regulation**	**Congestion management**
EV ability for service provision	-	+	+	+	+

EVs can be a valuable resource for the power system, but there is still much room for improvement. First of all, the EV charging system should not be designed only to guarantee the charging current below the set limit, but also to be as close as possible to the set limit. Additional standards are required for obliging the manufacturers to optimise the EV response in terms of accuracy. Furthermore, the overall EV responsiveness could be additionally shortened by optimising the internal EV hardware and software which is necessary if EVs are to provide very fast ancillary services such as virtual inertia. Finally, the granularity of 1 A for the EV charging limit defined by the contemporary standards may not be fine enough if utilising EVs for flexibility services, since it amounts to approximately 10% of the EV's flexibility range. It is worth noting that the experimental validation has been done on a single EV model, so thorough experimental investigation is needed for other EV brands and models as well.

CHAPTER 7

Conclusion and future work

This dissertation focused on the question of how EVs can mitigate the self-induced adverse grid effect and actively help with the system operation. Around this major thread, in section 1.2, five research questions have been outlined for the PhD project. In the following, the results are concluded:

[Q1] *What is the impact of uncontrolled EV charging and the potential of EV interacting with the power system?*

First of all, the general aspects of EV mobility, contemporary charging standards and uncontrolled charging were discussed in Chapter 2 to frame the issues arising within the power system context. It was recognised that EVs introduce considerable issues at the distribution level before substantial impact on the system level is seen. Based on the literature review as well as the conducted simulations, it was concluded that the simultaneity between the uncontrolled EV charging and the peak residential consumption results in high peak demand, severe voltage magnitude deviations and increased losses.

On the other hand, it was recognised that EVs hold great flexibility potential as they are usually connected for long periods, i.e., they could sustain a variation in power for a given duration. Therefore, opportunities of controlled EV charging were discussed with the potential value of EV flexibility provision to various power system stakeholders. It was recognised that the technical complexity of EV coordination should be handled by an external expert and not the individual EV owners, so a new entity was introduced, namely the EV aggregator. This entity could aggregate the individual EV flexibility and offer various services to the EV owner, the TSO or the DSOs. Considering the aforementioned self-induced detrimental effects, EV flexibility provision for distribution grid services is recognised to be vital for successful EV integration if additional grid reinforcement is to be avoided. Therefore, the prominent services EVs can provide to the DSO were presented and discussed in Chapter 3.

Essentially, distribution grid services were categorised based on the targeted constraint: services for solving voltage issues, including voltage magnitude regulation and voltage unbalance reduction; and services for solving loading issues, including congestion prevention and loss reduction. It was recognised that, regardless if EVs provide flexibility in an autonomous or a coordinated fashion, each distribution grid service enhances the efficient system operation, therefore making it a valuable resource for the DSO. In general, the potential for EVs providing services beyond transportation makes them an attractive asset for DSOs who should not consider them merely as passive electric loads, but as distributed flexibility resources.

[Q2] *Focusing on the distribution level, what are the prerequisites for supporting active EV involvement?*

There are several challenges regarding active EV involvement in the distribution grid with respect to the technical, the organisational and the regulatory aspect. In Chapter 3, it was noted that the technical prerequisites mainly remain on deploying the needed infrastructure with standardised communication and control capabilities, whereas the organisational and the regulatory support for procuring EV distribution grid services present a bigger limitation. There is a clear lack of existing means for DSOs to procure EV flexibility due to historical reasons and the way they are financed. However, with the growing number of EVs and other distributed resources, there is also a growing need for establishing the required mechanisms which would allow active EV participation and appropriate remuneration. Hence, a set of recommendations was given for overcoming the recognised barriers, out of which the most important ones are as follows:

- Regulations should support wide-scale deployment of smart meters with a standardised sampling rate and clear pre-qualification protocols.
- Standardised communication protocols must be determined for the communication among the EV aggregator and other power system stakeholders.
- Regulation is needed for deploying standardised EV supply equipment with sufficient communication and control capabilities.
- Regulations which forbid aggregation and flexibility procurement should be removed.
- DSO regulations should incentivise long-term innovation and active grid management. Moreover, current DSO services should be remunerated to provide basis for comparing different solutions and estimating the flexibility price.
- Local flexibility platforms with clear and generic flexibility products should be established for EV flexibility trading. Furthermore, technical attributes must be clearly defined when determining flexibility products, including, but not limited to, power capacity, duration, direction, location, maximum activation time, accuracy, precision, and ramp-up/ramp-down time. As an intermediate step towards developing flexibility platforms, bilateral agreements should be established between the DSO and the EV aggregator, in which the DSO could directly invoke flexibility for a fixed price.
- If EV flexibility trading is established, the minimum bid should be in the kilowatt range and the settlement period should be maximum 5 minutes to encourage EV users' participation. It is necessary to include capacity and energy payments, as well as a premium for rewarding the more reliable resources.
- Clear priorities and interfaces should be defined between the TSO and the DSO, both for normal operation and for emergency situations.

[Q3] *What is the potential of introducing EV reactive power control for distribution grid support?*

As contemporary EV chargers can be extended to exchange reactive power control with the grid, the potential benefits and drawbacks of such a new EV capability were investigated in Chapter 4. A decentralised reactive power strategy was proposed for single-phase connected EVs to partially mitigate the self-inflicted voltage issues. Such autonomous controllers rely only on the local phase-to-neutral voltage measurement without requiring any additional communication between the individual EV and the grid operator, and can therefore be implemented in the short-term future by using the inherent functionality of the EV power electronics. The proposed support is fair and does not penalise the EVs connected towards the end of the feeder, in addition to not being dependent on the plug-in time or estimated EV schedules. Hence, voltage support can be provided in real-time whenever EVs are charging while the users' privacy is not jeopardised.

For a representative study case based on a real Danish low-voltage network with the corresponding measurement data, the proposed reactive power support was investigated for various grid conditions, and the impact on voltage deviations, grid losses and grid unbalances was analysed. The results showed that EV reactive power capability has a beneficial impact on voltage deviations and voltage unbalances, without substantially influencing the losses. Given that the EV converter is properly sized, such control can provide grid support without influencing the battery state of charge and, consequently, user comfort. Moreover, the reactive power support increases with the increasing EV penetration rate, therefore making it an effective mean for increasing the hosting capacity in case of uncontrolled charging. It was also shown that it could be used for concurrent distribution grid support if EV active power is modulated to provide other flexibility services. Since the proposed control is autonomous, the operational transparency over the controller is limited, making it more applicable for mandatory voltage support as it could be difficult to trade such a service. However, the cost related to the increased power rating discourages the manufactures to implement such a capability for commercial EVs. Thus, it was concluded that EV reactive power control will not become available unless it is made part of the grid compliance requirements, similar to the recent grid codes for PVs in several European countries.

[Q4] *How can the EV aggregator's economic concerns be combined with the distribution system concerns?*

In Chapter 5, the importance of combining both the DSO's and the EV aggregator's economic concerns with relation to the EV day-ahead scheduling was discussed. If EV owners are willing to participate in active power flexibility schemes, it is highly likely that they are motivated by minimising the charging cost which then becomes the EV aggregator's main concern. However, it was shown that such optimal EV schedule considerably differs from the one desired by the local DSO. Hence, a bi-objective optimisation model was proposed to combine the economic concerns of both entities, namely minimising the loss cost with minimising the EV charging cost. The problem of optimal EV scheduling was formulated as a full non-linear AC optimal power flow for unbalanced grid conditions, and implemented as a single non-linear program which can be solved by commercial non-linear solvers such as CONOPT or IPOPT. An ϵ-constraint method was used for obtaining the Pareto frontier with a range of possible solutions, whereas the fuzzy set approach was applied to weight each solution compared to the alternatives.

The proposed model was tested on a real Danish low-voltage network in case when EVs were the only flexible resource as well as when combined with other demand response. It was shown that the obtained Pareto front provides a range of solutions with evidence that there is a relatively small, but non-negligible trade-off between the two objective functions. The fuzzy set approach determined a good compromise between the considered objectives in all scenarios, since the final schedule was chosen as the one where both entities were dissatisfied the least. Secondly, the importance of including unbalanced grid conditions was noted, since individual EV schedules were influenced by local conditions and greatly differed based on the connection point. If only balanced grid conditions were taken into account, the interaction between the phases would be neglected and the obtained schedules would be sub-optimal. Finally, it was observed that the DSO can benefit from the EV reactive power support without significantly affecting the EV aggregator's cost. This provides additional indications for including the EV reactive power capability in the grid codes.

[Q5] *What are the issues arising with practical implementation of EVs providing flexibility services according to contemporary standards and requirements?*

In Chapter 6, the capability of current series-produced EVs to provide several flexibility services was investigated through laboratory and field validation. A smart charging controller, which can be applied to any EV compliant with IEC 61851/SAE J1772 standards, was presented. The implemented control logic was based on an ideal droop characteristic which was then modified into discrete steps due to practical charging limitations defined by the standards. The controller was tested through a field trial in a real distribution grid with no controllability over other residential units and a limited amount of measurement equipment. Three services were tested, namely congestion management, local voltage support and frequency-controlled normal operation reserve. Furthermore, the coordination of several EVs for a specific application of improving the power quality was tested in laboratory environment. As the future power system entities will treat EVs as "black boxes", the experimental validation focused on assessing several parameters such as EV responsiveness and EV accuracy.

With respect to the EV responsiveness, it was shown that current series-produced EVs respond within 2-3 seconds on average, including all the measurement and control delays. Such fast response is more than sufficient for providing all required power system services, except of the very fast ones such as virtual inertia. On the other hand, whereas the EV responsiveness had not been observed as an issue, the EV accuracy arose as a topic of concern. More precisely, the mismatch between the set EV charging limit and the measured EV current greatly differed depending on the tested EV and the external conditions. Based on the obtained results, several recommendations were identified with respect to the contemporary charging standards and EV technology. First of all, the need for additional standards was recognised in order to oblige EV manufacturers to optimise the internal charging system, i.e., that the charging current is not only below the set limit, but also as close as possible to it. Secondly, the responsiveness could be additionally shortened by optimising the internal EV components which is necessary if EVs are to provide very fast services. Finally, the defined charging granularity of 1 A may not be fine enough and reducing it would provide a wider range of possibilities for the DSO's flexibility requests as well as for the EV aggregator's flexibility offers.

In summary, the main contributions of this thesis to the state of the art are the following. First, an evaluation of the technical, the organisational and the regulatory barriers for supporting active EV involvement in the distribution grid was provided with the respective implications for reform. Then, the potential technical benefits of introducing voltage-dependent EV reactive power capability were investigated, both when active power is allowed and when it is not desirable. Furthermore, a multi-objective framework was developed to assess the trade-off between the DSO's and the EV aggregator's economic concerns, with a best-compromise approach for scheduling the EV active and reactive power profiles. Finally, a set of laboratory and field trials was conducted to evaluate the feasibility of contemporary series-produced EVs to provide various flexibility services, with the emphasis on determining the EV response time and accuracy. Overall, the findings of this thesis show that controlled EV charging solutions would be beneficial for all stakeholders involved in the EV value chain and especially for distribution grid operators. However, regulations, market designs and technical standards must evolve in order to capture the full potential of these resources.

7.1 Future work

The results obtained in this project have also uncovered possible topics for further research. These topics are as following:

- The quantification of economic benefits related to EVs providing distribution grid services for postponing the grid reinforcement has not been addressed. Such analysis could bring to light for which EV penetration rate there is no value in flexibility as the grid reinforcement is inevitable.
- Validation of flexibility procurement by numerous geographically distributed EVs remains an open research topic. Since the traditional validation protocols cannot be easily applied to aggregated resources, it is necessary to establish tests which the EV aggregator could use for performance evaluation and service verification.
- With respect to the EV reactive power capability, it was observed that synchronisation issues may arise for decentralised control strategies due to the nature of unbalanced systems and the mutual influences among the phases. Hence, different settings should be compared to derive an optimal droop control dependent on the grid X/R ratio and the EV connection distance from the transformer substation. Moreover, in this thesis, only radial feeder was considered and studied, so an extended case would be analysing potential EV reactive power capability in meshed distribution grids.
- The multi-objective model could be extended to include the impact of price uncertainty in order to guarantee that the cost of the obtained EV schedule is below a predefined limit. Moreover, the model could be extended for distribution grid planning purposes to plan the optimal allocation of EV charging connections, which is of special interest when determining the phase to which the EV should be connected.
- One must note how all conducted experimental validations were done on a single EV model and other series-produced EVs might not have the same response delays and inaccuracies. Therefore, a thorough experimental investigation is needed for other EV models in order to test their ability to comply with the service requirements. The collected data could then be used for system-identification in order to establish dynamic models of various EV models. This topic could be of particular value for theoretical studies on fast frequency control from aggregated units.

APPENDIX **A**

Unbalance indicators

Contrary to other disturbances in the power system for which the performance is evident for the ordinary customers, unbalance belongs to those disturbances whose perceptible effects are produced in the long run. Voltage and current unbalances due to unsymmetrical consumption and production lead to greater power losses, interference with the protection systems and components' performance degradation. For calculating the unbalanced voltages and currents in three-phase systems, symmetrical components are generally employed. Then, the voltage can be decomposed into a direct sequence component U_+, an inverse sequence component U_- and a zero sequence component U_0 with the relationship between the initial system and the symmetrical components as follows:

$$\begin{bmatrix} U_+ \\ U_- \\ U_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{A.1}$$

where $\alpha = e^{j2\pi/3}$.

The inverse sequence voltage unbalance factor VUF_- is then defined as the ratio between the inverse and the direct component as follows:

$$VUF_-[\%] = \frac{|U_-|}{|U_+|} \times 100. \tag{A.2}$$

Most of the voltage unbalance definitions, including equation (A.2), assume that the zero sequence current is negligible since it cannot flow through a three-phase three-wire system. However, the zero sequence component can have a significant impact in the three-phase four-wire systems. As such systems are common in the LV distribution grids, the impact should be taken into consideration when assessing the unbalances. Hence, similarly to VUF_-, the zero sequence voltage unbalance factor VUF_0 is defined as:

$$VUF_0[\%] = \frac{|U_0|}{|U_+|} \times 100. \tag{A.3}$$

In order to combine the impact of both the inverse and the zero sequence component, i.e., to combine equations (A.2) and (A.3), [187] proposed a new root mean square VUF_{rms} defined as:

$$VUF_{rms}[\%] = \frac{\sqrt{|U_0|^2 + |U_-|^2}}{|U_+|} \times 100, \tag{A.4}$$

which was found as the best fitted variable for assessing unbalance consequences, and can be applicable both for three-wire and four-wire systems.

The same definitions can be applied for defining the current direct, inverse and zero component, and analogously the current unbalance factors CUF_- and CUF_0.

Appendix B

Danish distribution grids

B.1 Borup LV distribution grid

A real Danish LV distribution feeder is provided by SEAS-NVE for the research activities in the NIKOLA project. The analysed network is a semi-urban LV grid located in southern Zealand, Denmark. There are 4 distribution feeders in total with approximately the same amount of houses under each of them. This piece of network is radially run and connected to the 10 kV MV network through a typical 400 kVA distribution transformer. The voltage level is 400 V.

Due to the lack of individual data for all 4 feeders, only one is modelled in detail as depicted in Figure B.1, whereas the remaining three are modelled as a lump load directly connected to the LV side of the transformer. All LV network is supplied by underground cables composed of 13 segments whose specifications are given in Table B.1.

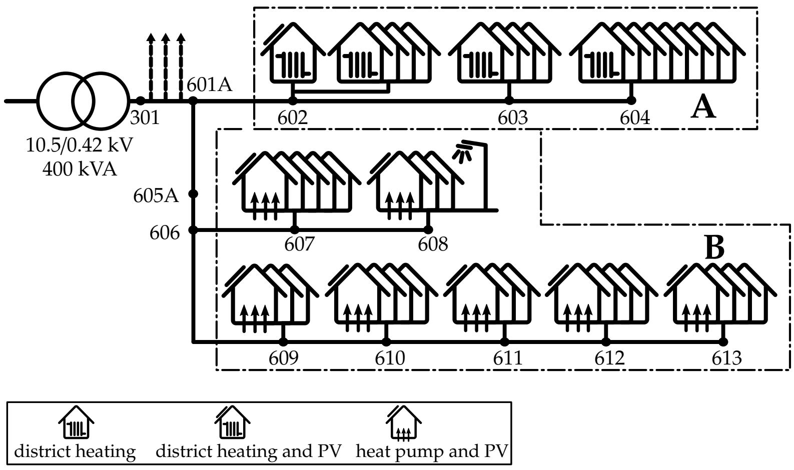

Figure B.1: The topology of a real LV Danish distribution grid. Data source: SEAS-NVE.

There are 43 houses in total under the observed area which are three-phase connected with a common neutral conductor grounded only at the transformer station. The feeder can be divided into two zones due to the house location and specific characteristics:

(1) zone A where houses have implemented district heating and no PVs, and

(2) zone B where each house is equipped with a heat pump and a PV installation.

Table B.1: The cable parameters of the LV feeder model.

From	To	Type	Length(m)	R(Ω/km)	X(Ω/km)	I_{max} (A)
transformer	601A	$4 \times 150\ mm^2$ Al PEX	112	0.207	0.078	335
601A	602	$4 \times 150\ mm^2$ Al PEX	49	0.207	0.078	335
602	603	$4 \times 150\ mm^2$ Al PEX	64	0.207	0.078	335
603	604	$4 \times 150\ mm^2$ Al PEX	87	0.207	0.078	335
601A	605A	$4 \times 150\ mm^2$ Al PEX	80	0.207	0.078	335
605A	606	$4 \times 150\ mm^2$ Al PEX	25	0.207	0.078	335
606	609	$4 \times 150\ mm^2$ Al PEX	40	0.207	0.078	335
609	610	$4 \times 150\ mm^2$ Al PEX	35	0.207	0.078	335
610	611	$4 \times 150\ mm^2$ Al PEX	36	0.207	0.078	335
611	612	$4 \times 150\ mm^2$ Al PEX	35	0.207	0.078	335
612	613	$4 \times 150\ mm^2$ Al PEX	35	0.207	0.078	335
606	607	$4 \times 150\ mm^2$ Al PEX	46	0.207	0.078	335
607	608	$4 \times 150\ mm^2$ Al PEX	37	0.207	0.078	335

The individual consumption and production profiles are based on real hourly measurement data available for the period March 2013 to February 2013. Figure B.2 shows the total demand as well as the PV production of zone B for 12 characteristic days representing respective months. Due to implemented district heating, area A has low consumption which is similar throughout the year, and resembles the area B consumption in the non-heating period.

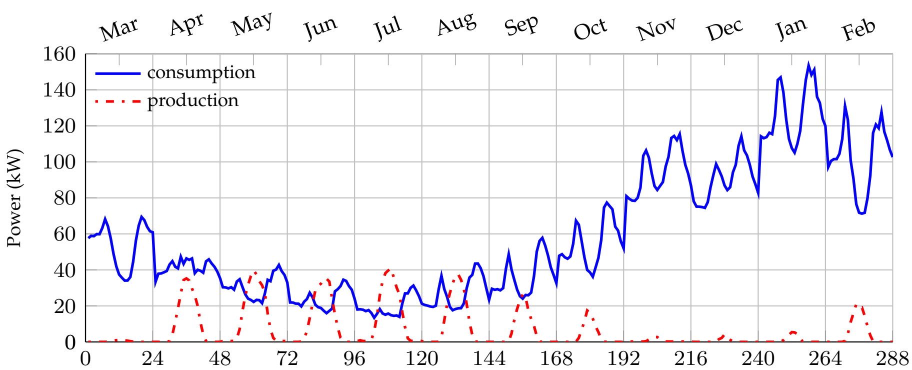

Figure B.2: Total consumption and production profiles in zone B for 12 characteristic days representing respective months from March 2012 to February 2013.

B.2 SYSLAB PowerLabDK grid

SYSLAB [188] is a flexible intelligent laboratory for distributed energy resources located at DTU Risø Campus. It is a part of the PowerLabDK platform belonging to the Center for Elecric Power and Energy, DTU Electrical Engineering.

SYSLAB facilities include number od decentralised production and consumption components paralleled with communication infrastructure and control nodes in a dedicated network. As shown in Figure B.3, the grid topology is designed to be highly configurable, and it can be operated in grid connected or islanded mode. SYSLAB components are shown in Figure B.4, whereas the cable parameters are given in Table B.2.

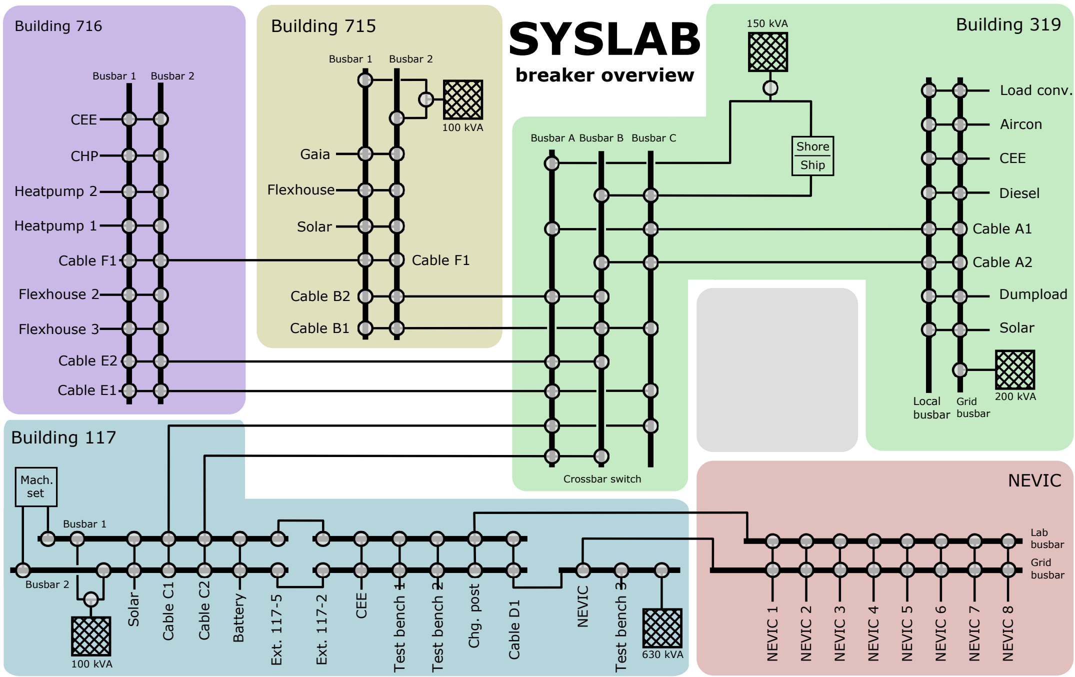

Figure B.3: Electrical layout of SYSLAB PowerLabDK.

Figure B.4: SYSLAB PowerLabDK components.

Table B.2: SYSLAB PowerLabDK cable parameters.

Name	From	To	Length(m)	$R_1(\Omega)$	$X_1(\Omega)$	$B_1(\mu S)$	$X_1(\mu F)$
A1	Vindmøllehal (B-319)	Crossbar A/C	0.025	0.008025	0.00195	2.7489	0.00875
A2	Vindmøllehal (B-319)	Crossbar B/C	0.025	0.008025	0.00195	2.7489	0.00875
B1	Flexhouse (B-716)	Crossbar A/B	0.25	0.11235	0.0273	38.4845	0.1225
B2	Flexhouse (B-716)	Crossbar B/C	0.25	0.11235	0.0273	38.4845	0.1225
C1	DR1 (B-117)	Crossbar A/C	0.7	0.089	0.0539	74.7699	0.238
C2	DR1 (B-117)	Crossbar A/B	0.7	0.089	0.0539	74.7699	0.238

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Pub. A. Distribution grid services and flexibility provision by electric vehicles: A review of options

Distribution Grid Services and Flexibility Provision by Electric Vehicles: a Review of Options

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***Abstract*—Due to the increasing penetration of distributed generation and new high-power consumption loads – such as electric vehicles (EVs) – distribution system operators (DSO) are facing new grid security challenges. DSOs have historically dealt with such issues by making investments in grid reinforcement. However, an alternative solution, enabled by the expected roll-out of smart meters and high penetration of flexible loads, would be the increased use of flexibility services. Flexible loads, with EVs at their forefront, can modulate their consumption or even inject power back to the grid depending on current grid conditions. In return, flexibility provision should be remunerated accordingly. In this paper, the authors are interested in making an accurate description of the flexibility services at the distribution level which could be provided by EVs as well as their requirements, e.g. location, activation time and duration. Market design recommendations for enhancing the provision of DSO grid services by EVs are derived from the conducted analysis.**

***Index Terms*—Distribution network, electric vehicles, flexibility services, market design, regulation.**

I. Introduction

HISTORICALLY, electric grids used to be vertically integrated with large power plants producing electricity for end-users, and single-direction electricity flowing from production units through the transmission and distribution grids to the consumers. In this context, Distribution System Operators (DSOs) have traditionally dealt with grid security issues by using planning and network development methods [1]. However, the security of DSO grid operations is nowadays threatened by the penetration of distributed generation (DG) units and electric vehicles (EVs), which impose new constraints such as bi-directional flows, high power during peak periods and unpredictability [2]. If not managed properly, these constraints could result in over-investments and additional energy losses [3].

Apart from traditional grid reinforcement strategies, using flexible resources could be a mean to deal with these arising issues [4]. In particular, EVs could be valuable flexibility service providers [5]–[7] since their charging rate is controllable within a very short response time, they can potentially inject power back to the grid via Vehicle-to-Grid (V2G) technology, and they are typically plugged in most of the day [8].

However, clear stakeholder roles, responsibilities and market design rules for allowing these flexibility resources to be managed efficiently still need to be defined. The issue of defining suitable and proper market rules for demand response participation has been highlighted for TSO services [9]–[11], but much less tackled for DSO services. In this paper, the authors aim at deducing the technical requirements as well as the organizational framework for the provision of DSO flexibility services by EVs through the literature survey of papers and reports focusing on the flexibility at the distribution level. Market design recommendations are derived from the findings of this survey. The authors focus specifically on EVs as distributed flexibility sources since they have promising characteristics compared to other sources: high power, good availability and predictability, and easy controllability. However, the approach and the results could be extended to other types of flexibility resources such as electric heating systems, water heaters and similar.

The paper is organized as follows. In Section II, the way DSOs have been operating their networks for the past decades is recalled. Then, Section III provides the literature review of previous work dealing with the provision of flexibility services by EVs, from which we deduce market design recommendations presented in Section IV. Finally, Section V presents the conclusion.

II. Historical Grid Operation by DSOs

The distribution sector is characterized by high diversity of DSOs, both in the number which varies from country to country, as well as in the magnitude of corresponding control areas. Some DSOs operate large sets of distribution networks over large regions while others operate a limited amount of MV feeders. Table I summarizes the number of DSOs for several European countries – including Denmark, Italy and France – in order to provide a brief overview of the current system complexity. No matter where, all DSOs have historically operated grids with radial topologies, from HV/MV substations to the end-users. Electricity flow was unidirectional only, and consumption loads were largely inflexible. In this context, DSO activities were mainly focused on long term grid planning and design rather than on real-time

TABLE I
ACTIVE DSOS IN SELECTED EUROPEAN COUNTRIES, ADAPTED FROM [12], [13]

Country	Total DSOs	DSOs with under 100000 customers	Dominant DSO (> 80% of distributed power)
Denmark	76	68	n/a
France	148	143	ERDF
Germany	883	780	n/a
Italy	151	124	ENEL Distribuzione
Ireland	1	0	ESB Networks

operation.

As a matter of fact, utilities address two main concerns, i.e. voltage and congestion issues, by investing in grid reinforcement in a rather passive way. Congestion is dealt with by upgrading the cables/transformers to equivalent components with higher rated power (70% capacity limit is used as a "rule-of-thumb" since remaining 30% is saved for supplying neighbouring feeders in case of fault [14]). Voltage regulation is mainly performed with the addition of capacitor banks, or by means of transformers with automatically adjusting taps [15] since according to European standard EN50160, the 10 minutes voltage deviation should not exceed $\pm 10\% U_n$ on a weekly basis [16]. In addition, some countries have already proposed stricter voltage requirements, e.g. Germany is considering lowering the band to $\pm 4\% U_n$ [17].

Moreover, DSOs remuneration scheme is most of the time based on a cost of service method, meaning that the remuneration is based on an estimation of their costs, tightly linked to their investment plans [1]. Thus, DSOs have a strong incentive in promoting their investments to solve their management issues. Considering the current funding methods, and even though quality of service indicators are sometimes included in the remuneration calculation, it is more attractive for the DSOs to conduct grid reinforcement work than to implement active demand management strategies. We will call this historical DSO methodology as "investment programs to fit and forget". In this approach, the value of flexibility is non-existent.

On the other hand, with the liberalization of the electricity industry and the recent technological improvements, all stakeholders' roles are evolving and more active management could be introduced in the electricity industry, which is particularly true for DSOs. This new methodology of investments, management and remuneration of decentralized flexibility resources will be called "proactive DSO".

Indeed, where the production, the transportation and the distribution used to be bundled, most of the European countries have now more or less unbundled those activities depending on the national institutional and industrial contexts [1]. Moreover, the traditional system operation is challenged by the introduction of new units, such as distributed renewable resources and EVs. The latter represent a high load compared to the household consumption and should not be considered only as passive assets. Proper coordination and activation can provide more flexibility, which can enhance both efficiency and the reliability of the distribution system. The roll-out of smart meters may provide DSOs with the ability to forecast, monitor and control distributed unit behaviors more accurately than they used to, thus allowing them to change their activities from ex-post corrective activities to performing proactive grid management, if the remuneration scheme and the building of appropriate competencies are performed.

However, this change would require regulation evolutions as highlighted by the THINK project [18]. We want to stress the fact that the development of ICT and smart grid is not fostered by the current remuneration schemes. In order to promote them, flexibility contracting and procurement either on bilateral basis or through a clearing house are required.

In the rest of the paper, the authors aim at characterizing the required future DSO market design for flexibility procurement.

III. FLEXIBILITY PROVISION BY ELECTRIC VEHICLES

A. General considerations about flexibility services

In this section, the authors are concerned with showing how EVs could be efficient flexibility providers for both voltage control and congestion issues, which are the two main problems arising with the penetration of new units, and under which conditions. In the following subsections, literature review focusing on projects and research papers demonstrating the value of EV flexibility for voltage and congestion control is conducted. Voltage regulation is of paramount importance. Among others, under- and over-voltages can cause [15]:

- equipment dysfunctions or failure due to operation out of the rated ranges;
- tripping of sensitive loads;
- overloading of induction motors;
- higher no-load losses in transformers.

Therefore, the cost of voltage regulation to society amounts to significant values. Voltage could be controlled through the modulation of active and reactive power of end-user flexible loads to comply with the standard.

Transformers, underground and overhead lines are manufactured to operate at a given rated power or current (ampacity). Overloading will inevitably result in overheating temperatures, and thus in shortened life expectancies for the mentioned components. Reducing the transformer and cable lifetime can significantly increase the grid operating costs. Table II provides orders of magnitude for cost estimations of the main distribution grid components: underground cables, overhead lines and transformer substations. HV, MV and LV respectively stand for High Voltage Medium Voltage and Low Voltage, while PM and GM stand respectively for Pole Mounted and Ground Mounted.

Active power consumed by flexible loads could be modulated as an effective way to mitigate congestion and overloading. For instance, reference [4] finds out that a flexibility product of 100 – 200 kW that would be called for

TABLE II
ASSETS COST, ADAPTED FROM [2], [3]

Component	Estimated cost
MV lines/cables	100-200 k€/km
LV cables	70-100 k€/km
LV lines	30-65 k€/km
GM MV/LV transformer	14-35 k€
PM MV/LV transformer	5 k€
HV/MV transformer	1700-5200 k€

a duration of 1 – 4 hours once a year would be worth 7500 €/year.

Further subsections present literature review on flexibility provision by EVs, i.e. congestion management in III-B and voltage regulation in III-C.

B. Local congestion issues

In [19], the authors are concerned with the supervision of the overloading occurrences of an eco-district transformer. First, an optimal sizing of the substation transformer is proposed, considering only commercial and residential consumptions. Then, EVs and PV panels are introduced in the district, triggering major transformer overloading periods. Finally, with the implementation of an Energy Management System using EVs as flexible resources, the authors show significant improvements in transformer operating conditions: the average overloading power is reduced by 71% and the yearly electricity costs by 17%. This work considers a centralized approach with an aggregator which is responsible for dispatching the required power flow among the EVs with V2G capability, depending on the transformer conditions, at 10 minutes basis. It is assumed that EV users provide the aggregator with their future needs for transportation. The location of the EVs in the district (i.e. to which node there are plugged-in) is of little importance.

Reference [20] proposes an algorithm for global system operation where EVs modify their charging pattern to alleviate network congestions. The algorithm was tested on a microgrid with three different EV patterns. In every case, a small contribution from EVs mitigates the congestion problems. However, if the congestion problem is too high, the change in reactive power is needed since modulating the active power is not enough to reduce the apparent power.

Congestion management based on direct control and price-based coordination is discussed in [7]. A market framework, which can minimize the charging cost while respecting the hard constraints imposed by the EV owners and DSOs, is proposed. The algorithm is tested on a 10 kV radial grid with 1400 households on 15 minutes values showing that EVs reschedule the charging to the lower-price period in order to avoid congestions. However, additional coordination is needed since all EVs react to the same shadow price signal and can therefore cause new congestion. This is easily solved by limiting the number of EVs which respond to the price signal. Since this framework is based on linear programming methodology for modelling the EV charging process, it is flexible and scalable for diverse control schemes.

C. Voltage control issues

In reference [21], the authors suggest a decentralized approach to provide voltage regulation with electric vehicles, both using active and reactive power control with unidirectional power flows. A central aggregator gathers all the voltage values for all the network nodes, and communicates these data to all EVs which then adjust their charging rates accordingly. The EV decision can be either global (taking into account all the network nodes) or local (considering only the neighbour nodes). The simulation time step is 30 minutes, and each EV is located at a precise network node. The method employed provides fair results; however, a comparison with a simple droop-controller method is conducted and the results from the proposed strategy barely outweigh those achieved with the droop-controller.

Reference [22] also tackles the issue of voltage control, but with 11kWh Plug-in Hybrid Vehicles (PHEVs). As in the previous reference, an IEEE node test feeder and load-flow equations are used to compute the voltage in each node of the network – thus the location of the EVs is determinant. Bidirectional 4kW charging stations are available for all EVs, which control their charging/discharging power in response to a charging cost-minimization problem. Voltage deviation limitations are expressed in the constraints of the optimization algorithm. It is noticeable that the EV only takes into account the voltage at the node it is plugged in; thus, an embedded controller could be responsible for designing the entire command – no need for a third party sending control commands over. As a matter of fact, the authors argue that such a controller could be embedded in the EV charger. A comparison is conducted between uncoordinated and coordinated charging scenarios; the percentage of excessive voltage deviations is reduced to zero for a PHEV penetration rate of 30% under the coordinated scenario.

Decentralized approach of active power modulation based on voltage droop control is presented in [23]. The impact of such a controller is simulated for different scenarios differing in EV charging simultaneity and charging duration. The analysis shows that voltage droop eliminates EV-induced voltage magnitudes below 0.85 p.u. and reduces the voltage unbalance factor. Droop parameters can also be optimized to support other objectives such as decreasing the grid losses.

In order not to modulate active power and consequently affect user comfort, decentralized voltage regulation can be done only by the means of reactive power control as shown in [5] and [6]. In addition, this leaves the possibility of using the active power for other services if the user agrees, e.g. frequency regulation [24]. When controlling the voltage by reactive power, one has to address the additional losses caused by increased currents. In [6], the authors show that voltage benefits are greater than the increased loading drawbacks. More precisely, relative voltage increase is up to 2.5% while the losses are not notably increased. Moreover, in one of the cases, the reactive power control is even needed to maintain the voltages within the technical limits while the losses are decreased due to compensation of already present inductive reactive power.

IV. Market Design Recommendations

A. Technical requirements for efficient provision of flexibility services

Various technical requirements for EVs providing flexibility services have been derived from the literature review. First of all, since the distribution services are used for voltage and congestion regulation, location of the flexible load has to be defined. It can be listed either as the corresponding connection node or as the superior substation depending on the provided service. For example, [19] reports that exact EV location is of little importance for transformer congestion control, whereas [6] shows that voltage management services are highly dependent on the point of common connection.

Secondly, additional requirement is the information on active and/or reactive power capabilities, as well as if the EV can provide only unidirectional or bidirectional power flow. Moreover, the size (in kW) of available resources is of utter importance. Depending on the given information, the controllers are defined differently as shown in examined literature. Hence, each unit has to provide the DSO or the aggregator with these pieces of information in order for them to know what their flexibility options are.

Even though some literature reports that distributed flexibility resources would be used only few hours in the year [4], others show that they could be valuable asset whenever connected to the grid [24]. Therefore, estimating the frequency of activation during the contracting period is necessary. Moreover, the way the service is activated should be clearly defined since there are diverse possibilities, e.g. direct load control [20] or price-based control [7].

In addition to mentioned pre-requisitions, several other points have been identified within projects dealing with flexibility markets and flexibility products for the distribution grid. Fig. 1 presents the technical requirements recognized for flexibility services in the Nikola project mapped to the requirements defined in three selected projects: iPower project [14], ADDRESS project [25] and VDE RegioFlex project [26]. These projects focus respectively on: developing a platform for SmartGrid flexibility products, enabling the active participation of small consumers in the power system markets, and establishing a regional flexibility market for using regional flexibility options by different DSOs; whereas Nikola project aims at, among others, demonstrating that EVs can provide distribution grid services [27].

Technical requirements shown in Fig. 1 have been recognized as the crucial aspects which must be defined when contracting a flexibility product. It can be seen that most of them have been recognized in all observed projects, e.g. the activation frequency defines how many times can a service be activated within the contracting period, the size (kW) defines the maximal power which can be requested

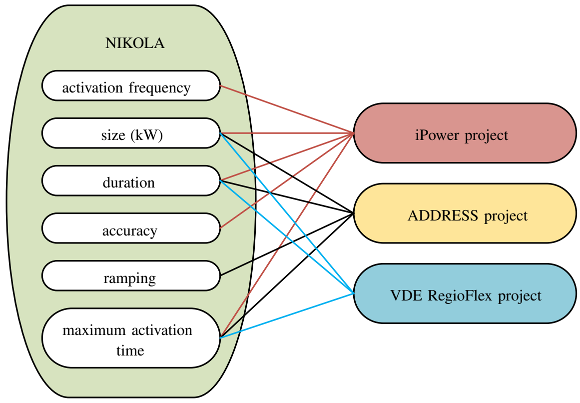

Fig. 1. Technical requirements recognized for DSO flexibility services.

from the flexible load and the duration defines the period within which the service must be active. iPower project also defines the size (kWh) as the maximum energy which can be requested in the contracting period. However, other projects do not recognize this requirement as a crucial one since it is implicitly contained in the power size and the duration. Maximum allowed activation time, ramping and accuracy are considered to be part of the quality of service. In addition to the mentioned requirements, iPower also defines the accuracy as maximum allowed deviations in duration, activation time and size as well as acceptable number of unsuccessful activations.

B. Economic requirements for efficient provision of flexibility services

Flexibility provision by EVs can provide valuable benefits, such as limiting the need for infrastructure reinforcement, enhancing the congestion management process by direct (V2G) or indirect means (load shifting), and providing voltage management. Nevertheless, in order to activate these resources, some market design adaptations are required.

Firstly, all services provided by the DSOs should be remunerated and/or incentivized. With this transparency effort, economic calculations can be performed to compare the efficiency of choosing between “fit and forget” and “proactive solutions” to solve each DSO task. The regulator must challenge the investment plans of any DSO. It should ask for minimum two scenarios, the “fit and forget” and a “proactive one with the appropriate contractual arrangement to finance it”. The authors think that DSOs should have the burden of proving that not managing flexible resources is socially cost-efficient. At minimum, a cost-benefit analysis would be required in order to explain under which conditions the “fit and forget” approach saves public funding compared to “proactive management”. Such regulation could encourage DSOs to develop active demand management programs since they would be held responsible for improving their grid management efficiency.

Secondly, definition of clear DSO roles and responsibilities is needed for the implementation of proactive distribution system. Reference [28] describes the existing DSO roles including network planning and operation, grid reinforcing and maintaining smart metering infrastructure, and introduces a new role called Distribution Constraints Market Operator which covers contracting and activating flexibilities at different time frames. Flexibility service contracting can be either on bilateral or market basis. The authors believe that an open flexibility platform is needed since individually negotiated bilateral contracts imply transaction costs. This platform would enable to trade several flexibility products through different markets, with their own rules and requirements, and could improve the TSO-DSO cooperation as explained later on. However, if DSOs made an over-investment permitted by the Cost of Service regulation, the value of flexibility would be totally destroyed leading to no need for flexibility market. Hence, regulations have to be carefully formulated to stimulate DSOs in proactive grid management and not to induce unnecessary reinforcement costs.

Further on, the main facilitator for enabling DSO flexibility is the roll-out of smart meters which would allow net metering and is seen as the first step to contracting flexibility services. Currently, the penetration of smart meters varies from country to country, e.g. around 95% in Italy but only 1.6% in Germany [29] where the roll-out is not expected in the near future due to their negative cost-benefit analysis. Nevertheless, overall increased penetration is expected at the European level [30]. All installed smart meters have to be certified by the DSO or an independent third party to ensure that they are compatible with the Measuring Instruments Directive. For efficient flexibility provision, the smart meter sampling rate has to be chosen as a trade-off between the need for accuracy and information speed on the one hand, and related metering and data management costs on the other hand. In any case, the rate should not be larger than the market settlement period in which the electricity price does not change. Reference [31] suggests a 5 minutes resolution as a trade-off between the complexity and system performance. The authors believe that a maximum 5 minutes settlement period should be implemented for successful integration of EVs. This is seen as the psychological limit when the users are still willing to wait while their car is providing flexibility services. We assume that everything above 5 minutes would be unacceptable for the user considering that most of the users expect their battery to be fully charged in less than two hours [32]. In addition, many users have even greater expectations, so in average 45% of them expects the EV to be charged in less than an hour and around 23% in less than 30 minutes. If the EVs were to provide flexibility services for the transmission system operator as well, the sampling rate should be higher considering that frequency regulation is on second basis. This is not seen as a necessity from the DSO perspective, but can be of additional value.

Another barrier for the participation of small-scale prosumers in the present market structure is the minimum bid size which depends on the provided ancillary service. As an example, minimum capacity for primary frequency reserve in Denmark is 0.3 MW which is, to the authors' knowledge, one of the lowest required bids in all currently existing markets. However, this minimum bid is still considered to be too high for distribution flexibility services as it is seen that even one EV can be a valuable flexibility asset. Therefore, the minimum capacity should be as minimum as possible to enable demand-response participation in the market, whereas some literature even proposes bidless markets [31] where anybody can respond to the real-time price signals at any time.

Finally, defining the priority between TSO and DSO is of crucial value since providing distribution grid services could trigger the need for system-wide services. Therefore, TSOs and DSOs need to cooperate and exchange information in the proactive grid management [33]. There are two possible ways to improve the relationship between TSOs and DSOs: through *cooperation* or *coordination*. The former one implies mutual agreements between the DSOs and TSOs for all the use cases that would require a strong information exchange between the two stakeholders; for instance, such agreements could define priorities for one over the other depending on the considered use case. It is also possible to have a third party (e.g. the regulator) deciding on these agreements. The later one relies on the flexibility platform previously mentioned. If market design is properly addressed, trading flexibility products on this platform could induce a smooth coordination between the different products. In this case, the flexibility providers, e.g. aggregators, could naturally bear the function of coordinators (for instance, if they loose money when making several counter-effective offers, they will enhance coordination inherently). Information exchange via the platform would also allow network operators to act in coordinated manner and re-dispatch flexibility resources if needed.

V. Conclusion

In this paper, the way DSOs have been operating their grids in the past was first reminded. Because very few loads used to be flexible, and due to their remuneration scheme structure, DSOs had better investing in grid reinforcement costs rather than in implementing active demand management strategies. However, considering the policy and technology changes, the paradigm may evolve. This is especially expected considering that some loads, in particular Electric Vehicles, could turn out to be very efficient flexibility providing units, as it was demonstrated in this work through a literature survey.

Market design recommendations were provided both from a technical and a policy perspective in order to set efficient frameworks for the provision and utilization of flexibility products. The main technical requirements recognized for flexibility products are the activation frequency, size in kW, duration, geographical location and quality of service which includes maximum allowed time, ramping and allowed deviations. In addition, it should be defined if the service is provided by active and/or reactive power modulation as well as if the flexibility provider is unidirectional or bidirectional.

Several non-technical recommendations have been made as well. First of all, adequate regulation is needed to remunerate DSO services and challenge the investment plans. This would enable easy economic comparison of "fit and forget" approach to "proactive solutions". Secondly, a new DSO role which includes contracting flexibility services needs to be established. Furthermore, the authors believe that contracting the services should be market based with an open flexibility platform which provides transparency for all involved actors. This way TSO would have insights on the flexibility market and could request deactivation of a DSO service if it inadequately interacts with TSO needs. Finally, smart meter roll-out is seen as a main facilitator for enabling distribution flexibility. The smart meter sampling time must not be less than the market settlement period which should be, in authors' opinion, maximum 5 minutes for successful provision of flexibility services by EVs. This would not impose high inconvenience for the user since the EV would be unavailable for the settlement period when it is providing flexibility services.

The future work includes calculating the potential value of flexibility services in Danish low-voltage network. The analysis of flexibility value will be based on real historical data in order to estimate the cost of grid reinforcement which can be postponed when using flexibility services.

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Pub. B. Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration

Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration

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Abstract

Increasing environmental concerns are driving an evolution of the energy system in which electric vehicles (EVs) play an important role. Still, as the EV number increases, the adverse impact of charging is observed more widely, especially at the low-voltage level where high EV concentrations cause various detrimental effects due to the coincidence between EV charging and residential peak load. However, if managed properly, EVs become flexible resources which can improve the system operation, making them an attractive asset for the distribution system operator. With the recent technology development, new forms of local EV support can be developed, provided that an appropriate regulatory framework is established. Whereas the technical value of such EV distribution grid services has already been proven, integrating them into the European regulatory context is not straightforward. In the context where active distribution grid management schemes are still to be developed, it is important to recognise the barriers for active EV involvement in the early stage of the development. This manuscript focuses on identifying these barriers from a technology and infrastructure perspective as well as from the regulatory and market aspect. Various policy recommendations are provided for the stakeholders involved in the EV value chain.

Keywords: distribution grid, electric vehicle, flexibility service, regulatory barriers

1. Introduction

Increasing environmental concerns are driving the evolution of the energy system in which the electrification of the transport sector is considered a crucial element in achieving the set sustainability goals. Successful electric vehicle (EV) introduction allows the reduction of CO_2 emissions, but also represents a challenge of daunting proportions for the power system. As the number of EVs increases, the impact of uncontrolled charging is observed more widely, especially at the distribution level where high EV concentrations cause various detrimental effects due to the to the conicidence between the EV charging and the peak residential consumption. It is generally agreed upon that, if not managed properly, EVs will cause challenges that may lead to grid over-investment in order to cope with the extreme operating conditions [1, 2, 3]. However, EVs should not be considered merely as passive loads as they hold potential for providing services beyond transportation due to their defining characteristics: they are a considerably large load compared to other conventional residential loads, they are idle more than 90% of the day with a high degree of flexibility, and they are a quick-response unit with an attached storage and potential capabilities for bi-directional power flow [4]. If managed properly, EVs become resources which can be used to enhance the system operation by providing flexibility, making them an attractive asset for the distribution system operator (DSO) [5, 6].

Nevertheless, procuring EV flexibility at the distribution level is far away from being realised despite the technical value shown in various pilot projects and numerous theoretical studies [5]. Indeed, exploiting EV flexibility to support the distribution system operation has been negligible up to now as the organisational and regulatory aspect remain unclear for such distribution grid services. Hence, it is becoming increasingly important to systematically and thoroughly investigate the requirements for enabling the active EV participation in distribution grids both from the regulatory aspect and from the technical perspective. The regulatory requirements for active participation of various demand response units have been tackled in numerous reports by relevant regulatory and industrial institutions, such as the Smart Energy Demand Coalition (SEDC) [7], Council of European Energy Regulators (CEER) [8], and The Union of the Electricity Industry (Eurelectric)[9, 10, 11]. The scope of this manuscript is to review the existing literature and the distribution sector status in several European countries in order to identify barriers for active EV involvement, and provide recommendations for overcoming them. The main contributions of the paper are:

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- Definition of an EV flexibility service with specific technical attributes which must be addressed when procuring flexibility products as well as a classification of prominent services EVs can provide to the DSO to optimise grid operation and defer grid reinforcement.
- Identification of main technology and infrastructure related barriers as well as regulatory and market related barriers that potentially obstruct successful EV integration and deployment of distribution grid services.
- Proposal of series of recommendations for overcoming the recognised barriers with a respective roadmap for supporting active EV involvement in the distribution grids.

The remainder of this manuscript is organised as follows. Section 2 provides a conceptual basis including an overview of historical distribution grid operation with the emerging changes, the definition of an EV flexibility service and the introduction of prominent EV distribution grid services. Further, in Section 3, the main barriers for active EV involvement at the distribution level are analysed. Finally, the general policy recommendations are given in Section 4 followed by a conclusion in Section 5.

2. Value of EV flexibility at the distribution level

Before describing the potential value of EV flexibility, it is necessary to outline the historical grid operation, and the main concerns of the respective distribution grid operator. Then, the emerging changes in the electric power system and the importance of EV flexibility can be presented in the relevant context.

2.1. Historical distribution grid operation and emerging changes

DSO is the entity concerned about efficient and reliable electric power delivery to the end customer whose main tasks include maintaining the distribution network and ensuring the power quality according to the international and national regulations. Whereas the transmission system operator is usually unique for the whole transmission system of the European countries, the distribution sector is characterised by high diversity of DSOs [12]. They differ both in number and in the magnitude of the corresponding control areas. Some operate large sets of distribution grids over several regions while others operate a limited amount of feeders with a small number of customers. In order to provide a brief overview of the current system complexity, Table 1 summarizes the number of DSOs for several European countries, from which it can easily be seen that the DSO number is often large, even when there is a dominant one which is responsible for most of the distribution feeders. However, essentially everywhere, all DSOs have historically operated grids with radial topology and unidirectional flows, where consumption has been largely inflexible, so grid security issues were dealt with by planning and network development methods [13]. As a matter of fact, DSO activities are mainly focused on long term planning and design, rather than on real-time operation. The distribution business is generally regulated as a natural monopoly and the regulator defines the way in which the DSO is remunerated. In any case, DSOs have a strong incentive in promoting grid reinforcement for solving management issues as they are directly remunerated for the reinforcement expenditures, so there is no need for solutions which would defer them. The described DSO methodology is called the "fit-and-forget" approach. In this context, DSOs focus on solving grid contingencies, namely the overloading and the voltage issues.

Table 1: Active DSOs in selected European countries, adapted from [8, 9].

Country	Total DSOs	DSOs with <100000 customers	Dominant DSO (>80% of distributed power)
Denmark	76	68	n/a
France	148	143	ERDF
Germany	883	780	n/a
Italy	151	124	ENEL Distribuzione
Ireland	1	0	ESB Networks

Voltage regulation is of paramount importance as it can cause equipment dysfunctions, tripping of sensitive loads, overloading of induction motors and higher losses. In Europe, responsible DSO must ensure that its distribution feeders are operated within the suitable voltage range to ensure the required voltage quality to its end customers according to the European standard EN 50160 [14]. Nowadays, DSOs mainly perform voltage regulation by adding capacitor banks or installing transformers with an on-load automatic tap adjustment [15]. If such strategies are not successful, the distribution feeders are usually reinforced. In addition to voltage regulation, DSOs are mainly dealing with congestion issues as grid components are manufactured to operate at a given rated power or current, so overloading inevitably results in shorter life expectancy. Reducing the components' lifetime can significantly increase the cost since, as shown in Table 2, replacing large amount of components is rather costly. In Denmark, the capacity limit is kept at 70% as a "rule-of-thumb" since the remaining 30% is saved for supplying the neighbouring feeders in case of a fault [16]. Hence, if components are often operating above this limit, the DSO will reinforce the grid by upgrading to components with a higher rated power.

Table 2: Assets cost, adapted from [1, 17].

Component	Estimated cost
MV over-head lines/cables	100-200 k€/km
LV cables	70-100 k€/km
LV over-head lines	30-65 k€/km
ground-mounted MV/LV transformer	14-35 k€
pole-mounted MV/LV transformer	5 k€
HV/MV transformer	1700-5200 k€

With increasing DER penetration, the reliability and the economical operation of the power system become non-trivial since the new resources impose additional constraints and challenges to the system such as unpredictability, intermittency and bi-directional flows, which cannot be easily solved by the traditional system operators' means. In addition, considering the adverse effects of uncontrolled EV charging, the integration of high EV numbers cannot be done by the traditional "fit-and-forget" approach as great grid reinforcement would be needed, resulting in an overall high cost for the society.

With the liberalization of the electricity industry and the recent technological improvements, a new kind of DSO is needed to take on the responsibility for balancing supply and demand at the distribution level and procuring flexibility services from distributed resources [18]. In order to efficiently solve the operational challenges and fulfil the core responsibilities, DSOs could exploit flexibility for achieving the technical objectives linked to their physical assets and grid constraints. The new design could also include a market mechanism at the distribution level in which available, feasible and cost-effective solutions become part of any distribution system planning efforts. This new methodology of investments, management and remuneration of decentralized flexibility resources, including EVs, is called the "proactive distribution grid operation".

2.2. The definition of an EV flexibility service

In general, EV flexibility service can be defined as *a **power adjustment** maintained from a particular **moment** for a certain **duration** at a specific **location***. Despite the fact that flexibility services can be provided by the individual EV, some can have a significant impact only if provided by a large fleet. In order to make such management possible, the existence of a dedicated entity is required, which is often called EV aggregator and typically acts as the middleman among EV owners and power system stakeholders [19, 20]. Regardless if the required flexibility is provided by an individual EV or a pool of aggregated EVs, the flexibility service is characterised by five theoretical attributes, as seen in Figure 1a as well as by five practical attributes which arise due to resource imperfections, as shown in Figure 1b.

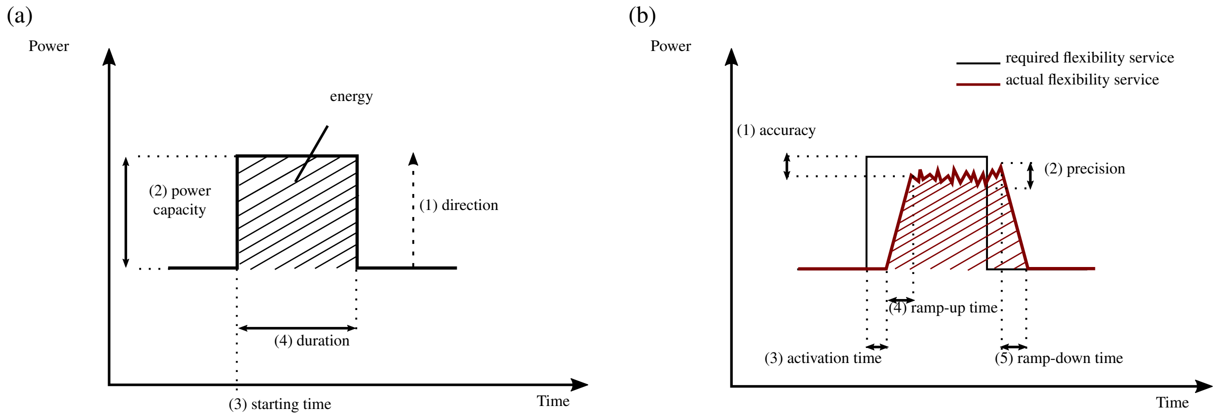

Figure 1: (a) Theoretical and (b) practical attributes of a flexibility service (excluding the location).

These attributes are:

- *Direction*: The information if an EV can provide only unidirectional or bidirectional power flow must be known as well as the information on reactive power capabilities. These properties are obtained through contracts with the EV owners. The DSO requests and the EV offers a flexibility service of a certain active/reactive power direction.

- *Power capacity*: Limitations on available capabilities are required such as the nominal rating of the charging equipment and the active/reactive power capability. The required/offered power capacity must be defined for each flexibility request/offer.

- *Duration*: The period within which flexibility is acquired must be defined in the flexibility request/offer. Then, the maximum energy which can be requested in the contracting period is implicitly contained through the required power capacity and the duration.

- *Location*: Location of the flexible EV can be defined either as the node of coupling or as the corresponding superior substation depending on the required service. For example, exact EV location is of little importance if the EV is providing congestion prevention as long as it is supplied through the congested transformer, whereas the voltage regulation service is highly dependent on the point of common coupling.

- *Starting time and maximum activation time*: The period between receiving the required set-point and activating the required flexibility must be determined. More precisely, the DSO defines the maximum acceptable activation time in the flexibility request and the EV aggregator defines the maximum activation time of its resources in the flexibility offer.

- *Ramp-up/ramp-down time*: The acceptable and/or desirable upwards rate-of-change duration between the activation time and full service provision must be defined. Similarly, the acceptable and/or desirable downwards rate-of-change for service deactivation must be determined.

- *Accuracy*: The acceptable difference between the required and the delivered response must be defined, e.g., the acceptable response band.

- *Precision*: The acceptable variation of the delivered response must be defined, i.e., the amount of variation that exists in the delivered response for the same required value.

2.3. Prominent EV distribution grid services

With respect to EV flexibility service which can be provided to the DSO, different objectives can be taken into account. One has to bear in mind how the classification described here is just one of the possible categorisations which is derived based on the literature survey and the current DSO operation. These services correspond to the DSO's needs, but may not be the exact products defined in the future. In general, EV flexibility services for achieving the technical objectives can be divided in two groups depending on the targeted grid constraint, namely services for solving rated capacity issues and services for solving voltage issues. These two groups can further be split into several distribution grid services as depicted in Figure 2.

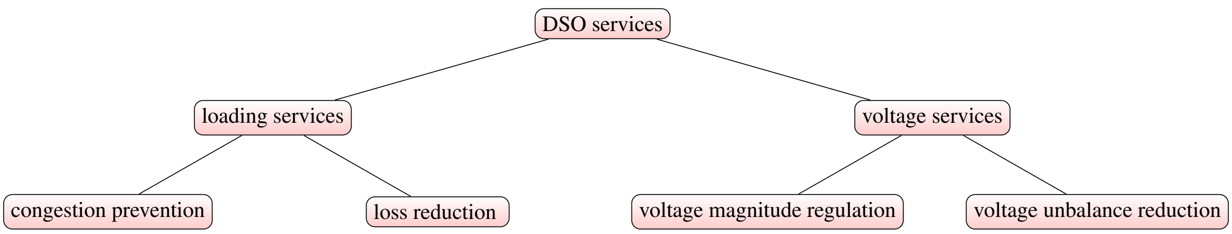

Figure 2: Classification of possible services EVs can provide to the DSO.

In the EV related literature, a wide range of algorithms for achieving the set objectives can be found, both for direct load management and indirect price control schemes as well as for different control architectures. For example, controlling the adverse EV voltage effects has been investigated in [21, 22, 23], congestion prevention methods have been studied in [24, 25, 26], whereas the loss reduction provision has been analysed in [27, 28]. It is generally agreed that EVs can provide services to mitigate the self-inflicted adverse effects as well as to compensate for the undesirable effects of other distributed renewable resources. However, whereas the technical value to the system has been proven for different EV operational strategies, integrating EV distribution grid services into the European regulatory context is not straightforward. Therefore, it is important to assess the current status from four aspects: (1) enabling EV participation and aggregation, (2) standardised measurement, communication and verification requirements, (3) payment structures, and (4) appropriate programme requirements for distribution grid services (minimum bid, penalty for non-delivery, etc.).

3. Barriers and challenges for proactive EV involvement at the distribution level

In a liberalised environment, local distribution grid support can be acquired either through the mandatory grid codes or through trading flexibility services. Unless a certain EV flexibility service is made mandatory, a number of issues must be investigated by the relevant stakeholders to make it a tradable commodity. Enabling EV flexibility procurement on local basis requires a dedicated framework which includes three layers [29]: (1) *the techno-institutional layer*, which defines what resources are controlled and by whom, (2) *the economic layer*, which defines the trading organisation and the remuneration schemes, and (3) *the operational layer*, which defines how the resources are controlled. When dealing with EV flexibility provision for emerging DSO services, key prerequisites must be identified as guidelines for large-scale procurement, regardless if the remunerated services are obtained through bilateral contracts or a local flexibility market. Indeed, the real applicability of EV distribution grid services will highly depend on the local regulatory conditions as well as on the deployed infrastructure. Hence, it is important to analyse the techno-institutional and the economic layers, with the emphasis on recognising barriers for active EV involvement and providing recommendations for overcoming them. These barriers and challenges can be divided in two categories: the technology and infrastructure related ones and the policy and market related ones.

3.1. Technology and infrastructure related barriers

This section is concerned with the main barriers for an efficient utilisation of EV flexibility at the distribution level which are related to technology and infrastructure, and can be observed across Europe. Special attention is put on practical attributes of EV flexibility services, grid observability and smart metering, deployment of EV supply equipment (EVSE), and the related standardisation support.

3.1.1. Assessing practical attributes of EV flexibility

If EVs are to be treated as "black boxes" when providing flexibility services, their internal parameters must be carefully addressed in order to provide both the DSO and the EV aggregator with the knowledge of the EV technical capabilities and the means for compensating the imperfections. It is clear that the practical attributes of EV flexibility services, such as the accuracy, the precision and the response time, must be thoroughly investigated for a vast amount of EV brands and models in order to test their ability to comply with flexibility service requirements. Yet, the vast majority of the EV related literature remains on simulation studies, and the experimental testing has widely been neglected, making it hard to evaluate the true value of EV flexibility.

In [30, 31, 32], the authors focused on assessing the technical feasibility of current series-produced EVs to provide different flexibility services. Experimental validations were carried out through laboratory and field trials, and the results provided various indications of the contemporary EV capabilities, but they are far away from being exhaustive. More specifically, the conducted analyses showed that EVs have a fast response within several seconds, but there is a significant difference in response accuracy based on the external conditions such as the ambient temperature, which arose as a topic of concern [32]. Moreover, the conducted experiments were done with a single EV model, so other series-produced EVs might not have the same response delays and inaccuracies as the ones obtained in these studies.

Since there is a clear lack of experimental data for assessing the reliability of series-produced EVs to provide distribution grid services, the research focus must be put on evaluating their contemporary capabilities under various external conditions. Establishing standardised tests for evaluating the internal EV parameters, including the accuracy and the response time, would enable benchmarking various vehicles to each other and encourage manufacturers to improve the grid integration performance. The collected data could also be used for further theoretical studies such as system-identification for establishing dynamic models of various EV models. This is of particular value for studying flexibility aggregation of numerous different EVs.

3.1.2. Grid observability and smart metering

It is widely acknowledged that the mass roll-out of smart meters is the main facilitator for enabling flexibility procurement since the accurate measurement of consumption patterns is crucial for an effective billing [33]. The measurements from the bottom of the distribution grid could provide the DSO with more knowledge about the respective grid, making it capable of judging if flexibility procurement is needed or grid reinforcement is inevitable. The meters could also be enhanced with advanced functionalities, such as voltage measurement, for a marginal cost which would avoid the additional roll-out of remote meters at MV-LV transformer substations to increase the grid observability [34].

The European Electricity Directive [35] requires the member states to ensure that at least 80% of consumers are equipped with smart meters by 2020 unless the conducted cost-benefit analysis provides indications that the roll-out volume should be smaller. As seen in Table 3, several European countries have plans for a wide-scale roll-out of smart meters supported by the national regulatory framework, but there is still a relatively large share of countries which have not started the deployment due to the negative or inconclusive results of the cost-benefit analysis. For example,

Table 3: Current status for several European countries in case of smart metering infrastructure [36, 37].

Country	Wide-scale roll-out by 2020[a]	Sampling rate	Data management responsible
Belgium	○	○	DSO
Denmark	●	15 min/1 h[b]	DSO
France	●	30 min	DSO
Germany	◐	15 min	meter operator/DSO
Ireland	●	30 min	DSO
Italy	●	10 min	DSO
Netherlands	●	15 min	DSO
Spain	●	○	DSO
UK	●	15 min	supplier

[a] ○ = the criteria is not fulfilled, ◐ = the criteria is fulfilled to some extent, ● = the criteria is fulfilled
[b] 1 h for smart meters installed until 2011, 15 min for the meters installed after 2011

in Germany only 23% roll-out is expected and in Belgium there is currently no plans for the deployment. In majority of the countries where smart-meters are being deployed, all units are certified and installed by the corresponding DSO, who is also responsible for the data collection and management. There is some exceptions, e.g., in Germany where the DSO remains the default metering supplier, but consumers can freely choose another one if wanted. Regardless if the DSO or an independent third party is deploying the smart-meters, the interoperability must be ensured by standards which guarantee the compatibility with the pre-defined requirements and verification protocols. It is of particular importance to clearly define the requirements on the specific measurement parameters, such as the sampling rate and the accuracy. The sampling rate must be chosen as a trade-off between the accuracy and information speed on one side, and the installation and the data management cost on the other hand. According to the European Commission's recommendation [38], the basic smart-meter functionalities should include remote reading with a two-way communication and the sampling rate which is not greater than 15 minutes. Yet, there is no international standards which would ensure these basic smart-meter functionalities, so the status across European countries considerably varies, as noted in Table 3.

The lack of homogeneous and standardized functionalities among smart meters prevents more sophisticated ways of flexibility procurement and is observed to be one of the major barriers. The same barrier applies to advanced metering infrastructure which must be available for individual EVs to allow verification of the flexibility delivery. In [39], a 5-min settlement period has been recognised as a trade-off between the related metering and communication cost, and the system performance. The sampling rate should also be aligned with the possible future settlement period if local flexibility markets are introduced. Moreover, if the meters installed in the EVSEs could serve for flexibility settlement, the overall system complexity would decrease. However, in order to make such a system viable, clear verification and pre-qualification protocols must be defined for the EVSE measurement equipment in addition to the responsible parties for carrying out the validation and the data management.

3.1.3. EV supply equipment

All users should have a non-discriminatory access to electricity network [40] and the same principle applies for the EV connection. Since the EV presence is relatively small in most of the European countries, national grid codes do not include any connection requirements considering the respective EV supply equipment, as the DSOs have not yet encountered any major challenges. However, as the EV number increases, EV charging will have a significant influence on the distribution system operation and the dedicated connection requirements will be needed. Similar process was experienced with the mass adoption of PV installations in Germany and Italy, which resulted in revisiting the grid connection rules and introducing the additional grid codes, respectively [41] and [42]. The most important requirements concerned the limitation of active power and the reactive power compensation, so it is expected that such will be necessary for the EV connection as well [23, 43].

Further on, the use of EVSEs with sufficient computational and communication capabilities is the key for enabling advanced flexibility services as it allows controlled EV charging, either autonomously or in a coordinated fashion. Whereas there is already commercially available equipment which allows the controlled EV charging, including the communication and the computational capabilities in the contemporary EVSEs is not a common practice as it imposes an additional cost. If such capabilities would be included from the beginning of the infrastructure roll-out, the additional cost of retrofitting the older EVSEs once EV smart charging becomes a common practice would be avoided. In order to make this process viable, the deployment of infrastructure with embedded intelligence should be supported and promoted via standards and regulations in the near-future.

Another important aspect with respect to the EV flexibility provision is the EV identification and user information. A standardised way of assigning a unique ID number to the individual EVSE, or alternatively to the EV, must be defined to ensure that the proper user is procured and remunerated for the delivered flexibility. Moreover, the basic EV information, such as the plug-in time, the maximum battery capacity and the initial SOC when plugged-in, should be recorded at the EVSE level by the respective measurement equipment. These information should also be made accessible by the EV manufacturers, which is, e.g., currently not the case for the SOC data which is encrypted. Naturally, the user privacy must be ensured by regulations, so that all the collected data treated as confidential and kept private. However, if the users themselves are willing to share some privacy-sensitive data with other parties for added-value services, they should be allowed to do so.

Finally, the users must be properly informed and provided with the tools to understand the complex contracts to which they can be exposed. It is necessary to develop EV interfaces which are user-friendly and provide insight into the signed contracts as well as the scheduled EV operation. Such interfaces should be connected with the automatised EVSE processes and provide the user with the possibility to override the charging schedule if desired. Otherwise, the user willingness to participate in the flexibility schemes could be jeopardised.

3.1.4. EV communication standards

When talking about EV flexibility procurement, the practical implementation must guarantee interoperability between different equipment and the involved stakeholders, so specific terms and general requirements need to be defined through international standards. The mapping of the most important contemporary standards for supporting EV distribution grid services is depicted in Figure 3. Nowadays, the vast majority of contemporary EVs are compliant with

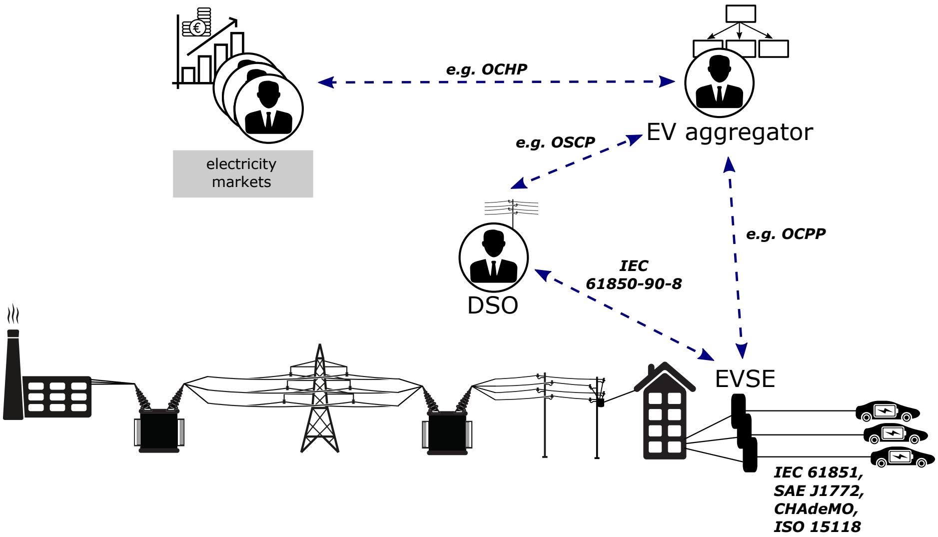

Figure 3: Relevant EV standards and protocols between power system stakeholders with respect to EV distribution grid services. Adapted from [44].

IEC 61851 [45] or SAE J1772 standard [46] according to which the EV charging current can be limited between the minimum charging current of 6 A and the maximum one, which is the EVSE rated current (10 A, 16 A, 32 A, etc.), in discrete 1 A steps. Such capability of limiting the current is seen as the first step in enabling the EV distribution grid services. As opposed to the low level communication described in these standards, a newer standard ISO/IEC 15118 [47] specifies the communication between the EV and the EVSE on a higher level. The standard covers information exchange between all actors involved in the electrical energy supply process to the EV, taking into account the data encryption for both confidentiality and data integrity purposes. This standard is highly relevant for the EV flexibility procurement, yet it is not widely supported by the contemporary EV equipment since it is still under development. Similarly, the scope of the standard IEC TR 61850-90-8 is to describe the communication link between the EVSEs and the power system operator as well as to harmonize information flow models independent of the underlying hardware and software protocols, but the standard is expected to be included in the second edition of IEC 61850-7-420 and is still not widely supported. Additionally, three open application protocols are relevant for procuring the EV distribution grid services due to the lack of international standards: the Open Charge Point Protocol (OCPP) [48] which is developed for the communication between the EVSE and the EV aggregator; the Open Clearing House Protocol (OCHP) [49] which enables communication between the EV service provider and the clearing house system; and the Open Smart Charging Protocol (OSCP) [50] which is used for communication between the EV aggregator and the DSO.

As EV flexibility provision is not a common practice, the lack of international standards for supporting it is not surprising. Still, this lack represents a major barrier for utilising the full-scale potential of EV flexibility at the distribution level. Therefore, harmonisation of communication standards and protocols between all actors participating in flexibility procurement is the key prerequisites for ensuring the interoperability between various equipment and successful provision of EV distribution grid services.

3.2. Regulation and market related barriers

Since DSOs are natural monopolies, the support of regulatory frameworks is essential, so identifying and overcoming the regulatory barriers is crucial to ensure that the future distribution system effectively deals with the EV integration. This section focuses on identifying the policy and market related barriers. The particular emphasis is put on the DSO business paradigm including the aggregation regulation and remuneration schemes as well as the potential introduction of the local platforms for flexibility trading.

3.2.1. DSO business paradigm

Even though the DSO regulatory framework differs from country to country, some common factors for enabling EV distribution grid services can be clearly identified. The regulatory support must cover the procurement of such services as well as the respective metering and the data management aspects.

First of all, to procure any kind of flexibility, these actions must be allowed by the respective regulation, which includes the regulation for introducing independent EV aggregators as well as for DSOs contracting flexibility services. The DSO should be free to consider both the traditional reinforcement means and the flexibility based solutions, or a combination of the two, to assess the most cost-efficient solution. Currently, many national regulations do not explicitly allow any flexibility procurement and some even forbid the aggregation, as seen in Table 4. This major barrier must be addressed as soon as possible. Even if regulations do not encourage flexibility procurement, they must be revised in order to explicitly allow it.

Table 4: Current status for several European countries with respect to DSO regulation [7, 37, 11, 51].

Country	**Aggregation enabled by regulation** [a]	**Network tariff structure** [b]	**DSO regulatory period (years)**	**Mechanisms for stimulating innovation** [a]
Belgium	◐	€ + €/kWh	4	○
Denmark	◐	(€)[c] + €/kWh	3	◐
France	●	€ + €/kW + €/kWh	4	○
Germany	◐	€ + €/kWh	5	○
Ireland	◐	€ + €/kWh	5	◐
Italy	○	€ + €/kW + €/kWh	4	◐
Netherlands	◐	€ + €/kW + (€/kVArh)[c]	3	○
Spain	○	€/kW + €/kWh	6	○
UK	◐	€ + €/kWh	8	◐

[a] ○ = the criteria is not fulfilled, ◐ = the criteria is fulfilled to some extent, ● = the criteria is fulfilled
[b] fixed charge (€); capacity charge (€/kW); energy charge (€/kWh); reactive energy charge (€/kVArh)
[c] possible

Secondly, DSOs are regulated entities which recover their cost through regulated revenues based on a cost-of-service method or an incentive-based method [13]. The first one is based on the DSO expenditure and investment records, whereas the latter one incentivizes the DSO to achieve better performance by making the DSO a partial claimant of the residual gains. For both methods, DSO costs are calculated by evaluating the operational expenditures (OPEX) and the capital expenditures (CAPEX) which are then included in the regulatory formula for the chosen remuneration approach. Incentive regulation is a common practice across Europe after deregulation of the electricity sector [51]. In such a scheme, the regulator sets the allowed yearly revenues for the regulatory period and the DSO can gain an extra profit by decoupling the costs from the revenue and increasing the efficiency. However, in practice, it is difficult to regulate the long technical and economic lifetime of grid components, so regulators exclude the CAPEX from the efficiency requirements and remunerate the actual cost of grid reinforcement, which effectively discourages the DSOs from active grid management.

Bearing in mind this barrier, the regulatory framework must define clear DSO roles related to the active system management, including data management and flexibility operation responsibilities, and recognise the potential cost of flexibility procurement. It is necessary to revise the current incentives for performing the traditional DSO tasks, including the remuneration and tariff structures [52, 11]. Ideally, the regulation should provide explicit support via incentives for acquiring flexibility services in addition to incentives for reducing the cost both for the capital and the operational expenditures. The remuneration formulas should contain incentives to lower energy losses and improve the quality of supply, with bonuses and penalties charged according to the established performance targets. Moreover, the regulated electricity tariffs must be designed in order to ensure the full cost-recovery for the DSO's allowed expenses while encouraging a more efficient grid use. As network upgrades will still be needed, the predictable and appropriate regulatory regime must be supported by sufficient incentives for the necessary network reinforcement. The electricity tariff should include at least two components: a capacity (€/kW) and an energy component (€/kWh), with the right balance between them, which is currently not the case in many European countries, as seen from Table 4. The capacity component would cover the necessary grid reinforcement cost and discourage high instantaneous power consumption, whereas the energy component could vary to reflect the local network conditions. Such tariff system would also encourage the EV user participation in flexibility schemes as the EV is a significant load compared to other residential consumption which would increase the peak power, making the users more likely to allow EV control. Additionally, the current tariff systems are revised quite rarely and such practice should be changed by revising the tariffs more often if needed to reflect the contemporary technology status. This would provide a strong incentive for DSOs to make efficiency gains and ensure they do not over-invest for avoiding grid issues.

Another aspect which must be taken into account for supporting EV distribution grid services is the regulatory period which often does not incentivise the long-term innovation. As shown in Table 4, the regulatory periods usually last for 4 or 5 years which is too short to see major efficiency improvements from EV flexibility. Hence, the regulatory period should be prolonged with a smooth transition between the different periods, so that regulatory uncertainty is reduced when investing in new technologies, therefore incentivising DSOs to reduce the cost in the long-run. Additionally, in most of the countries, there is no direct mechanisms to stimulate the innovation in the distribution networks, so innovation funding should be established to stimulate DSO active grid management by recovering the cost of research in new technologies.

3.2.2. *Local flexibility trading*

Unless certain EV distribution grid service is made mandatory through grid codes, it will be treated as a commodity which can be either directly invoked by the DSO for a fixed price or traded on the flexibility market. As pointed out in [53], it is still unclear who should initiate the development of local DSO markets or if the trading should be on bilateral basis due to locational restrictions. However, it is mainly agreed that a dedicated flexibility platform is needed to invoke the trading of resource flexibility [10], as via such interface DSOs could require and service providers, including EV aggregators, could offer flexibility. The open flexibility platform would enable trading of flexibility products through different markets with their own rules, or, if local flexibility markets are not established, it could be used for contracting services on bilateral basis. A possible organisation of such a flexibility framework with the basic functionality is given in Figure 4.

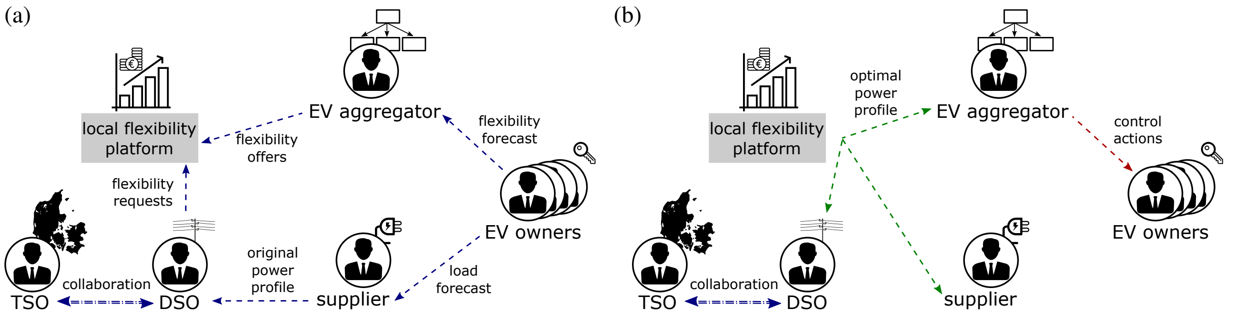

Figure 4: Possible local flexibility framework for the day-ahead trading of EV distribution grid services: (a) before, and (b) after the clearing process. The TSO-DSO collaboration is indicated without a detailed elaboration, as the focus is put on the local level. Adapted from [54, 55].

Trading EV flexibility at the distribution level is nowadays non-existent in all European countries, so various aspects must be addressed when establishing such local platforms. These include:

- *Flexibility platform administration and operation*: Who is to operate and administrate the flexibility platform is debated and it is conceptually possible to have separate entities for the distribution system operation and the distribution system flexibility operation. Some claim that assigning a dual role to the future DSO is more beneficial as the DSO is aware of the grid status and the operational conditions [56]. However, this can also lead to market manipulations depending on the regulatory environment, so the introduction of an independent entity may be needed in case local markets are introduced. Regardless, the flexibility operator, which is defined by the regulator, must manage and operate the flexibility platform in the day-ahead and intra-day phase by accumulating the bids and obtaining the optimal EV schedules.

- *Independence and fair access*: The flexibility operator must be independent of any participant or EV owner to operate flexibility trading in a fair and an impartial manner. Flexibility operator should not own any flexibility assets in the corresponding distribution area to avoid conflict of interest. Regulations are required to ensure open and fair access to the flexibility platform for all interested participants.

- *Transparency*: Participants must have access to financial information such as the cleared prices and other financial figures, whereas the bidding process, if existing, should be blind. The flexibility framework must be transparent in terms of data exchange among different parties, rules on the clearing process, operating costs, and system operation procedures. Clarity is needed on criteria how to become a participant with the corresponding pre-qualification process, respective rights and obligations as well as criteria for terminating the participation.

- *Flexibility products*: Clear and generic flexibility products, which are applicable to any EV, must be defined. Contractual arrangements should be simple, transparent and fair to allow all willing EV owners to participate in such schemes. Each flexibility product must be transparent with clear conditions for procurement and defined flexibility requirements including the aforementioned theoretical and practical attributes (response time, accuracy, power capacity, duration, etc.).

- *Minimum bid*: The power consumption at the distribution level is of much lower values than at the transmission level, so even one EV can be a valuable asset for a certain distribution feeder. If flexibility trading is introduced, lowering the requirements for minimum participation would allow easier entry of many players to the local flexibility platform. The minimum bid requirement for flexibility trading should reflect this fact and be in the kilowatt range to facilitate the EV distribution grid services. This would allow both the DSO and the EV aggregator to be more pliable in their flexibility requests and offers. Some literature even proposes bidless markets where any resource can respond to the real-time signals at any time [39].

- *Settlement period*: The settlement frequency of the local trading process must correspond to the measurement interval, i.e., the settlement period should not be lower than the data sampling rate. From the EV integration perspective, the settlement period should be as short as possible and the authors believe it should not be higher than the afore recommended sampling rate of 5 minutes. This is seen as a psychological limit which would not impose a high inconvenience for the owner in case the EV is unavailable during the contracted period and the user has to wait until flexibility provision is terminated without incurring the penalties for non-delivery. However, settlement period above 5 minutes may discourage the user to participate in flexibility trading as it can influence his comfort. From the DSO perspective, sampling rates on second basis are not a necessity, but such could be of additional value if EVs were to provide flexibility services to the TSO as well.

- *Consumption baseline*: Flexibility only exists because we can estimate what would the load profile look like if flexibility was not activated, but after all, only the actual load profile can be measured and the unperturbed one never really existed. If a common baseline is not accepted by all involved participants, many settlement disputes will arise. In case of EVs, the baseline can be constructed more easily than for other flexible resources by estimating the load demand if uncontrolled charging is applied, i.e., as the case where the EV charges at the maximum rate from the plug-in time until it is completely full. For this, three parameters should be known in addition to the maximum battery capacity: the maximum charging power, the recorded initial SOC and the recorded plug-in time.

- *Flexibility price*: The price for each flexibility product should be determined and transparently communicated in advance. However, how it should be defined is not straightforward as it is not easy to assess the value of demand shifting and potential impact on the user comfort, making it difficult to assign a monetary value for providing flexibility. In any case, the settled price must be lower than the cost of grid reinforcement, so the first step in overcoming this barrier are new regulations which impose transparent service remuneration of all current DSOs services. With this transparency effort, economic calculations can be performed to compare the efficiency between the "fit-and-forget" approach and "proactive solutions", and provide the basis for calculating the flexibility price. The maximum price C_{max} that the DSO is willing to pay for reserving the flexibility service can be defined as follows [57]:

$$C_{max} = \left(C_{reinforcement} - N_{activation} \cdot \lambda_{activation} - C_{transaction}\right) \cdot (1 - u) \tag{1}$$

  where $C_{reinforcement}$ is the present value of the deferred cost for grid reinforcement, $N_{activation}$ is the expected number of service activations, $\lambda_{activation}$ is the activation price determined in the contract, $C_{transaction}$ is the cost of transaction and u is the uncertainty premium which reflects the DSOs risk preferences. The activation price $\lambda_{activation}$ is dependent both on the capacity and the duration of the required service and reflects the aggregator's operational cost which is determined for each flexibility offer. The uncertainty premium u directly rewards the more reliable resources, since the DSO can decrease the premium for the resources which are considered to be less risky. Moreover, as flexibility trading develops and many participant get involved, the transactions costs are expected to decrease.

It is important to note how this list is not exhaustive and many other aspects must be addressed as well. For example, it is important to define how the local flexibility trading would interact with the wholesale electricity market and the parties involved in those trading processes [54].

3.2.3. Collaboration between the TSO and the DSO

When procuring the EV distribution grid service, the interaction between the DSO and the TSO must be ensured, particularly if procuring flexibility services at the distribution level inadequately interacts with the transmission system needs and triggers the need for the system-wide services. The coordination of resources for both the DSO and the TSO purposes is needed and procurement of distribution grid services needs to take into account the effects on the TSO operation. Nowadays, the interaction between the TSO and the DSO is limited, and for such reasons there is an increasing attention put on improving the TSO-DSO relationship [58, 59**?**]. Two possible ways for improving it are *cooperation* and *coordination*. The former implies a mutual agreement for a set of use-cases, with clear roles and defined priority list between the TSO and the DSO for each of them. Cooperation is necessary to define mandatory assistance procedures and cascading principles between the operators, especially in emergency situations. The latter one relies on the flexibility platform with a proper set of market rules to avoid double bidding and coordinate the use of flexible resources on different markets, e.g., for frequency regulation and congestion management. For instance, if EV aggregators lose money when making counter-effective offers, they could inherently enhance the coordination.

In any case, to enhance the TSO-DSO collaboration, open and interoperable standards with clear data exchange rules should be defined for interfaces in place. The regulations must ensure that data sharing is free of charge for all eligible players and that the processes for data exchange are defined with clear responsibility for data management. Moreover, if local DSO flexibility platforms are established, they must be transparent and provide the TSO with the possibility of requesting certain service deactivation.

4. Policy recommendations

Based on the current regulatory and infrastructure status across the European distribution sector as well as the previously identified barriers, a series of recommendations was provided as guidelines for transitioning to a future flexible distribution system where EVs become proactive participants at the distribution level. These recommendations are divided in several categories depending on the targeted aspect, as presented in Table 5. Additionally, the phases for the listed recommendations as well as the intermediate steps needed for fulfilling them are presented via the roadmap depicted in Figure 5.

Table 5: Main recommendations for supporting active EV involvement in distribution grids.

Smart metering	Wide-scale deployment of smart meters. Standardised functionalities to ensure interoperability. Sampling frequency in accordance with flexibility trading settlement period (maximum 5-min). Clear pre-qualification and validation protocols.
DSO regulation	Remove regulation which forbids aggregation and flexibility procurement. Incentivise long-term innovation (longer regulatory period, incentives for new technologies, etc.). Revise tariffs to include both the capacity and the energy charge. Define new DSO tasks (active grid operation and data management). Remunerate current DSO services to provide basis for comparing different solutions and estimating the flexibility price.
Flexibility trading	Establish an open, transparent and fair flexibility trading platform with the corresponding roles. Define clear and generic flexibility products. Define technical requirements which must be included in flexibility requests/offers (power capacity, duration, direction, location, etc.). Define the minimum bid in the kilowatt range and the settlement period of maximum 5 minutes to encourage EV owner participation. Define common EV baseline (uncontrolled charging) and the corresponding measurement methodology. Introduce capacity and energy payments, and a premium for rewarding the more reliable resources.
TSO-DSO collaboration	Define standards for the interface and data exchange between the TSO and DSOs. Define clear priorities between TSO and DSOs for normal operation and emergency situations. Make local flexibility trading platform transparent to the TSO.
Consumer	Determine regulations for ensuring data protection. Allow sharing of privacy-sensitive data if user is willing to do so. Develop interface for providing insight into signed contracts and EV schedules. Define standards for providing an unique ID for flexibility procurement and remuneration.
EV/EVSE technology	Define standards and regulation for deploying EVSEs with embedded intelligence. Harmonise communication protocols between the EV aggregator and other participants. Determine standardised tests for evaluating internal EV parameters (accuracy, response time, etc.).

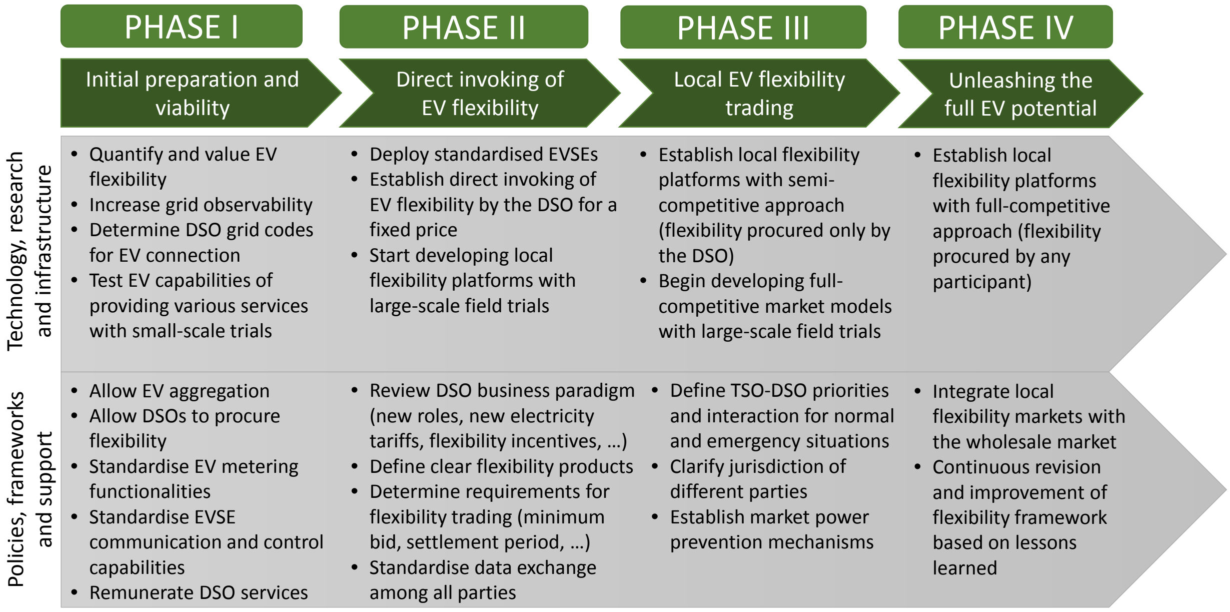

Figure 5: Roadmap with key recommendations for supporting active EV involvement in distribution grids.

5. Conclusion

Enabling EV distribution grid services requires a coordinated participation of the full electricity value chain, but most European countries still suffer from a critical gap between the political sustainability plans and the implemented regulatory frameworks.

This paper investigated and defined the EV flexibility service, highlighting the prominent ones that could be provided to distribution system operators. In addition, it assessed the technical and the non-technical prerequisites for enabling EV flexibility procurement at the distribution level. It was observed that the identified regulatory and policy barriers present a greater challenge than the technology and infrastructure due to large diversity of distribution systems and respective regulatory frameworks across Europe. Based on the identified barriers from the technology and infrastructure aspect as well as from the policy and market perspective, a set of policy recommendations was provided for supporting the proactive EV involvement in the energy system. Since the transition to such a proactive system should be evolutionary, the phases for the listed recommendations as well as the intermediate steps needed for fulfilling them were presented via a roadmap.

One must bear in mind that the provided recommendations are not exhaustive. Due to system complexity and diversity across different European countries, other non-listed organisational and regulatory barriers also exist both on the pan-European level and on the individual country basis. However, without addressing the listed recommendations, it will not be possible to unleash the full potential of procuring EV flexibility for distribution grid services. Moreover, political interference creates regulatory uncertainty and unique local environment may detrimentally affect the regulatory stability. Periodically comparing and contrasting various regulations across Europe is a useful source for identifying the barriers and the best-case solutions, and should become a common practice for all stakeholders involved in the EV value chain. Only then could the regulations be properly revised to ensure the technical and economic competitiveness of EVs providing distribution grid services.

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Pub. C. Analysis of voltage support by electric vehicles and photovoltaic in a real Danish low voltage network

Analysis of Voltage Support by Electric Vehicles and Photovoltaic in a Real Danish Low Voltage Network

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***Abstract* – With conventional generating units being replaced by renewable sources which are not required to provide same high level of ancillary services, there is an increasing need for additional resources to achieve certain standards regarding frequency and voltage. This paper investigates the potential of incorporating electric vehicles (EVs) in a low voltage distribution network with high penetration of photovoltaic installations (PVs), and focuses on analysing potential voltage support functions from EVs and PVs. In addition, the paper evaluates the benefits that reactive power control may provide with addressing the issues regarding voltage control at the expense of increased loading. Analysed real Danish low voltage network has been modelled in Matlab SimPowerSystems and is based on consumption and PV production data measured individually for number of households.**

***Index Terms*--distribution network, electric vehicles, photovoltaic, power system modelling, voltage control**

I. Introduction

Electrical power system is operated in order to follow the continually changing load demand with the minimum ecological impact and at minimum cost. In addition, the quality of power supply must meet certain standards regarding frequency and voltage, which are usually achieved through ancillary services provided to the system operator by other market participants. Due to independent liberalization of electricity sectors in different jurisdictions, technical features of these services vary considerably [1].

Today, conventional generating units are being replaced by renewable resources which are not required to provide the same high level of ancillary services. Increasing number of photovoltaic installations (PVs) influences residential energy consumption profiles causing voltage gradients in the distribution network [2], [3], especially in the areas where dense clusters have appeared [4]. Low electricity demand usually coincides with high power injections from PVs resulting in voltage rise issues and disabling greater integration of distributed resources. Hence, modern solar inverters typically have the capability of supplying or absorbing reactive power in times when active power flow is less than inverter's rated power [5].

On the other hand, electric vehicles (EVs) are a viable alternative to traditional vehicles and can be used for mitigating adverse effects of distributed renewable energy resources. A moderate penetration scenario from Danish Energy Association estimates 47,000 EVs will be present in Denmark by 2020 [5]. Comparing such a prediction to 1,400 EVs registered in January 2013, it is anticipated that EVs will have a great impact on the network consumption in the near future. However, EVs should not be considered as merely passive loads additionally stressing the network, but as distributed energy storage systems with great potential for network regulation. Since they are typically plugged-in 90% of the time, they are capable of providing different ancillary services for supporting the power grid, such as primary frequency control or voltage control [7]-[9]. Development of Vehicle-to-Grid technology will, among other things, enable EVs to provide voltage support functions similar to the ones from solar inverters.

This paper investigates the potential of incorporating EVs in a real Danish low voltage distribution network and focuses on analysing potential reactive power support by PVs and EVs. Furthermore, it evaluates the benefits that reactive power control may provide to the grid with addressing the issues regarding voltage control at the expense of increased loading. As the model represents a real low voltage network, this work may be used as a practical tool for the distribution system operator (DSO) in assessing PV and EV impacts on their low voltage grid.

II. Methodology

A. *Low voltage grid*

The analysed Danish low voltage network has been modelled in the software Matlab SimPowerSystems which uses graphical modelling with built-in common power grid components, and can easily be extended with arbitrary modelled ones. The observed low voltage feeder has been connected to the medium voltage grid represented by a 10 kV three-phase voltage source with in series with a RL branch. As this is the only feeding point of the grid, the voltage source is assumed to be a swing generator with three-phase short circuit power of 20 MVA. The MV/LV transformer is modelled as a typical distribution transformer used in Danish low voltage networks: a 400 kVA transformer with nominal ratio of 10.5/0.42 kV, and resistance and leakage inductance of each winding set to 0.005 p.u. and 0.02 p.u. respectively.

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The secondary star point winding of the transformer has been directly grounded.

The low voltage feeder is a line which bifurcates into three parts coinciding with physical streets where the households are located, and is run in radial configuration. The line consists of 14 nodes and 13 line segments with total length of 681 meters. All segments are the same type of 4x150 mm^2 Al PEX conductor with R=0.207 Ω/km and X=0.078 Ω/km. The single phase configuration of the described low-voltage network is given in Fig. 1. Part A represents 17 houses located in Hørmarken Street while part B represents 26 households located in Græsmarken Street. Households with PV installations and EVs are marked green, while the ones without PV are blue. In addition, there is a street light connected to the grid in Græsmarken Street at node 608 which is marked black.

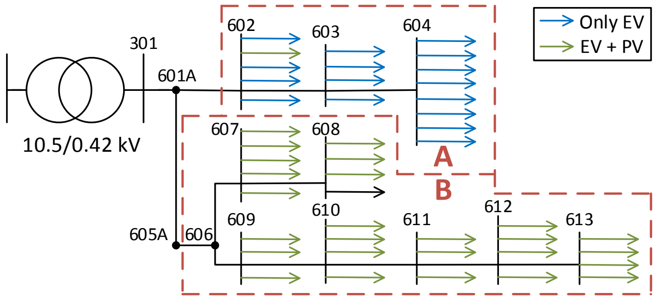

Fig. 1. Single phase diagram of modelled real Danish low voltage network

B. Household consumption

There are 43 households in total which can be divided in two categories due to their similar characteristics: (1) residential houses in Hørmarken Street, and (2) residential houses in Græsmarken Street. The first group has somewhat lower consumption profile during the heating season as a result of implemented district heating. Furthermore, none of the houses in this group have a PV installation except of one located at node 602. The second group covers households with PV installations, as well as with heat pumps and consequently higher consumption during heating season.

Consumption profiles are based on real metering data read on hourly basis through a period of one year (from March 2012 until March 2013). However, measured power flows are three-phased with no insight into shares of individual phases. Therefore, it is assumed that the loading is equally distributed and symmetrically balanced between the phases. Moreover, there are no data for the reactive power component, so the minimum required power factor has been taken as the reference value for all households (cos φ = 0.95[10]).

Since this paper focuses on voltage support in steady-state, the two most interesting weeks in the given year have been chosen for further analysis: (1) a spring week with low consumption and high PV production, and (2) a winter week with high consumption and almost no PV production. Fig. 2 shows total weekly consumption and average daily profile per house for the observed spring week. The later was calculated as a mean of all household consumptions at each hour of the

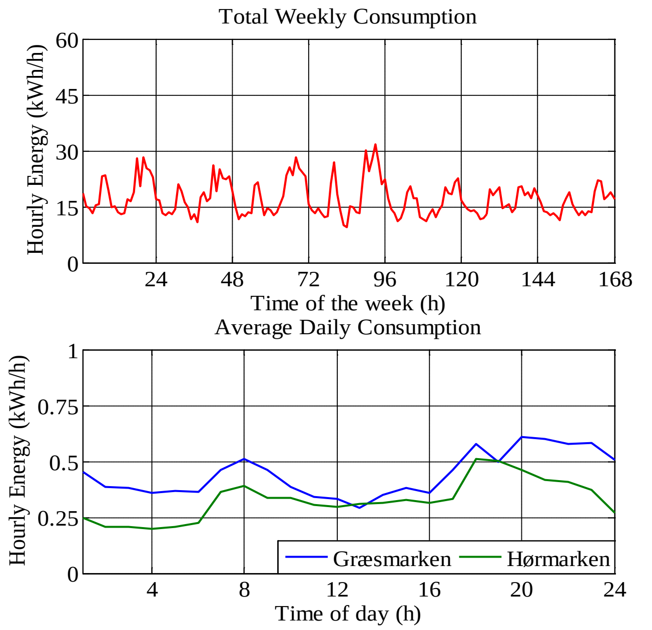

Fig. 2. Total weekly and average daily consumption per house for the observed spring week

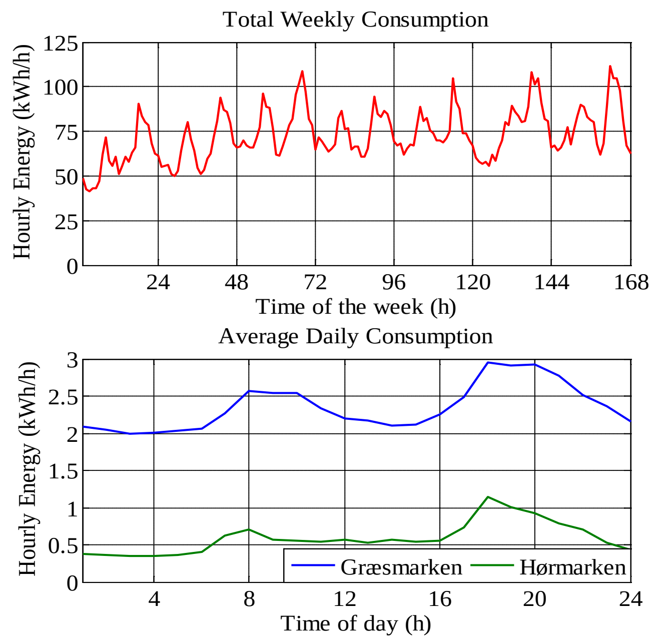

Fig. 3. Total weekly and average daily consumption per house for the observed winter week

day, separately for Hørmarken and Græsmarken. Similarly, Fig. 3 presents total consumption and average daily profile per house for the chosen winter week. It is clear that Græsmarken households have bigger consumption in the winter week as already mentioned, while the consumptions during the spring week are similar for both household groups.

Besides the modelled feeder, there are additional three feeders with number of houses under the same transformer substation. However, the data for these feeders are not available and thus, they are not modelled in this paper. When analysing the results, one has to bear in mind there is an additional load which will lower the voltage levels at the substation level more than in the simulated scenarios.

C. Photovoltaic installations with reactive power control

PV installations are mostly located in Græsmarken (only one located in Hørmarken) and all of them are connected through single-phase inverters. Modelled network contains 27 PV installations in total: 24 installations with peak power P=2.96 kW_p and 3 upgraded installations with P=4.07 kW_p, which are respectively connected through 3.6 kW_p and 5.4 kW_p inverters. The number of PVs connected to a particular phase is not known, so the installations have been connected randomly taking into consideration that the overall production on each phase should be approximately the same. The PV production has been measured separately for every house also on hourly basis along with the consumption data. Total weekly and average daily production values for the observed weeks have been summarised in Table I. Similarly to the average daily consumption, the average daily production is calculated as the mean of all PV productions at each hour which have then been summed up for the 24 hour period.

TABLE I
PV PRODUCTION FOR OBSERVED WEEKS

	Total weekly PV production (kWh)	Average daily production per PV (kWh)
Spring week	3096.20	17.01
Winter week	32.07	0.18

PV installations are connected through single-phase inverters equipped with reactive power control (RPC) related to voltage level and produced active power. Voltage control specifications regarding overvoltage and undervoltage limits are chosen according to the Danish technical regulation for generation facilities with rated current 16 A per phase or lower [9]. According to the regulation, voltage limits are set to ±10% U_n, i.e. U_{min}=0.9 p.u. and U_{max}=1.1 p.u. However, all the specifications required for RPC are not determined by this regulation, thus the function of the controller has been modified according to technical rules for low voltage active users recommended by the Italian technical standards [11] which provide rules for both passive and active users. These standards set different requirements on the reactive power production by the PV inverter greater than 3 kW and define several variations depending on the size of the plant together with specific DSO-users agreements. The main objective of this control is voltage lowering by reactive inductive power injection whenever the PV is producing high amount of power. The voltage rises may be particularly sensible if the PV is localized in weak feeders or feeders with high density of other active sources. Since both Italy and part of Denmark belong to the same synchronous region, it is reasonable to expect that future Danish requirements will experience harmonization with other European regulations.

In this paper the application of mentioned technical rules is extended to EV charger. Since an EV charger with V2G capability could in principle allow both charge and discharge, it also includes the possibility to inject both reactive inductive power and reactive capacitive power for sustaining voltage drops. The implemented RPC capability from PVs is depicted in Fig. 4 and has already been used in [12] for studying a real Italian medium voltage network with high penetration of small-size PV plants. The green area between 0.99 U_n and 1.01 U_n can be interpreted as a dead band with no RPC regardless how the produced active power changes. The blue area represents operation in overvoltage conditions when the inverter consumes reactive power up to 0.5 p.u. in order to lower the voltages. Likewise, the inverter injects up to 0.5. p.u. of reactive power when operation conditions are in the red undervoltage area.

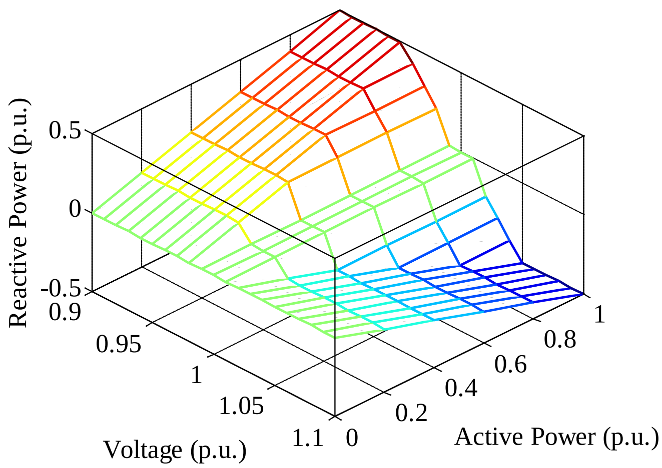

Fig. 4. Reactive Power Control capability for the PV inverters

D. Electric vehicles

Each of the 43 houses is equipped with a full electric vehicle whose charger has reactive power control resembling to the one of the PV inverters (just opposite in terms of injecting/consuming reactive power). The charging pattern of the vehicles has been taken from Test-en-EV program where real charging data were collected from 184 EVs spread around 10 Danish cities [13]. The charging starts immediately after the vehicle is connected with average charging time of 5 hours and total consumed energy of 14.3 kWh, which corresponds to the so called “dumb charging”. This can be seen as the worst case scenario which could happen in the existing grid where there are no new reinforcements and the EV charging coincides with the critical peak time. The charging process starts at 6 p.m. with drawn power of 3 kW in the first hour followed by three hours of charging at nominal power of 3.7 kW and ending with only 0.2 kW in the last charging hour. Since EVs are connected to a single phase as well as the PVs, connection points were also randomly taken with overall even distribution on the phases and additional condition that the EV cannot be connected to the same phase as the PV installation.

This paper compares relevant network parameters between different scenarios, such as voltage values at the end of the lines and energy losses. Several steady-state analyses have been carried out depending on the observed week and combinations of available RPC from PVs and EVs. The differences between the scenarios have been described in Table II.

TABLE II
SUMMARIZED DETAILS OF DIFFERENT CONDUCTED SCENARIOS

Scenario	Season	PV status	EV status
1	Spring	All connected without RPC	All connected without RPC
2	Winter	All connected without RPC	All connected without RPC
3	Spring	All connected with RPC	All connected without RPC
4	Winter	All connected with RPC	All connected without RPC
5	Spring	All connected with RPC	All connected with RPC
6	Winter	All connected with RPC	All connected with RPC

III. Results and Discussion

A. *Base scenarios (scenarios #1 and #2)*

As it is assumed that the consumption is equally divided on three phases as well that PVs and EVs are evenly distributed between the phases, all presented results depict the single phase states. Moreover, most of the results will be shown using boxplots – descriptive statistical method which graphically depicts data through its quartiles indicating the degree of dispersion and outliers located within ±1.5 of extreme quartiles. The term base scenarios refers to two conducted analyses described in Table II as scenarios one and two, which present the situation where PV installations and EVs are connected to the grid in addition to the households' consumption. Fig. 5 illustrates current distribution at the most important nodes for the base scenarios. The blue box indicates 50% of simulation results within the covered range where the median is highlighted in red. Upper and lower quartiles, i.e. 25% of the data are located within the vertically extended black lines, the so-called "whiskers". Outliers which can be considered as the extreme cases are marked with red plus signs. Fig. 5 clearly shows that the network is more loaded during the winter week with the median current value of 106.2 A than during the spring week when the median current value is 29.4 A. Furthermore, node voltages are depicted in Fig. 6. With the connection of EVs, voltage profiles have significantly dropped with some values exceeding the ±10% limit of nominal voltage, which clearly indicates the need for voltage support.

B. *Activation of RPC from PV installations (scenarios #3 and #4)*

In this section, the results for spring scenario of the modelled grid with added RPC from photovoltaic installations are reported. This analysis has been listed in Table II as scenario three, and differs from the base scenarios in terms of PV reactive power control capability. Similar scenario four is not of major interest here since PV production during the winter week is so small it leads to the same results as in scenario two. Accordingly, the potential of reactive power control from PV systems in scenario six is quite non-existent.

Current values for the given scenario increase when the RPC is activated (median value at 301 rises from 29.4 A to 30.9 A, with maximum current increasing up to 11 A during the peak hours), which can be linked to reactive power providence resulting in excessive loading of the lines. Since grid losses are directly related to the current with quadratic dependence, excessive loading can cause high energy losses which will be reported in later subchapter. Fig. 7 and Table III present the voltages at specific nodes (e.g. at the beginning and the end of the segments) and show the RPC benefit in terms of voltage improvement. At the times of maximum PV production, the greatest benefit has been noticed for the furthest node of the line (node 613) where the voltage deviation has been decreased by 0.49%.

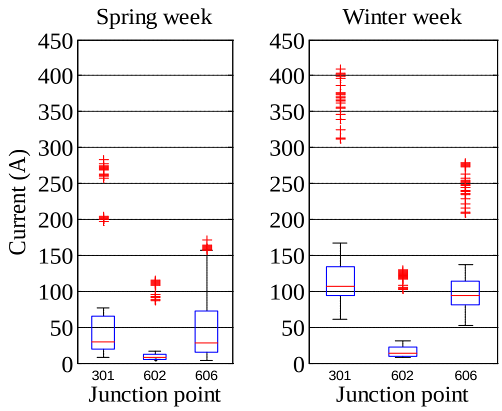

Fig. 5. Current comparison at selected junction points for the base scenarios

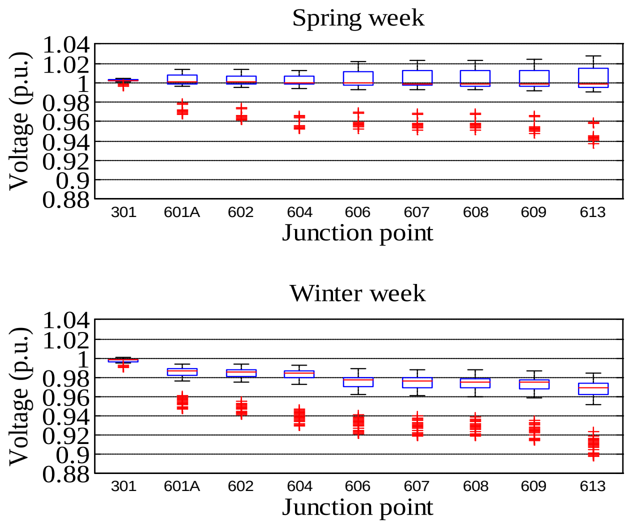

Fig. 6. Voltage comparison at selected junction points for the base scenarios

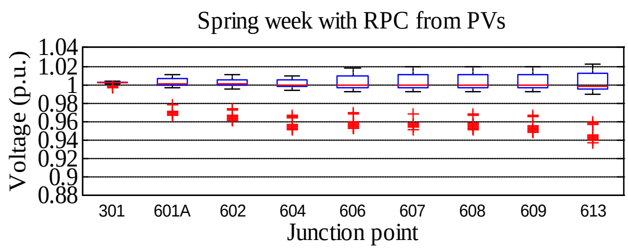

Fig. 7. Voltage profile at selected junction points after RPC activation from PVs for the spring week

TABLE III
MAXIMUM VOLTAGES AT SELECTED JUNCTION POINTS BEFORE AND AFTER PV RPC ACTIVATION – SPRING WEEK

Node	Maximum voltage without RPC (p.u.)	Maximum voltage with RPC (p.u.)	Relative voltage decrease (%)
301	1.0052	1.0044	0.08
601A	1.0137	1.0106	0.31
602	1.0134	1.0103	0.31
604	1.0130	1.0098	0.32
606	1.0222	1.0181	0.40
607	1.0235	1.0192	0.42
608	1.0236	1.0193	0.42
609	1.0244	1.0199	0.44
613	1.0275	1.0225	0.49

C. Activation of RPC from EVs (scenarios #5 and #6)

This section reports results for the scenarios when the RPC capability from EVs has been activated in addition to RPC from PV installations. These scenarios refer to scenarios five and six according to Table II. During the spring week, voltage support comes from two sources while there is only EV voltage support during the winter week due to small PV production as mentioned before. As the EV and PV times don't coincide and the spring scenario doesn't differ from the winter one in terms of peak hours, the focus point will be on the winter week when the loading is higher.

Fig. 8 compares current distribution at selected junction points before and after RPC activation for the winter week. It is interesting to observe how the maximum current at 301 in the case with activated EV reactive power control is lower than the one without (value falls from 408.9 A to 403.9 A). The reason lies in the fact EVs first consume already existing reactive power in the grid and then continues the provide voltage support through extra reactive power consumption. This leads to overall smaller cable loading and energy losses. In addition to lowering current values at peak times, the EVs provide considerable voltage support comparing to the base winter scenario, especially for the end-line nodes, shown in Fig. 9. Minimum voltages for the winter week before and after EV reactive power control activation are presented in Table IV. It is clearly shown how RPC is crucial in peak times as it increases overall voltages and puts the end-line voltages back well within the ±10% limit.

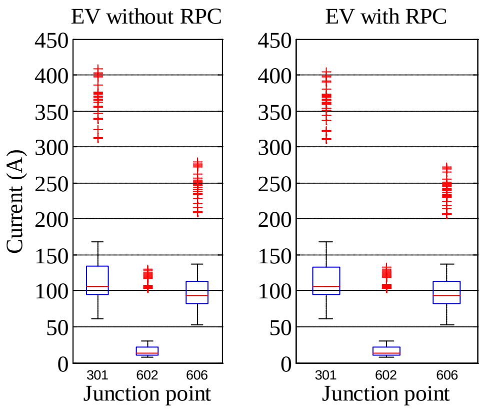

Fig. 8. Current comparison at selected junction points for the winter scenarios with and without EV RPC

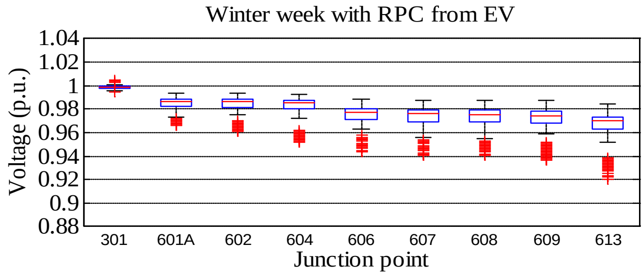

Fig. 9. Voltages at selected junction points after RPC activation from EVs for the winter week

TABLE IV
MINIMUM VOLTAGES AT SELECTED JUNCTION POINTS BEFORE AND AFTER EV RPC ACTIVATION – WINTER WEEK

Node	Minimum voltage without RPC (p.u.)	Minimum voltage with RPC (p.u.)	Relative voltage increase (%)
301	0.9898	0.9947	0.50
601A	0.9475	0.9659	1.94
602	0.9410	0.9607	2.09
604	0.9293	0.9518	2.42
606	0.9219	0.9433	2.32
607	0.9196	0.9411	2.34
608	0.9186	0.9403	2.36
609	0.9142	0.9366	2.45
613	0.8978	0.9205	2.53

D. Results overview

Fig. 10 presents energy flows at the substation level for the presented scenarios. To maintain the figure clarity, active and reactive power for the base scenarios are represented with solid lines, and reactive power when all voltage support is activated with the dashed line. In the case of RPC only from PVs, there would merely be no reactive power consumption in the evening peak hours. Total active and reactive power

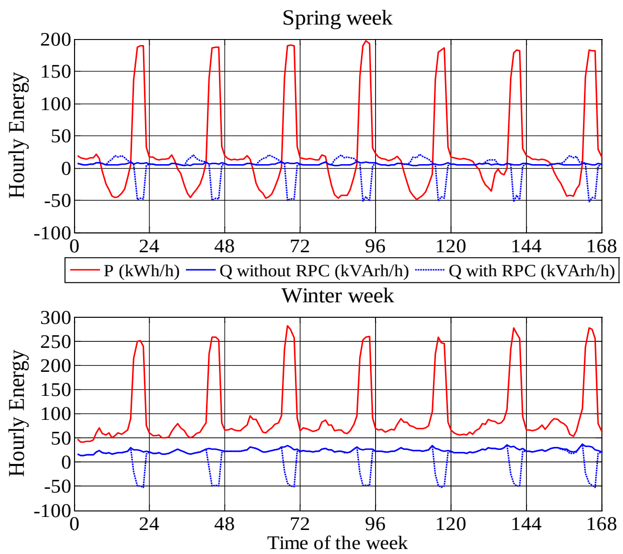

Fig. 10. Power profiles at the substation level for observed weeks

TABLE V
RESULT OVERVIEW FOR PRESENTED SCENARIOS

Scenario	Season	PV RPC	EV RPC	Total absolute active energy (kWh)	Total absolute reactive energy (kVArh)	Active losses (kWh)	Ratio of active losses and total active energy (%)	Ratio of active losses and total apparent energy (%)
1	spring	-	-	7885.4	1007.1	242.4	3.07	3.01
2	winter	-	-	16881.2	4032.3	689.8	4.08	3.95
3	spring	X	-	7889.6	1436.6	245.7	3.12	3.01
4	winter	X	-	16881.2	4032.3	689.6	4.08	3.95
5	spring	X	X	7896.7	2279.5	253.7	3.21	3.07
6	winter	X	X	16753.8	4376.3	677.5	4.04	3.90

refer to values at the substation level at each point of time where positive values mean import and negative values export to the grid.

To address the issue of energy losses due to excessive loading, Table V compares losses in absolute and relative values as well as the ratio of active losses and total apparent energy. It is clear from the table that active losses throughout all spring scenarios do not change significantly and amount to around 3%. Similarly, during the winter scenarios, the losses come to around 4% with maximum deviation up to 12 kWh/h during the day. The ratio of active losses and total apparent energy also changes due to different amounts of reactive energy in the grid. However, these changes are not substantial leading to the conclusion that RPC activation does not influence the losses much even when doubling total reactive energy in the grid. On the contrary, the observed ratio in scenario six is somewhat lower due to consuming already existing reactive power in the network during the peak hours.

IV. CONCLUSION

PV and EV employment will greatly affect modern distribution networks leading to additional requirements concerning voltage support to reduce the negative impacts and increase potential benefits. The case study presented in this work shows that RPC implementation from both PVs and EVs in a real Danish low voltage network positively effects the voltage conditions. Moreover, in a worst case scenario with all EVs charging at the same time, RPC is necessary to maintain the voltages within the allowable technical limits at the end of the lines. Since the voltage support is based on increased consumption of reactive power and consequently increased loading, this paper addressed changes in energy losses and cable loading. It can be concluded that the benefits regarding voltage improvement are greater than the side effects of additional cable loading for this low voltage network where the increase in median current is only 2 A. Furthermore, the energy losses are not notably increased, but are in some cases even somewhat lower due to consumption of already existing reactive power in the network. For the analysed feeder, voltage support in the form of reactive power control is relevant for maintain the voltages within technical limits when integrating larger amount of EVs.

Although not addressed in this work, unbalanced phases might be limiting factor for EV and PV integration since most of them are connected to a single phase. This model will be extended for further research with unbalanced loading and different EV connections to gain insight into network conditions when providing unevenly distributed voltage support between the phases.

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Pub. D. Concurrent provision of frequency regulation and overvoltage support by electric vehicles in a real Danish low voltage network

Concurrent Provision of Frequency Regulation and Overvoltage Support by Electric Vehicles in a Real Danish Low Voltage Network

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***Abstract*—Expected deployment of electric vehicles (EVs) introduces big technical challenges for power system operation, but also offers advantages provided that EVs are not considered merely as passive loads. With the development of Vehicle-to-Grid technology, EVs will be able to provide a number of ancillary services for grid support, e.g. implemented electronic equipment will allow them to exchange reactive power with the grid for voltage regulation while using active power for other services. This paper investigates the concurrent provision of local and system wide services from EVs in a real Danish low voltage network with high penetration of photovoltaic installations (PVs). The main focus is potential reactive power support when EV provision of frequency regulation coincides with PV production. Furthermore, the paper evaluates benefits of overvoltage support and addresses the issue of increased loading. The analysed network has been modelled in Matlab SimPowerSystems and is based on real hourly metered data from a Danish MV/LV substation with numerous households.**

Keywords— distribution network, electric vehicles, frequency regulation, photovoltaic, power system modelling, reactive power control, voltage support

I. Introduction

With conventional generating units being replaced by renewable resources, there is an increased demand for additional ancillary services in order to achieve certain frequency and voltage requirements. Growing number of photovoltaic installations in distribution networks highly influences voltage gradients since the production usually coincides with low residential consumption [1], [2]. Therefore, modern solar inverters typically have the capability of providing reactive power control (RPC) by injecting inductive or capacitive reactive power and decreasing voltage deviations [3]. In addition, electric vehicles (EVs) are a viable alternative to traditional vehicles and should not be considered as merely passive loads since development of smart grid enabling technologies and Vehicle-to-Grid enables them to provide numerous services [4]-[7]. Considering they are typically plugged-in 90% of the time, EVs can contribute to grid support by providing various ancillary services such as frequency [8] and voltage regulation [9]. However, when providing such services, it is necessary to analyse the grid impact, especially in critical situations when the network is already stressed with high penetration of distributed generation, as triggering the need for other services is not desirable [10]. Since EV charging infrastructure enables provision of reactive power for voltage support without affecting battery state-of-charge [11], it can be used simultaneously with other services to mitigate their adverse effects.

This paper analyses the potential of reactive power control from EVs, similar to the one of PV inverters, in a real Danish low voltage distribution network with focus on overvoltages caused by providing frequency regulation in times of high PV production. Furthermore, relevant network parameters such as current and energy losses are evaluated to provide insight into RPC benefits and drawbacks. The rest of the paper develops as follows: Section II reports the used methodology and the simulation model of the observed network, Section III presents and discusses conducted scenarios with their results, and Section IV concludes the potential benefits and drawback of implementing this concept.

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II. Methodology

A. Low voltage network

The analysed real network has been modelled in Matlab SimPowerSystems and illustrates a typical Danish semi-urban low voltage network located in eastern Denmark. This paragraph will briefly describe the network topography, further network details can be found in [9]. The observed 0.42 kV feeder is radially run and connected to 10 kV medium voltage network through a typical Danish 400 kVA distribution transformer with three-phase short circuit power of 20 MVA. It contains approximately 680 m of cables in 13 line segments and 43 households in total which are categorized in two groups depending on their location and consumption characteristics. There are three additional feeders under the same transformer

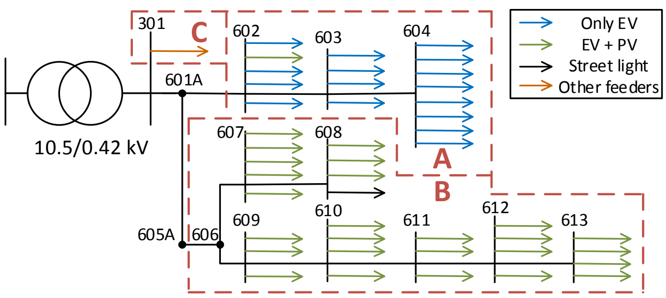

Fig. 1. Analysed low voltage network – single line diagram

substation which are represented as a single aggregated household due to lack of data for individual house. Moreover, it is assumed that the voltage at the transformer low-voltage side is kept at 1 p.u.

The single line diagram for the described network is depicted in Fig. 1. All households marked with green contain PV installations in addition to electric vehicles. These are mainly the households located in the Græsmarken Street, i.e. area B. Besides them, there is a street light connected to the grid at node 608 which is marked black. On the other side, area A represents households located in the Hørmarken Street which do not contain PV installations but only electric vehicles. The rest of the consumption and PV production located in the three other feeders under the same transformer is marked brown and highlighted as area C.

B. Household consumption profiles

As already mentioned, the households are divided in two categories: (1) residential houses in Hørmarken Street with lower consumption during the heating season due to implemented district heating, and (2) residential houses in Græsmarken Street which have heat pumps and consequently higher consumption during the heating period.Individual consumption profiles are based on real hourly metered data for a period of one year (from March 2012 to March 2013). Even though the modelled network is three-phased, there is no insight into individual phase fractions for the measured power flows. Therefore, it is assumed that the loading is equally distributed and symmetrically balanced between the phases. Additionally, the measured data contain only active power component, so a fixed power factor (equal to 0.95 inductive) has been assumed as a reference value for all households.

This paper focuses on overvoltage support in steady-state, so the most interesting period for the analysis is a spring week in mid-May. This week has been chosen due to low consumption and high PV production resulting in the highest net power flow from the feeder to the MV grid in the given year. Fig. 2shows consumption pattern for the observed spring week distinguishing feeder consumption and total transformer consumption, as well as the average daily house profile calculated as a mean of all consumption values at specific hour, separately for Hørmarken and for Græsmarken.

C. Photovoltaic production profiles

Photovoltaic installations in the observed feeder are almost entirely located in Græsmarken and are all connected through single phase inverters. However, the connection point of each installation to the individual phase is not known since there is no specific DSO regulation but it depends on the accredited electrician's technical choice. Therefore, the PVs in the model have been randomly connected taking into consideration that overall production per phase is approximately the same. In addition, one single production representing the cumulated PV production from other three feeders has been added to the low voltage side of the transformer and has been evenly distributed between the phases.

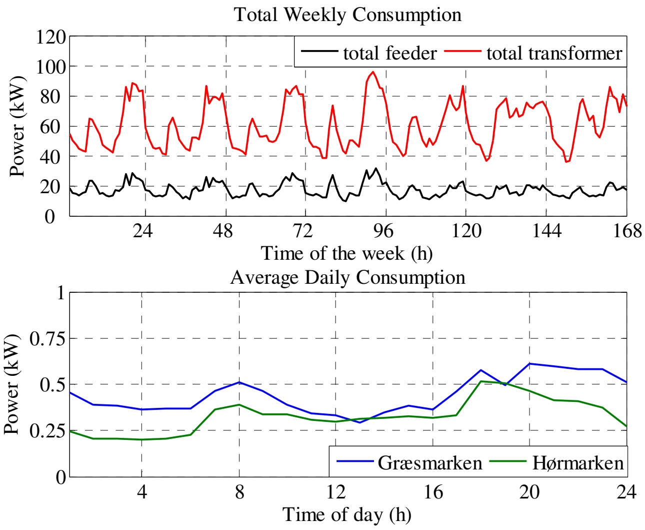

Fig. 2. Total weekly and average daily consumption for the observed week

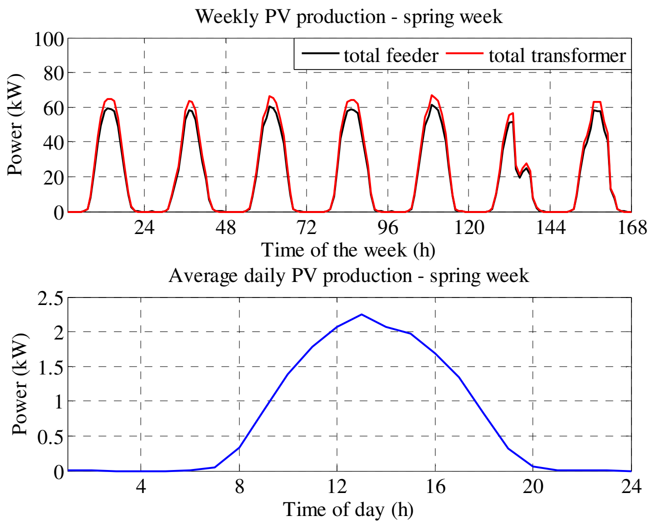

Fig. 3. Total weekly and average daily PV production for the observed week

The modelled feeder contains 27 PV installations in total: 24 installations with peak power P=2.96 kWp and 3 upgraded installations with P=4.07 kWp connected respectively through 3.6 kWp and 5.4 kWp inverters. As well as the consumption profiles, the production profiles are based on hourly metered data for individual household. Fig. 3 shows total production for the observed spring week at the transformer and feeder level as well as the typical bell-curved profile for a single PV. A comparison of total weekly production and average daily production per household is given in Table I for the observed week. The average daily production is calculated alike the average daily consumption on hourly basis and has been summed up for the 24 hour period. The production under the rest of the feeders is quite low as seen by comparing the values in the table, so it can be assumed that only few installations are located in that part of the network. Besides the PV production, Table I also compares EV active power injection values which are explained in following subchapter.

TABLE I. OVERVIEW OF ACTIVE POWER INJECTION FOR THE OBSERVED SPRING WEEK

	Total weekly on transformer level (kWh)	Total weekly on feeder level (kWh)	Average daily per unit (kWh)
PV	3403.7	3096.2	17.01
EV	4204.2	4204.2	100.1

D. Electric vehicles

Every household is equipped with an electric vehicle connected to a random single phase different from the PV connection point. The overall EV distribution per phase is balanced in the feeder. All EVs have the same "dumb-charging" pattern which has been taken from Test-en-EV program that collected real charging data from 184 vehicles in Denmark [16]. Most of the tested EVs had 16 kWh battery resulting in average charging session of 14.3 kWh with average charging time of 5 h corresponding to approximately 90% of the full battery. Implemented charging process starts at 18:00 with 3 kW in the first hour, 3.7 kW in the following three hours and ending with 0.2 kW in the last hour. It mostly coincides with evening peak hours meaning that the vehicles are able to provide ancillary services, e.g. frequency control, at other times.

Because a single EV does not have adequate capacity to participate in energy markets, aggregators are required to combine the capacity of many. The aggregator then bids in the appropriate market and dispatches the signal to EVs requiring certain amount of power [12]. Conducted scenarios assume that the TSO requires maximum active power injection from all EVs through the aggregator in order to maintain the frequency stability. This paper analyses the worst case scenario: when providing such a service takes place in times of high PV production and already high voltages. The active power injection for frequency regulation starts at 12:00 and has the same pattern as "dumb-charging", just the opposite direction bearing in mind that 90% of the battery is discharged while the remaining 10% is left for emergency situations. Additional variation for the observed week has been conducted for comparison. It differs only in the time of EV active power injection which is moved to the night period starting from midnight as shown in Fig. 4. The charging period in both analyses is out of scope for this analysis since it causes undervoltage issues.

E. Reactive power control

Single phase PV inverters are equipped with a reactive power control (RPC) capability related to voltage and produced active power. Voltage limits, i.e. Umin=0.9 p.u. and Umax=1.1 p.u, are chosen according to the Danish technical regulation for generation facilities with rated current 16 A per phase or lower [13]. Considering that the regulation does not specify all RPC requirements, the controller has been modified according to the Italian technical standards [14]. The main objective of this control is lowering the voltage by injecting inductive reactive power whenever the active power injection is high. Since both Italy and part of Denmark belong to the same synchronous zone, it is reasonable to expect that future Danish requirements

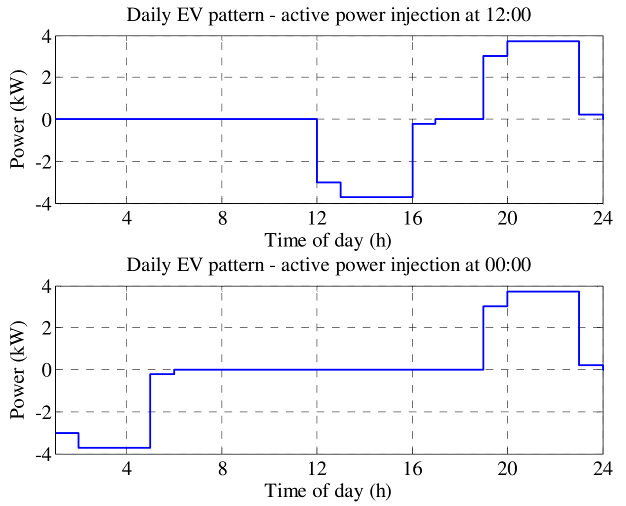

Fig. 4. Daily EV patterns differing in active power injection, i.e. frequency regulation time for the observed week

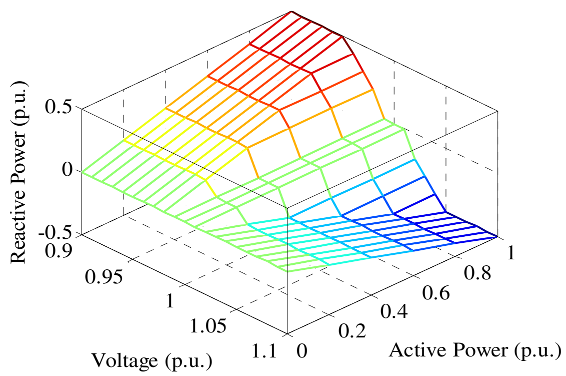

Fig. 5. Reactive Power Control capability for the PV inverters and EV chargers while injecting active power to the grid

will correspond to other European regulations. The implemented RPC function used for these studies is presented in Fig. 5 and has already been used in [9] and [15]. The green range acts as a certain dead band where the controller is active but provides no reactive power, the blue area represents injection of up to 0.5 p.u. inductive reactive power in overvoltage conditions while likewise the red area represents injection of up to 0.5. p.u. capacitive reactive power in undervoltage conditions.

Since V2G in principle allows both charge/discharge control and inductive/capacitive reactive power control, the described RPC capability was extended to EV chargers assuming they consist of PWM converters. The simplified control scheme for the developed model is given in Fig. 7. As seen from the picture, the controller has three main inputs: active power, voltage and phase shift, while the output is the reference current. Depending on the first two inputs, the controller sets the reactive power according to the described function shown in Fig. 5 or to zero if the RPC activation parameter is off. Afterwards, constant phase shift depending on the device's connection point is added to the apparent power from which the reference current is then calculated. This current is used as the set point for the EV charger.

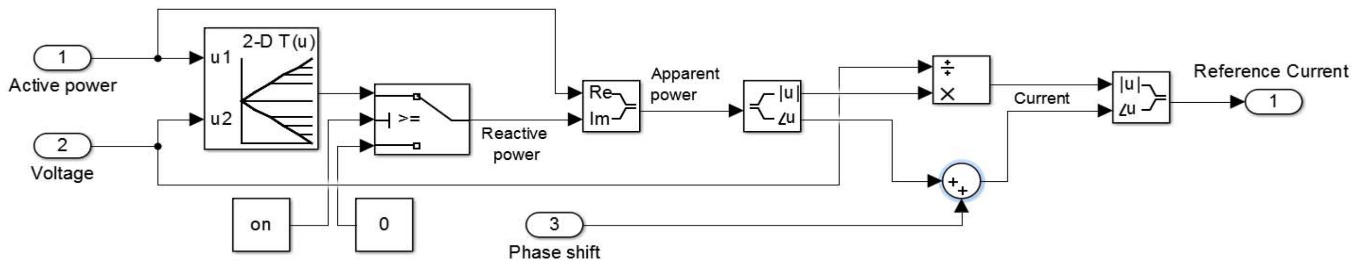

Fig. 7. Simplified Reactive Power Control scheme for PV inverters and EV chargers

F. *Scenarios*

This paper compares relevant network parameters such as voltage values, currents and energy losses between different scenarios. Several steady-state analyses listed in Table II have been carried out with results presented in the following section.

All scenarios were conducted in the spring week, but differ with regard to RPC activation as well as to the time of frequency regulation, i.e. active power injection. It is important to note that RPC from PVs does not change through the scenarios, i.e. it is always turned on. Therefore, PV inverters are always contributing to voltage regulation by injecting inductive reactive power whenever the active power production differs from zero. This can be considered as a base setup to which RPC by EVs has been added and analysed.

TABLE II. SUMMARIZED DETAILS FOR DIFFERENT CONDUCTED SCENARIOS

Scenario	Season	Start time of EV active power injection (frequency regulation)	RPC by PVs	RPC by EVs
1	Spring	00:00	On	Off
2	Spring	00:00	On	On
3	Spring	12:00	On	Off
4	Spring	12:00	On	On

III. RESULTS

Since the system is assumed to be balanced, all results are reported using the single phase equivalent. Voltage and current results are depicted via boxplots – a statistical method which divides data in quartiles and indicates dispersion as well as outliers within ±1.5 of extreme quartiles (50% of data are located within the blue box, upper and lower 25% are located within the black lines also knows as "whiskers" and outliers are marked with red plus signs). As mentioned before, the results focus on injection periods and disregard charging periods so presented graphs do not include undervoltages occurring in peak periods due to additional load, but instead depict the state as if there were no EVs at those periods for the sake of statistical evaluation.

A. *Scenarios with active power injection at 00:00 (scenarios #1 and #2)*

First two scenarios describe the situation when EVs are providing frequency regulation by injecting active power at midnight. The difference between the scenarios is in RPC activation; more precisely, while in the first scenario the RPC

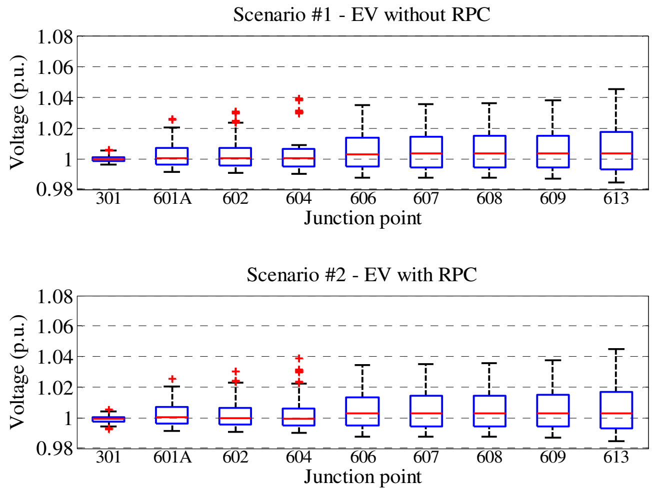

Fig. 6. Voltage comparison for selected junction points in case of EVs injecting active power at 00:00 with and without RPC

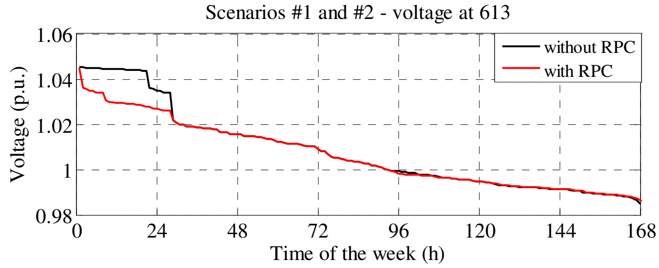

Fig. 8. Voltage magnitude profile at junction point 613 in case of EVs injecting active power at 00:00 with and without RPC

is turned off, in the second one it is activated and provides voltage support during 5 hours of active power injection.

The results for conducted simulations are given in Fig. 6 where node voltage comparison before and after RPC activation is presented. As it can be seen, maximum voltages along the feeder do not change notably after the RPC activation. This was expected as extremes occur in time of high PV production when there is no voltage support from EVs since they provide frequency regulation during the night. However, even though the maximum value of 1.0453 p.u. is not lowered, RPC lowers the deviation dispersion which can especially be seen at node 604 where most of the outliers have been moved closer to nominal voltage. Moreover, Fig. 8 shows voltage magnitude profile at the end of the line with and without RPC. It can easily be noticed that voltages are lower with RPC. For instance, there was 21 hour in a week with voltages above 1.04 p.u. in case of no RPC while this number has been lowered to only 1 hour when RPC was added.

B. Scenarios with active power injection at 12:00 (scenarios #3 and #4)

After studying active power injection during the night, the analysis in case of EVs injecting power at midday was conducted. This can be considered as the worst-case scenario where EV active power injection coincides with PV production causing even higher voltages in the network than already occurring ones.

Obtained voltage results have been reported in Fig. 9 and summarized in Table III. Fig. 9 depicts a three-dimensional representation of the voltage magnitude along the feeder. The x-asis represents time of the week, the y-axis represents the junction points, i.e. feeder nodes, while the voltage values are represented on the z-axis. For an illustration, if one would look at the xz-plane, the voltage profile for a specific feeder node throughout the whole week would be seen. On the other hand, if one would look at the yz-plane, a voltage profile for the whole feeder at a specific point of time could be observed. It is obvious from the figure there are no overvoltages in the observed feeder since the upper technical limit is 1.1 p.u. while the maximum occurring voltage is around 1.06 p.u. in both scenarios. Nonetheless, it is shown that RPC lowers the overall voltages, especially at the end of the feeder. By analysing the results from previous two scenarios, 1.04 p.u. has been taken as a certain voltage threshold, so all the voltages above this limit will be referred to as overvoltages.

Table IV compares number of hours for which the overvoltages appear at each node before and after the RPC activation. For most of the nodes (except for the node 613) the overvoltage hours have been reduced to the order of several hours and for node 604 even to zero. The situation for node 613 is somewhat different and can be seen in Fig. 10 more closely. It is obvious that even though most of the overvoltages are still over 1.04 p.u., they have mainly been lowered, e.g. there are only 6 hours of voltages above 1.05 comparing to 26 hours before the RPC activation.

Keeping in mind that voltage benefits are at the expense of increased cable loading, current analysis has been carried out and presented in Fig. 11 for four specific junction points: transformer low voltage side (node 301), the beginning of the observed feeder (node 601A) and the beginning of each group of households (nodes 602 and 606). First of all, it is important to note how the current at the feeder beginning is higher than the current at the transformer substation level. The reason lies in three other feeders which consume part of the active power injected from EVs. Secondly, the current increase after RPC activation is evident at all nodes due to rise of total reactive power. The active power injection from all EVs is quite high in addition to already existing PV production. Hence, the injected inductive reactive power is high as well in order to maintain the voltages close to 1 p.u. resulting in maximum current increase of almost 38 A at the beginning of the feeder (node 601A) and higher energy losses as reported later on.

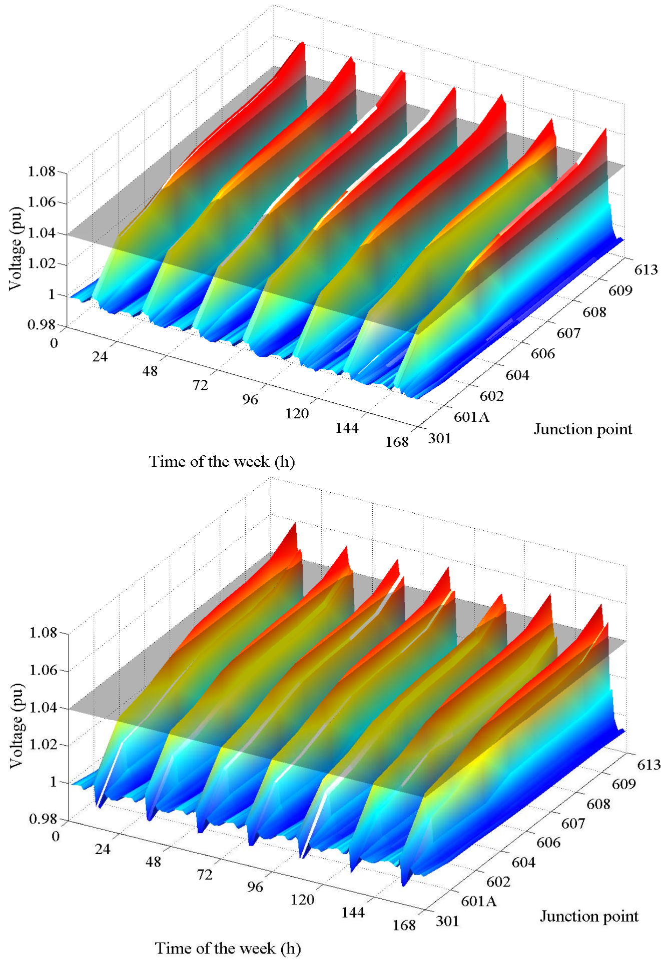

Fig. 9. Voltage magnitude profile along the feeder in case of EVs injecting active power at 12:00 without RPC (upper inset) and with RPC (lower inset)

TABLE III. MAXIMUM VOLTAGES AT SELECTED JUNCTION POINTS BEFORE AND AFTER EV RPC ACTIVATION – SCENARIOS #3 AND #

Node	Maximum voltage without RPC (p.u.)	Maximum voltage with RPC (p.u.)	Relative voltage decrease (%)
301	1.0060	1.0046	0.14
601A	1.0313	1.0289	0.23
602	1.0359	1.0327	0.32
606	1.0489	1.0456	0.31
613	1.0641	1.0597	0.42

TABLE IV. NUMBER OF OVERVOLTAGE HOURS BEFORE AND AFTER EV RPC ACTIVATION – SCENARIOS #3 AND #4

Node	Overvoltage time without RPC	Overvoltage time with RPC
604	22 h	0 h
606	27 h	6 h
607	27 h	6 h
608	27 h	6 h
609	28 h	6 h
613	29 h	26

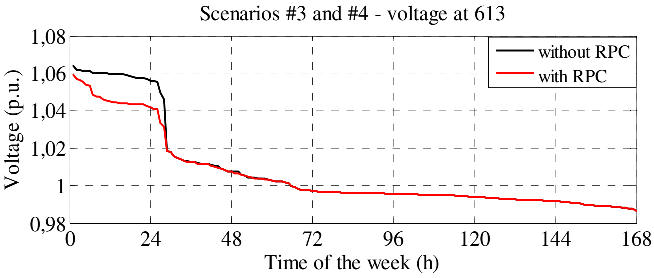

Fig. 10. Voltage magnitude profile at junction point 613 in case of EVs injecting active power at 12:00 with and without RPC

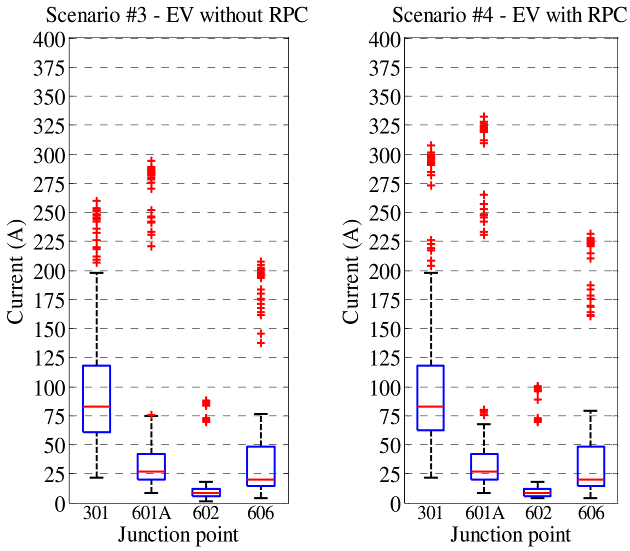

Fig. 11. Current comparison for selected junction points in case of EVs injecting active power at 12:00 with and without RPC

C. Result overview

An overview of all presented scenarios is given in Table V which, besides total absolute active and reactive energy flow without distinguishability of power direction, also reports maximum occurring current and energy losses. Maximum voltage values have not been included since they have been presented before. As it has already been described, the maximum voltage is in neither scenario above the technical requirements which is due to the network topology, more precisely to the relatively long feeder.

For addressing maximum current increase throughout the different scenarios, relative current changes were calculated from reported values. Obtained increase amounted to almost 29 A and 38 A, i.e. 14% and 13% when activating RPC in scenarios two and four respectively, which is considered to be a high rise. However, even though the total reactive energy has been increased by nearly 40%, the ratio of energy losses and total apparent energy does not change substantially. Comparing the first two scenarios where frequency regulation starts at 00:00, the difference equals to only 0.19% with maximum deviation of 1.77 kWh/h while in the case of scenarios three and four, when the provision starts at 12:00, this difference reaches 0.37% with maximum deviation of 3.2 kWh/h.

IV. Conclusion

EV integration will highly influence future distribution networks, especially when providing ancillary services to the transmission operator which has no insight in the local network itself. Therefore, when providing such services for the TSO, it is important to maintain voltage requirements in order not to trigger additional ancillary services that the distribution system operator would then need to provide.

This paper presents a case study where concurrent provision of frequency regulation and reactive power control by the EVs was analysed in a real Danish distribution network. Focusing on overvoltage conditions, especially in times when EV active power injection coincides with the PV production, several network parameters such as voltages and energy losses were compared before and after the RPC activation.

The analysis shows that even though the voltages in the network never exceed the upper +10% Un limit due to relatively long feeders, reactive power control is preferable as it provides smaller voltage deviations. Due to extra reactive power in the grid which reaches up to 40% increase, excessive cable loading and consequent additional energy losses have also been addressed. It has been noticed that the maximum current had substantially increased with relative change up to 14% comparing to the scenarios without RPC. Nonetheless, cables and the transformer are not overloaded and relative energy losses have increased only 0.37% in total leading to conclusion that voltage benefits from RPC activation are greater that the influence on energy losses in the observed distribution network.

Furthermore, presented results assume that the voltage at the transformer low-voltage side is kept at 1 p.u. which may not be the case for the whole week. Bearing that in mind and the fact that few PVs have been upgraded to higher power indicating a trend that could expand to other households, it is desirable and maybe even necessary to implement RPC for maintaining the voltages within technical limits.

TABLE V Result overview for presented scenarios

Case	Injection period	RPC by EVs	Maximum current at node 601A (A)	Total absolute active energy (kWh)	Total absolute reactive energy (kVArh)	Active losses (kWh)	Apparent losses (kVAh)	Ratio of active losses and total apparent energy (%)	Ratio of apparent losses and total apparent energy (%)
1	00:00	Off	204.11	8640.4	3597.2	293.87	392.95	3.01	4.02
2	00:00	On	232.75	8668.4	5005.4	328.07	437.07	3.16	4.21
3	12:00	Off	294.36	11032.0	4026.1	420.54	551.42	3.51	4.60
4	12:00	On	332.20	11075.0	5637.8	485.02	632.92	3.81	4.97

Although not undertaken in this work, unbalanced phases might also be the limiting factor since most of the PVs and EVs are single-phase connected. Overvoltages appearing on the specific single phase could cause even bigger problems in the network, especially if the EV frequency regulation was provided on the same phase. Therefore, this model will be extended to single phase analysis for further research concerning unbalanced production and to gain insight into network conditions when providing unevenly distributed ancillary services from EVs.

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Phase-wise enhanced voltage support from electric vehicles in a Danish low-voltage distribution grid

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ABSTRACT

High deployment of electric vehicles (EVs) imposes great challenges for the distribution grids, especially in unbalanced systems with notable voltage variations which detrimentally affect security of supply. On the other hand, with development of Vehicle-to-Grid technology, EVs may be able to provide numerous services for grid support, e.g., voltage control. Implemented electronic equipment will allow them to exchange reactive power for autonomous voltage support without communicating with the distribution system operator or influencing the available active power for primary transportation function. This paper proposes a voltage dependent EV reactive power control and quantifies its impact on a real Danish low-voltage grid. The observed network is a heavily unbalanced three-phase four-wire grid modeled in Matlab SimPowerSystems based on real hourly measurement data. Simulations are performed in order to evaluate phase-to-neutral voltage support benefits as well as to address neutral-to-ground values, active power losses and the unbalances at the same time. The analysis shows that reactive power support both raises minimum phase-to-neutral voltage magnitudes and improves voltage dispersion while the energy losses are not notably increased. Further on, since the control is voltage dependent, provided reactive power is unequal among the phases leading to greater support on heavily loaded phases and decreased unbalances caused by residential consumption. Hence, implementation of such a phase-wise enhanced voltage support could defer the need for grid reinforcement in case of large EV penetration rates, especially in highly unbalanced networks.

1. Introduction

Distribution system operators (DSOs) have historically designed and operated their networks in order to follow a predicted demand with single-direction power flow only. Nowadays, due to increased share of renewable energy resources, DSOs are confronted with changes in the low-voltage grid operation [1]. Additionaly, since the market share of electric vehicles (EVs) is expected to grow significantly in the following years, even greater system complexity is imposed [2,3]. Danish Energy Association predicts 47,000 EVs in Denmark by 2020 in a moderate penetration scenario [4] meaning that distribution networks will have to cope with great increase in consumption and overall voltage degradation, especially in unbalanced systems where voltage quality is already decreased.

Unlike in other European countries, the three-phase connection is not reserved only for industrial consumers in Denmark, but it is also available for residential customers. Distribution system operators experience high unbalances in the semi-urban areas where more loads are eventually connected to phase *a* due to the lack of regulation for per phase load connection [5]. Uncontrolled EV charging in such grids may result in violation of the minimum voltage boundary followed by the need for grid reinforcement. As an economic alternative, different EV charging strategies can be used for supporting the grid as well as providing various flexibility services.

An extensive amount of research has been made on coordinated EV charging proving that such concept can be used for lowering the impact on the power system [6] or providing ancillary services such as frequency control [7]. Most of these strategies require an aggregator to coordinate larger amount of EVs and, if possible, offer their services to the power system operators. However, high local EV concentrations may occur before significant penetration rates occur on the higher level. Taking into account that residential EV charging highly impacts the power profile, voltage magnitudes and voltage unbalances, different approaches are considered in order to alleviate these adverse effects and make the grid compliant with existing standards. In order to integrate electric vehicles in the distribution

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grid, both centralized and decentralized charging strategies have been explored in the literature. Comparison of such two charging strategies has been presented in [8,9]. Centralized algorithm leads to the least cost solution and is easily extended to a hierarchical scheme, but requires great communication infrastructure for information exchange. On the other hand, decentralized control provides similar results to the centralized one, both in terms of cost and robustness against forecast errors. This would seem to favor decentralized control since it is based on local measurements and does not require additional communication infrastructure. However, the drawback is charging simultaneity since all controllers would respond instantaneously to the measurements which could eventually lead to instability in some cases [10].

It is shown across a variety of studies that centralized EV control reduces losses, improves voltage stability and performs peak shaving or congestion control [11–14]. In addition to linear optimization methods, model predictive control is investigated for scheduling EV charging with various network constraints [15]. On the contrary, decentralized voltage dependent charging strategy which requires only local voltage measurement is discussed in [16]. EV charging power can also be modulated in order to compensate for the voltage unbalances [17], but such an autonomous procedure is possible only for three-phase charging since the single-phase charger has solely the voltage measurement of the phase to which the EV is connected and therefore, does not have any information on the voltage unbalances.

The impact of controlled EV charging on voltage profiles and unbalances has been investigated mainly by modulating the active power which influences the time needed for full charge and consequently, the user comfort. On the contrary, reactive power control (RPC) from electric vehicles has scarcely been discussed in the literature. Such reactive power compensation can be used for grid support and mitigating induced voltage issues, both while vehicles are charging, and discharging in Vehicle-to-Grid mode [18]. Balancing the phases by reactive power provision has been discussed in [19] where centralized control is used for scheduling the vehicles located on different phases, but this approach requires additional communication infrastructure. Decentralized approach, more precisely, autonomous reactive power control based on droop control has been investigated in [20–22], but only in the case of a balanced system. The reactive power support in an unbalanced network has been investigated in [23]. Despite showing that capacitive load behavior in EV chargers has beneficial impact on the voltage, this approach assumes a fixed power factor for all vehicles regardless of the their connection phase which may not be good enough for high EV penetration rates in case of highly unbalanced networks.

1.1. Objectives

To the authors' knowledge, phase-wise enhanced voltage support from electric vehicles has not been extensively discussed in the literature so far. Not only does such a control provide voltage support while vehicles are charging, it also provides unequal reactive power on different phases leading to greater support on highly loaded phases and partial mitigation of unbalances caused by other loads. Hence, this paper investigates the impact of voltage dependent EV reactive power control on a residential low-voltage network by conducting unbalanced three-phase load flow, and evaluating voltage deviations and several unbalance factors. The modeled network represents a typical Danish semi-urban feeder with high penetration of photovoltaic installations where hourly consumption and production data are available for individual units. Furthermore, the paper compares the phase-to-neutral along with neutral-to-ground voltage benefits at the expense of potential increased currents and power losses aiming to assess the grid impact as well as the need for including such a control in future grid compliance regulations to allow better EV integration.

This paper is organized as follows. Section 2 presents the unbalance indicators used for evaluating the results, and briefly recalls the standards regarding the voltage power quality as the main motivation for presented voltage support. In Section 3, the applied methodology has been presented, whereas the test case with the description of conducted scenarios is given in Section 4. Finally, the results are discussed in Section 5 followed by the conclusion in Section 6.

2. Unbalance indicators

Contrary to other disturbances in the power system for which the performance is evident for the ordinary customers, unbalance belongs to those disturbances whose perceptible effects are produced in the long run. Unsymmetrical consumption and production lead to voltage and current unbalances which imply greater power losses, interference with the protection systems, components' performance degradation and overheating possibly to the point-of-burnout. To calculate the unbalanced voltages and currents in three-phase systems, symmetrical components are generally employed. The voltage unbalance can be decomposed into a direct sequence voltage, an inverse sequence voltage and a zero sequence voltage, with the relationship between the symmetrical sequence systems and the initial system as follows:

$$\begin{bmatrix} U_{direct} \\ U_{inverse} \\ U_{zero} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{1}$$

where $\alpha = e^{j2\pi/3}$. The same definition can be applied for defining the current direct, inverse and zero component.

For ensuring that electric appliances are operated in a safe manner, the European standard EN50160 [24] defines acceptable limits for several grid parameters. More precisely, the standard defines the limits for rms phase-to-neutral voltage magnitude ($|U_{pn}|$) and the voltage unbalance factor (VUF) as follows:

$$0.9U_{nom} \leq |U_{pn}| \leq 1.1U_{nom} \tag{2}$$

$$VUF \leq 2\%, \tag{3}$$

for >95% of all weekly 10 min intervals, and

$$0.85U_{nom} \leq |U_{pn}| \leq 0.9U_{nom}, \tag{4}$$

for <5% of all weekly 10 min intervals. The inverse sequence VUF is defined as the ratio between the inverse and direct component as follows:

$$VUF_{-}[\%] = \frac{|U_{inverse}|}{|U_{direct}|} \times 100. \tag{5}$$

There are many voltage and current unbalance definitions for three-phase three-wire systems which assume that zero sequence current is negligible since it cannot flow through three-wire systems. However, the zero sequence unbalance has significant impact in the three-phase four-wire systems which are common in the distribution systems, and should be taken into consideration when assessing the unbalances in such cases. So, the zero sequence VUF can be defined as the ratio between the zero and the direct component as follows:

$$VUF_0[\%] = \frac{|U_{zero}|}{|U_{direct}|} \times 100. \tag{6}$$

Current unbalance factors CUF_{-} and CUF_0 are defined analogously to VUF definitions shown in Eqs. (5) and (6). In order to combine the impact of both VUF_{-} as well as VUF_0, i.e. to combine

Eqs. (5) and (6), [25] proposed a new root mean square VUF defined as:

$$VUF_{rms}[\%] = \frac{\sqrt{|U_{zero}|^2 + |U_{inverse}|^2}}{|U_{direct}|} \times 100, \quad (7)$$

which was found as the best fitted variable for assessing unbalance consequences, and can be applicable both for three-wire and four-wire systems. Hence, the authors will use all three definitions to evaluate the impact of the proposed control on the voltage unbalances.

3. Methodology

With increasing penetration of small scale energy resources on the distribution level, the net impact of many generators reaches a level where the power quality is significantly affected. Low voltage distribution grids typically have the X/R ratio between 0.2 and 2 [23] meaning that the reactive power contribution to voltage variations should not be ignored. For comparison, [26] reports typical X/R ratio to be between 6 and 9 for high voltage grids. Generally, as illustrated in Fig. 1 and seen in Eq. (8), offsetting the reactive current I_i from the voltage source with U_1 has an impact on the voltage magnitude U_2 at the end of the line with the impedance ($R + jX$).

$$| U_2 |= \sqrt{| U_1 |^2 - | I_i R + I_r X |^2} - | I_r R | + | I_i X | \quad (8)$$

Nowadays, there are already commercially available PV inverters which can modulate the power factor and provide inductive reactive power by using excess PV inverter capacity, which is even requested by some standards [27,28]. Similarly, the principle can be applied to electric vehicles which are equipped with advanced power electronics [29], in order to mitigate the induced voltage problems.

3.1. Voltage enhanced EV reactive power control

As EVs are big loads compared to other residential loads, if they do not provide support to the grid, the DSO will be forced to employ additional units for ensuring the power quality in case of high EV penetrations resulting in the overall higher cost for the society. The EV 4-quadrant converter can be enabled to exchange the reactive power with the grid and provide voltage support. As seen in Fig. 2, the nominal converter size S_{conv} and the EV active power (P_{EV}) determine the reactive power bounds ($\pm Q_{reg}$) within which the reactive power can be modulated (Q^*). The complex power at the point of common connection is then defined by S_{PCC}.

Fig. 2(a) presents the constant power factor concept which has widely been investigated for PVs and somewhat for the EVs [23], whereas Fig. 2(b) presents the proposed enhanced voltage support with a dynamical reactive power set point. It can be seen that the proposed enhanced reactive power support has a wider operational range since the reactive power is dynamically calculated as a function of consumed active power as well as the voltage at the EV connection point, i.e., the power factor is no longer fixed but can be dynamically changed during the operation, and can be either inductive or capacitive depending on the grid status. Such reactive

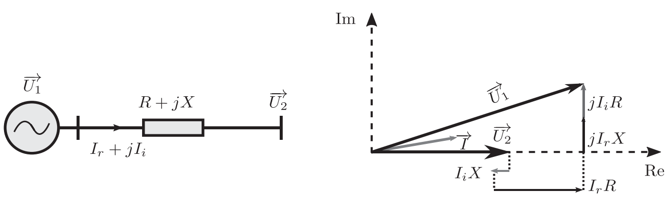

Fig. 1. Impact of active and reactive power on the voltage magnitude.

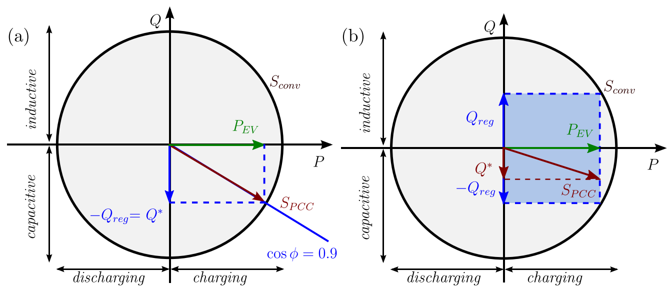

Fig. 2. 4-Quadrant EV converter operating scheme while charging for (a) constant power factor concept, and (b) proposed voltage enhanced support with dynamic power factor.

power control is autonomous with no need for external communication since an on-board controller monitors the voltage conditions during the charging process and compensates the voltage deviations by calculating the necessary reactive power. The control can adjust the EV power factor according to the local phase-to-neutral voltage measurements, instantaneous active power and predefined droop control. Not only does the proposed control mitigate the low-voltages induced by the EVs themselves, it also provides support in critical peak hours when other resources, e.g. PVs, are not active and cannot provide any support. In case of the EV charging period coinciding with other local renewable resources which inject power back to the grid leading to increased voltages even with the high EV load, the vehicle will provide inductive reactive power support potentially allowing more renewable resources to be connected. The proposed control can be used for vehicles whilst charging, but can also be expanded to the discharging period if the vehicles have V2G capability. Moreover, since the inverter is sized to provide reactive power additionally to the active power charging rate, there is no need for prioritizing between them, so the proposed control provides voltage support without affecting the state of charge, and consequently the user comfort and primary transportation purpose.

Implemented droop control, which is a function of consumed active power and the voltage at the EV connection point, can be seen in Fig. 3. Voltage limits have been set according to the Danish technical regulation for generation facilities with rated current 16 A per phase or lower [30]. Hence, the maximum capacitive or inductive reactive power provision occurs at 0.9 and 1.1 p.u. respectively. Considering that this regulation does not specify all RPC requirements, the control has been modified according to the Italian technical standards [27] since both countries belong to the same synchronous region and therefore harmonization of regulations is expected in the future. However, the dead-band where the controller is active but provides no reactive power has been

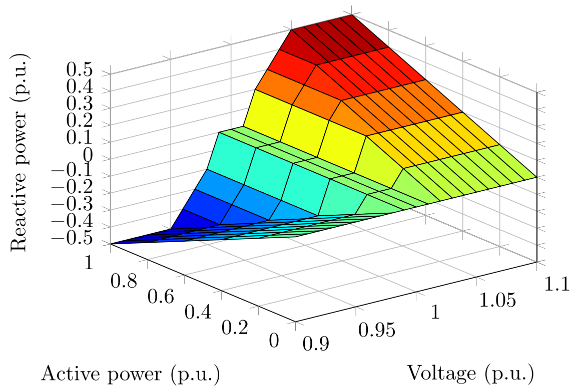

Fig. 3. Reactive power control capability of the EV converter.

arbitrarily chosen and set to ±0.01 p.u. The reactive power limits are assumed to be ±0.5 p.u. which equals to ±1.85 kVAr and corresponds to $\cos\phi = 0.9$ (*ind.*/*cap.*). For comparison, commercially available PV inverters from SMA Solar Technology have the possibility to modulate the reactive power up to $\cos\phi = 0.8$ (*ind.*/*cap.*). Remaining RPC droop values have been obtained by linear interpolation.

Similar droop control has been investigated in [21,22], but this controller was based on the three-phase voltage measurements as the considered system was balanced. This paper proposes an EV reactive power control dependent on the single phase voltage-to-neutral measurements which implies the support to more loaded phases, as well as partial mitigation of voltage unbalances caused by other units in the grid. In addition, since the neutral conductor is not grounded at the residential level and the control is based on voltage-to-neutral measurements, the proposed controller is influenced by the floating neutral point. Moreover, as reported in [31], a kick-back effect has been observed for larger amount of demand response units reacting to the same input signal due to their synchronous response, so a random term was introduced to diversify the units' behavior. Hence, short random delays have been implemented in the proposed control to represent different response times and in order for the EV controllers not to all react at the same time, which partially mitigates the short-term synchronization instability for high EV penetrations. This way the proposed controller remains a cheap and simple solution which can be implemented in all contemporary EV charging stations without the need for additional communication infrastructure for unit coordination.

4. Test case

The analyzed 400 V feeder is a real semi-urban low-voltage feeder located in Zealand, Denmark, and modeled based on the information provided by the Danish DSO, a partner in the Nikola project [32]. This feeder is radially run and connected to 10 kV medium voltage network through a 400 kVA distribution transformer whose secondary star point winding is directly grounded. As this is the only feeding point of the grid, the voltage source is assumed to be a swing generator with three-phase short circuit power of 10 MVA. In addition, it is assumed that the transformer's high voltage side is kept at 1 p.u. so the ±10% U_n is completely available for the LV regulation. However, this may not be the case if part of the range is reserved for MV regulation which could impose additional need for voltage support.

As seen in Fig. 4, the 43 residential loads are three-phase grid connected through 10 nodes ($p \in \{a, b, c\}$) with the common neutral conductor (n) grounded only at the transformer substation. The nominal phase-to-neutral voltage U_n equals to 230 V. Depending on their location and consumption characteristics, the loads can be categorized in two groups: (1) Hørmarken indicated as area A, and (2) Græsmarken indicated as area B. The peculiarities of each group will be described later on. The feeder is composed of 13 line segments, all of the same type: *Al PEX* $4 \times 150\,\text{mm}^2$ with $R = 0.207\,\Omega/\text{km}$ and $X = 0.078\,\Omega/\text{km}$ ($X/R = 0.37$), which corresponds to typical low-voltage grid parameters, e.g., similar to the ones of the CIGRE European low-voltage benchmark network [26]. The distance between the households and the transformer varies between 161 m and 398 m, whereas the cables are between 25 m and 112 m in length. There are three additional feeders under the same transformer station which have been represented as a single aggregated load connected to the low-voltage side of the transformer due to the lack of data per individual house.

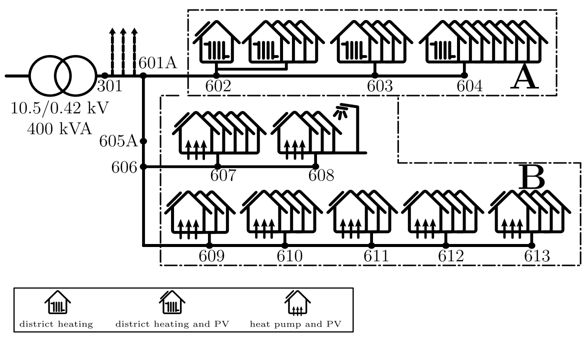

Fig. 4. Schematic overview of the observed network's topology.

4.1. Residential consumption and PV production

As already mentioned, households are divided in two groups: (1) houses in zone A which have implemented district heating and therefore lower consumption, and (2) houses in zone B which have heat pumps and consequently higher consumption during the heating period. All houses are equipped with smart meters, so individual consumption profiles are based on real metering data from March 2012 to March 2013 with an hourly sampling rate. However, due to the computational time, two characteristic weeks have been chosen for further analysis: (1) a spring week in mid-May with low consumption and high PV production resulting in the highest net power flow from the feeder to the MV grid in the observed year, and (2) a winter week with high consumption and almost no PV production resulting in the highest net power flow from the MV grid to the feeder in the same year.

Fig. 5 shows the total transformer consumption for the winter week distinguishing the observed feeder from the total load, and the average daily house consumption calculated as the mean of all consumption values at the specific hour. It can be seen that the observed feeder equals to around 40% of the total transformer load as well as that households in zone B have higher consumption due to installed heat pumps. Similarly, the same data analysis has been conducted for the observed spring week when the total consumption is much lower and the average daily profiles for the two zones are similar. Table 1 summarizes the obtained consumption values for both weeks.

The consumption values are based on the measured three-phase power flows with no insight into individual phase fractions. Since residential customers in Denmark have the three-phase connection available and there is no regulation for load connection but it

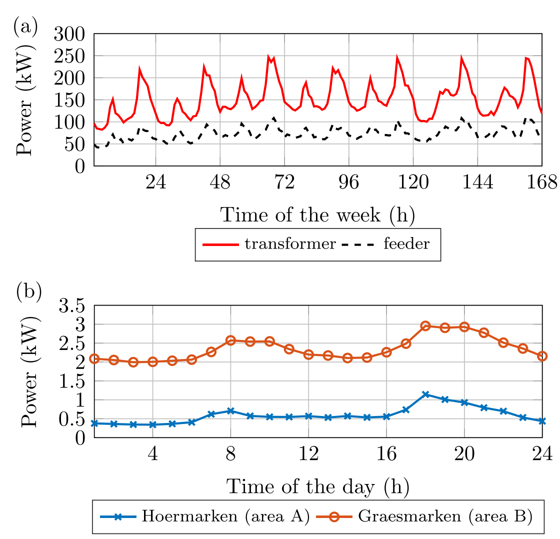

Fig. 5. (a) Total weekly and (b) average daily consumption for the observed winter week (phase distributed in ratio 50%:25%:25%).

Table 1
Consumption overview for the observed weeks.

Season	Transformer weekly consumption (kWh)	Feeder weekly consumption (kWh)	Average daily household consumption (kWh)
Spring	10,176	2,883	7.9/10.6[a]
Winter	25,416	12,251	14.2/56.4[a]

[a] Lower value stands for area A and greater for area B.

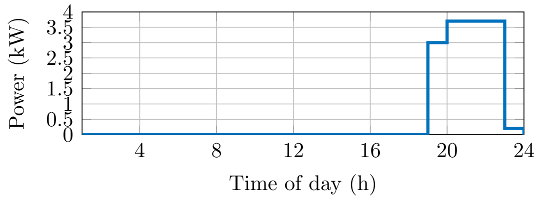

Fig. 6. Implemented single-phase EV "dumb-charging" pattern.

is solely dependent on the accredited electrician making the house installation, household appliances are usually randomly phase connected. However, based on the network operator's experience, the observed grid is heavily unbalanced with most of the loads connected to phase *a*. Hence, it has been assumed that phase *a* is loaded with 50% of the consumption, while the rest has been equally distributed among two other phases, i.e., 25% on phase *b* and 25% on phase *c*. Additionally, the measured data does not contain the reactive power component, so a fixed power factor has been assumed for all households based on DSO's recommendation, i.e., $\cos\varphi = 0.95$ (*ind.*).

As shown in Fig. 4, photovoltaic installations (PVs) are entirely located in area B, except of one installation located in area A. There are 27 PVs in total: 24 installations with peak power $P = 2.96$ kW and 3 installations upgraded to $P = 4.07$ kW connected through a 3.6 kW or a 5.4 kW single phase inverter respectively. Similarly to the load distribution per phase, the PV connection points are not known either due to the lack of regulation. Hence, PVs in the model have been randomly distributed on different phases taking into consideration that the overall production per phase is approximately the same. In addition, one single PV representing aggregated production in the three remaining feeders has been added to the low-voltage side of the transformer. This production is balanced among the three phases. Besides the residential consumption, individual PV production is also measured on hourly basis for the same year. By analyzing the data for the two observed weeks, it can be easily concluded that the PV production is negligible in the winter period whereas it exceeds the consumption multiple times in the spring time. Table 2 summarizes the total PV production and average daily production per household for the observed weeks. The later has been calculated on the same principal as the average daily consumption, more precisely as the mean of all production values for the specific hour. By comparing the values for the observed feeder and the remaining three feeders, it can be concluded that most of the PVs are located in area B whereas only a small fraction of the total production comes from the remaining feeders.

4.2. Electric vehicles

To every household in the observed Hørmarken–Græsmarken feeder, an EV has been added resulting in 100% penetration rate. However, looking at the transformer level, the penetration rate is around 25% since there is approximately the same amount of households under each of the four low-voltage feeders. If the penetration rate was higher and EVs were present in other feeders as well, the voltage at the low-voltage side of the transformer would decrease resulting in higher voltage deviations in the observed feeder as well. Nevertheless, the analyzed case can be seen as one of the biggest challenges for the network operator due to already high unbalanced nature of the observed grid and high local EV concentration.

Similarly to PVs, all vehicles are connected to a random single phase with overall equal number per phase. It is assumed that Mode 3 charging infrastructure [33] is used with single-phase 16 A connection plug. The EV charging pattern has been taken from Test-en-EV program where 184 vehicles were distributed to 1600 different Danish families over a three year period. It corresponds to an average "dumb-charging" profile which lasts for 5 h with total 14.3 kWh of consumption per session, i.e., approximately 90% of the total 16 kWh battery. Moreover, the starting time is randomly distributed between 18:45 and 19:15. Based on the same data set, [34] reports high probability (above 80%) for a single EV to be home after 18:00, so this paper aims to assess the worst case scenario when all EVs are charging at the same time which corresponds to the peak consumption hours. In addition, several parameters will also be presented for a lower EV penetration rate of 50%.

The charging process represented at Fig. 6 can be divided into three specific periods: (1) charging at the 3 kW rate for the first hour, (2) charging at the nominal 3.7 kW rate for the following 3 h, (3) charging at 0.2 kW rate in the last hour. The charging efficiency is included in the charging pattern. However, since it is highly dependent on the vehicle type as well as on the chosen charging rate, lower charging efficiency would result in higher consumption implying lower voltages and need for additional voltage regulation.

5. Results

5.1. Scenario overview

This paper compares relevant network parameters for four distinctive scenarios differing in the season and RPC activation, as listed in Table 3. It is important to note that PVs are also equipped with RPC similar to the EV one which cannot be deactivated, i.e., it is always turned on and PVs are continually contributing to voltage regulation by injecting inductive reactive power whenever the production differs from zero. Nevertheless, this does not influence the reactive power provision by EVs since the activation times do not coincide. Therefore, the base case is considered to be the one with active RPC from PVs to which then EV contribution has been added.

The simulations have been made in Matlab Simulink SimPowerSystems with a variable time step of maximum 1 min while the household load profiles are constant for their hourly period. The conducted analysis focused on several relevant network

Table 2
PV production overview for the observed weeks.

Season	Transformer weekly production (kWh)	Feeder weekly production (kWh)	Average daily household production (kWh)
Spring	3,404	3,096	17.0
Winter	38	32	0.2

Table 3
Conducted simulation scenarios.

Scenario	Season	RPC by PVs	RPC by EVs
I	Spring	On	Off
II	Spring	On	On
III	Winter	On	Off
IV	Winter	On	On

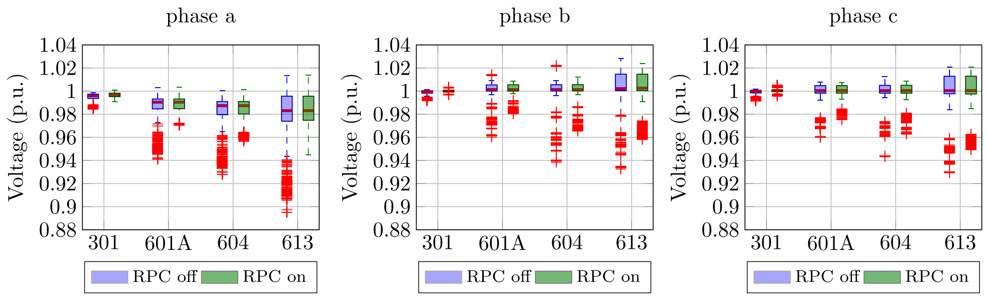

Fig. 7. Phase-to-neutral voltages at selected junction points for the spring scenarios.

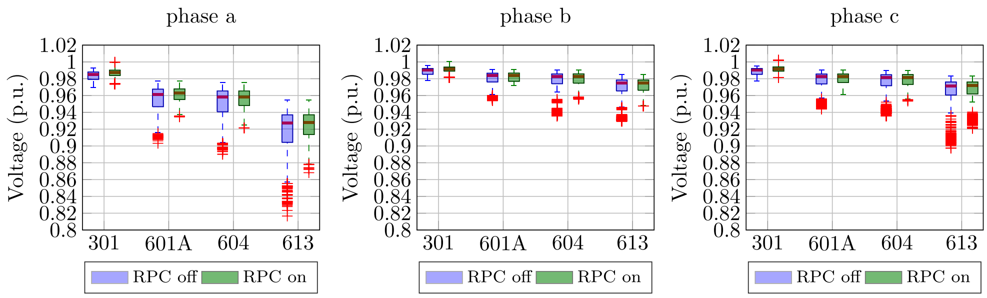

Fig. 8. Phase-to-neutral voltages at selected junction points for the winter scenarios.

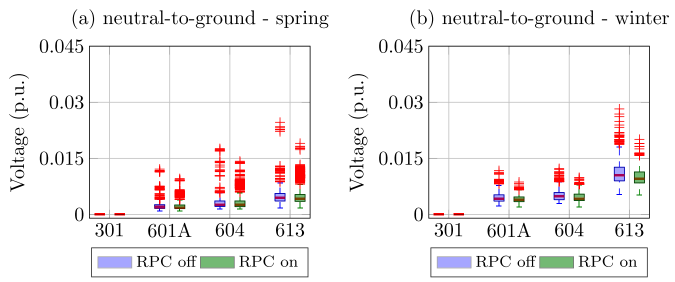

Fig. 9. Neutral-to-ground voltages at selected junction points for the spring and winter scenarios.

Table 4
Phase-to-neutral voltage improvements after RPC activation.

Season	Node	ΔV_{min} (%)			$\Delta\sigma_V$ (%)		
		a	*b*	*c*	*a*	*b*	*c*
Spring	301	0.6	0.5	0.4	−49	−56	−36
	601A	3.1	2.1	1.6	−46	−34	−32
	604	3.1	2.9	2.1	−41	−30	−29
	613	5.6	2.7	2.1	−39	−16	−19
Winter	301	0.4	0.4	0.4	−3	−9	−1
	601A	3.5	1.9	1.8	−47	−51	−44
	604	3.5	2.1	1.9	−45	−43	−41
	613	6.3	1.9	2.6	−44	−37	−31

parameters, i.e., voltage and current magnitude, voltage unbalance factor (VUF), current unbalance factor (CUF), and active power losses which will be presented in the following subsections. The voltage magnitude has been evaluated on 10 min rms values for each phase-to-neutral as well as for the neutral-to- ground. VUF has been analyzed by comparing the values for each time instance, whereas active losses have been addressed by comparing the maximum phase currents and cumulative energy loss values. All of the mentioned parameters will be presented for the selected junction points, i.e., transformer low-voltage side (node 301), the beginning of the observed feeder (node 601A), and the end points of each area (node 604 for area A and node 613 for area B).

5.2. Phase-to-neutral and neutral-to-ground voltage magnitudes

The 10 min rms voltage values for spring scenarios are given in Figs. 7 and 9a, whereas the winter scenarios are presented in Figs. 8 and 9b. While the minimum voltage on heavily loaded phase *a* is comparable to phases *b* and *c* in the spring time, it can be easily seen that the difference is much greater in the winter period since $V_{a_{min}}$ reaches almost 0.8 p.u. at the feeder end-point. The reason lies in already high household consumption which is unevenly distributed on the phases.

Even though the EVs could be integrated in the network without causing any substantial problems to the network in the spring time, voltage support is needed for charging the same cars in the winter time. It is clear from the figures that the voltages improve after activation of RPC by electric vehicles. Not only does the V_{min} increase at all junction points and all phases, but the voltage dispersion σ_V also decreases as summarized in Table 4. As anticipated, RPC has the highest influence on phase *a* where the relative deviation is decreased twice as much than on the other two phases. However, looking at the voltage dispersion (standard deviation), the change is comparable for all three phases with the highest value of 56% occurring for phase *b* in the spring period. Similarly, neutral-to-ground voltages are decreased from maximum 5.7 V to 4.4 V in the spring scenario, and from 6.5 V to 4.6 V in the winter one. Even though there is no regulation for neutral-to-ground values, keeping them as close as possible to zero is desired. Hence, the analyzed control is beneficial in achieving this goal.

For lower EV penetration rates, the qualitative effect of the proposed control is the same, whereas the quantitative is reduced since there is less units capable of providing voltage support. For example, in the spring case with 50% EV penetration rate, the minimum phase-to-neutral voltage on phase *a* at node 613 had been increased by 2.2% compared to 5.6% in 100% EV penetration case, whereas the voltage dispersion has been decreased by 33% compared to 39%.

As aforementioned, one of the benefits of the proposed EV reactive power control is more support to the more loaded phase. More precisely, for different unbalance scenarios, the vehicles will

Table 5
Maximum EV reactive power provision per phase and respective voltage improvement for different unbalance situations in the winter scenario.

Season	Load unbalance ratio (%)	$P_{load_{max}}$ (kW)			$Q_{EV_{max}}$ (kVAr)			ΔV_{min} (%)		
		a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
Winter	33:33:33	133.9	130.3	133.9	23.7	21.5	22.7	3.6	3.3	3.7
	40:30:30	150.4	122.1	125.8	25.9	18.6	21.6	3.8	3.1	3.5
	50:25:25	175.1	109.7	113.4	25.9	11.8	22.0	6.3	1.9	2.6

provide different amounts of reactive power at each phase as seen in Table 5 for the winter period with 100% EV penetration. First of all, the data indicates that the case of equal load distribution per phase is not completely balanced, which is due to different number of houses per node, and therefore unequal distribution of EVs per each node. Therefore, the maximum reactive power provision is similar, as well as the impact on the minimum voltage raise, but it is not entirely the same for all three phases. Secondly, it is clear that as the load unbalance increases, the reactive power support on phase *a* also increases, while the support on other two phases decreases. The same effect is seen on minimum voltage improvement which can be associated to the lower need for improving the voltages on phases *b* and *c*. Further on, the maximum reactive power limit is reached for vehicles on phase *a* indicating that the voltages are too low and there is need for additional support on this phase. Finally, it can be seen that in the heavily unbalanced case, the reactive power provision on phase *a* is much higher than on the other two phases, whereas the support to phase *b* is much less compared to the one to phase *c*. This can be explained by the fact that phase-to-neutral voltages are not completely decoupled one from each other, so supporting one phase will partially impact the other two phases due to moving of the floating neutral point. In this case, the voltage on phase *b* rises, and because the vehicles are not completely synchronized, some of the controllers will react later and adjust the support according to the voltage which has already been impacted by the controllers on the other two phases.

However, since the reported voltage improvements are at the expense of increased reactive power and potentially increased loading, grid power losses have been analyzed and reported in Section 5.5.

5.3. *Voltage oscillations*

Fig. 10 depicts the reactive power flow at phase *c* for one spring day, separately for the loads, PVs and EVs for a lower EV penetration of 50%. Since the simulation is run with a variable time step of maximum 1 min, short-term oscillations have been noticed due to simultaneous reaction of the RPC controllers from the PVs in the middle of the day. More precisely, as the phase *a* controller improves the corresponding voltage, it influences the voltages on the two other phases at the same time. Similarly, the controllers on other phases try to improve the matching voltages and impact the remaining phases. Since the controllers are autonomous, they do not count for the voltage deviations made by the other controllers and therefore do not compensate the reactive power accordingly. Hence, at a certain point when the phase-to-neutral voltages come close one to each other, reactive power oscillations occur which eventually cause voltage oscillations. Similar synchronization issues have been observed with other coordinated controllers for active power provision by distributed energy resources [12]. In the 50% EV penetration case, there is no oscillations for the EVs as there is no synchronization issue between them due to their lower number. As PVs and EVs do not coincide in time, the voltage at the peak time is influenced solely by the EV reactive power provision, so there is no voltage instability at that period, whereas the instability appears from the PVs in the middle of the day. Moreover, due to lower EV penetration and less available units for the voltage support, the minimum

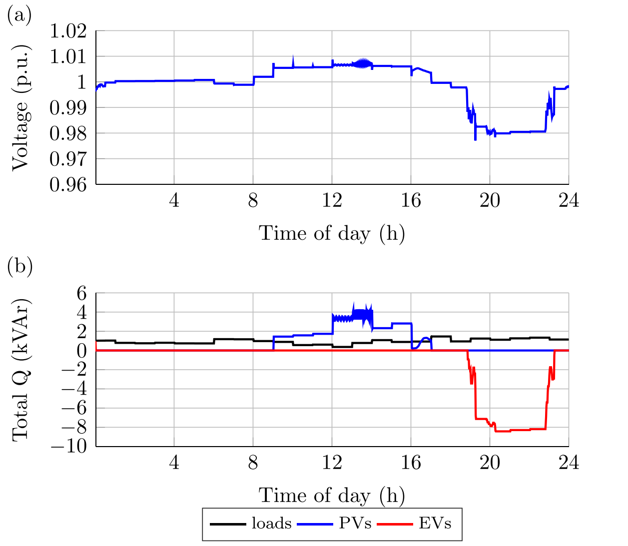

Fig. 10. (a) Phase-to-neutral voltage on phase *c* at node 601A, and (b) total reactive power for the observed feeder's phase *c* in case of 50% EV penetration for one spring day.

phase-to-neutral voltage has been improved only by 0.33%. It can be seen from Fig. 10 that EVs provide around 8 kVAr of reactive power support which is approximately 62% of the maximum capability for 7 vehicles on phase *b*. The maximum was not achieved as phase-to-neutral voltages are low enough so that the EVs provide full reactive power support constantly.

The mentioned voltage oscillations represent a potential drawback of the dynamic reactive power control which occurs for high local EV penetration rates. An example of reactive power control of a single vehicle connected to phase *c* can be seen in Fig. 11 for one working day of the observed winter and spring week with 100% EV penetration. Random delays up to 6 s have been implemented in

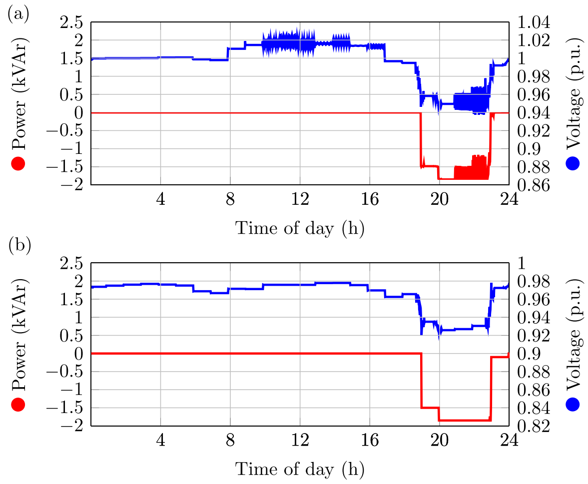

Fig. 11. Example of reactive power provision by a vehicle connected to phase *c* at node 613 for (a) spring and (b) winter.

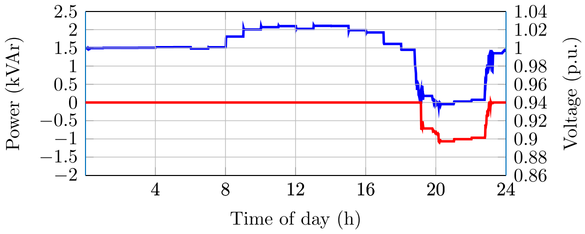

Fig. 12. Example of reactive power provision by a vehicle connected to phase *c* at node 613 for a spring scenario with reduced droop slope.

the controllers to address this oscillation issue and diversify the EV response. Even though the delays are successful in removing oscillations for the winter period, they are not enough for avoiding them completely in the spring case. Interestingly, Fig. 11 also shows that the controller reaches the saturation limit of 1.85 kVAr in the winter case indicating that the demand for voltage support is greater than it can be provided by the EV. There are still periods when the oscillations are present which could be resolved by implementing a moving average on the voltage measurements or by modifying the slope and maximum values for the RPC capability depending on the specific grid's parameters.

Implementing an adaptive droop slope for high EV penetrations which limits the maximum reactive power provision could be potential solution for mitigating the voltage oscillations. Fig. 12 depicts the reaction of the same vehicle shown in Fig. 11 for an adjusted droop with a reduced slope in 100% penetration scenario. It can be seen that the voltage oscillations have disappeared in this case as the reactive power provision has been limited for each unit, but the reactive power provision of the vehicle has been reduced almost by half resulting in greater voltage dispersion than in the case of the original control. However, the mentioned oscillation issues have not been thoroughly studied in this paper, so investigating an adaptive controller for different grid parameters and specific EV penetration rate is left for future work.

5.4. Voltage unbalance factor

Voltage unbalance factors VUF_-, VUF_0 and VUF_{rms} have been calculated according to (5), (6) and (7), respectively for all junction points. As expected, it was observed that voltage unbalances are higher in the winter case when the consumption is substantially greater due to the heating needs. Fig. 13 reports VUF_- values for the selected nodes in the winter period. Node 613 has been recognized as the most critical node since it is the most distant connection point in the network with the highest unbalances, and is therefore chosen as the focus point of further analysis.

Table 6 summarizes maximum *VUF* values at node 613, and the time for which VUF_- is not compliant with the standard [24]. Looking at the scenarios without the voltage support, it can be observed that VUF_- is always below the limit during the spring period while the limit violations occur in the winter period. However, they are still within the EN50160 requirements which allow

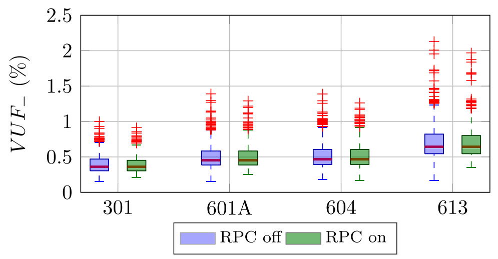

Fig. 13. VUF_- at selected junction points for the winter scenarios.

Table 6
Voltage unbalance factors at node 613 for conducted scenarios.

Scenario	Season	VUF_{-max} (%)	$VUF_- > 2\,\%$ (h)	VUF_{0max} (%)	$VUF_{rms_{max}}$ (%)
I	Spring	1.55	0	4.2	4.4
II	Spring	1.87	0	3.5	3.7
III	Winter	2.13	1.2	7.9	8.1
IV	Winter	1.99	0	5.6	5.8

5% or approximately 9 h of $VUF_- > 2\%$ in a week. On the other hand, maximum VUF_0 and VUF_{rms} are above the 2% limit well beyond the acceptable duration, especially in the winter time when the limit is almost constantly violated, mainly due to the large residential load unbalance.

By introducing droop RPC in the spring period, VUF_- is slightly increased which can be explained by the fact that the direct voltage component is decreased while the inverse one remains the same. Still, both values are within the limits so it can be considered as a minor drawback in regards to voltage improvements. On the other hand, even though $VUF_- > 2\%$ occurs less than 1% of the time in the winter period, it is additionally decreased with RPC introduction resulting in values below 2% at all times. However, it can be noted that assessing only the inverse sequence VUF may not be good enough in the three-phase four-wire systems as the zero sequence has significant impact on the system, so both inverse and zero VUF have to taken in consideration. Even though it was found that VUF_- increases in some cases after RPC activation, the positive impact of the proposed control on VUF_0 and consequently on VUF_{rms} is much higher, leading to overall unbalance reduction. Despite the fact that RPC is not making the grid fully compliant with the standard, it helps to decrease the VUF_0 and VUF_{rms} values, both in magnitude as well as in duration for both winter and spring scenario. In order to further analyze the RPC contribution to unbalance mitigation, the zero sequence current unbalance factor (CUF_0) has been calculated and reported in Section 5.5.

Moreover, this analysis has been carried out on a relatively strong network with the three-phase short circuit power of 10 MVA. In the case of a weaker grid, unbalances could be much higher resulting in additional need for voltage support. Since VUF_- is highly dependent on the external grid's strength, Table 7 shows the influence of a lower three-phase short circuit power (S_{k3}) on the VUF_- for the winter scenario, and clearly indicates how the unbalances increase for weaker grids. Reactive power control in such case could be crucial for mitigating the voltage unbalances and making the grid fully compliant with the standard EN50160.

5.5. Power losses

A major drawback of reactive power control is potential excessive loading and therefore increased energy losses. To address this issue, Table 8 compares the maximum currents and active energy losses for conducted scenarios, as well as the zero sequence current unbalance factor (CUF_0). It is evident from the table that the active losses throughout the spring scenarios do not increase significantly and amount to around 3.5% even though the total reactive energy increased after RPC activation. On the contrary, maximum phase and neutral currents are significantly lower in the winter period after RPC activation leading to decreased energy losses of 0.1%. The reason lies in the fact that there is inductive reactive power

Table 7
Influence of the three-phase short circuit power on the maximum VUF_- in the winter scenario.

S_{k3} (MVA)	VUF_{-max} (%) without RPC	VUF_{-max} (%) with RPC
5	4.31	2.89
10	2.13	1.99

Table 8
Maximum currents, current unbalance factor and active power losses in the observed feeder.

Scenario	Season	$I_{a_{max}}$ (A)	$I_{b_{max}}$ (A)	$I_{c_{max}}$ (A)	$I_{n_{max}}$ (A)	CUF_{0max} (%)	Active losses (kWh)	Relative active losses (%)
I	Spring	454	335	339	124	24.8	440	3.47
II	Spring	434	332	338	105	17.4	444	3.52
III	Winter	698	539	552	139	26.5	1008	3.57
IV	Winter	658	519	530	98	20.4	972	3.47

in the grid before the RPC implementation. Therefore, EVs firstly consume the inductive reactive power and then inject additional capacitive reactive power for voltage support. It can be concluded that RPC from EVs can be effectively used for voltage support without notably influencing the energy losses. In addition, the proposed control has positive effect on the current unbalance factor both in the spring and winter scenario, meaning that it contributes to reducing the neutral conductor current which implies partial unbalance mitigation.

6. Conclusion and future work

Electric vehicle employment will greatly affect future distribution networks leading to additional requirements concerning voltage regulation. On the other hand, the impact of EV charging can be substantially reduced with on-board strategies which do not require additional communication infrastructure, but solely depend on local measurements. This paper proposed a reactive power droop control for phase-wise enhanced voltage support which can be easily implemented with existing EV electronics and can be used for voltage support while charging regardless of the EV location and phase connection.

The proposed control was tested on a real Danish low-voltage grid, and the results show that voltage dependent reactive power control positively affects voltage conditions and supports high EV penetration rates in highly unbalanced low-voltage grids. Even though the tested grid is not fully compliant with EN50160 standard after RPC activation, the proposed control eliminates voltage magnitudes below 0.86 p.u. on all phases in both heavily and less heavy loaded scenarios. Considering that the grid is highly unbalanced, RPC provides great improvements since the minimum voltage is increased up to 6.3% depending on the season and phase-to-neutral voltage dispersion has been reduced up to 56%. Short term voltage oscillations have been noted for high EV penetration rates due to simultaneous controllers' reactions, but have been partially alleviated by implementation of random delays. In addition, such oscillations could be overcome by implementing an adaptive droop depending on the EV penetration rate, and specific system parameters and measurements. The proposed control has also been tested for a lower EV penetration rate when there are no synchronization issues. It was concluded that the controllers' qualitative impact is the same, whereas the quantitative one changes due to less available vehicles.

The paper also addresses the impact of the proposed control on grid unbalances. It was noted that inverse voltage unbalance factor can slightly increase in some cases, but the proposed control reduces VUF_0 as well as CUF_0 in all scenarios. EVs provide unequal reactive power to different phases resulting in reduction of neutral conductor current as well as partial mitigation of the unbalances caused by residential loads. In weaker grids where the unbalances are higher, such control could be crucial for integration of high EV amounts without additional grid reinforcement. Considering that RPC introduces potential increased loading due to increased reactive power, energy losses have been addressed in the study. It is concluded that voltage improvements are much higher than the side effects of additional loading since not only that the losses are marginally increased in the spring scenarios, but they are even decreased in the winter scenario due to the local consumption of already existing inductive reactive power.

If EVs do not provide support to the grid, the DSO will be forced to employ additional units for ensuring the power quality in case of high EV penetrations resulting in overall greater cost for the society. Droop parameters of the proposed reactive power controller can be easily changed depending on specific distribution grid making reactive power control applicable to any location and scalable for larger areas. Given the considered benefits, reactive power capability for EV chargers should be included in future grid compliance regulations, similarly to the current requirements for conventional power plants or PVs in countries with high penetration rates. Future work includes evaluating the RPC influence on short-term dynamics including finding the optimal slope for different grid parameters and specific EV penetration rate to avoid voltage oscillations, as well as investigating Mode 3 charging infrastructure with higher charging power.

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Pub. F. Multi-objective PQ scheduling for electric vehicles in flexible unbalanced distribution grids

Multi-Objective PQ Scheduling for Electric Vehicles in Flexible Unbalanced Distribution Grids

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Abstract: With increased penetration of distributed energy resources and electric vehicles (EVs), different EV strategies can be used for mitigating the adverse effects and supporting the distribution grid. This paper proposes a novel multi-objective methodology for determining the optimal day-ahead EV charging schedule while complying with unbalanced distribution grid constraints. The proposed methodology considers economic perspectives of both EV aggregator, and the distribution system operator, and applies fuzzy-based mechanism for obtaining the best compromise solution. Moreover, the impact of EV reactive power support on objective values and technical parameters is analysed both for the case when EVs are only flexible resources, and when interconnected with the residential demand response scheduling. The method is tested on a real Danish unbalanced distribution grid with 35% EV penetration to show the effectiveness of the proposed approach.

Nomenclature

Indices

- ϕ — Set of phases {a,b,c}.
- i, j — Network bus i,j.
- t — Set of time intervals.

Parameters

- $\eta_{ch,i}^{\phi,EV}$ — Charging efficiency of an EV connected to bus i on phase ϕ.
- λ_t — Electricity price at time t.
- $\mid Y_{ij}^{\phi_1\phi_2-n} \mid$ — Admittance magnitude between phase ϕ_1 at bus i and phase ϕ_2 at bus j of branch ij.
- $\theta_{ij}^{\phi_1\phi_2}$ — Admittance angle between phase ϕ_1 at bus i and phase ϕ_2 at bus j of branch ij.
- ξ_i — Demand flexibility parameter for bus i.
- $k_i^{\phi EV}$ — Converter parameter for reactive power control of an EV connected to bus i on phase ϕ.
- $SOC_{i,t}^{\phi EV}$ — State of charge of an EV connected to bus i on phase ϕ at time t.
- $t_{start/end,i}^{\phi EV}$ — Arrival/departure time of an EV connected to bus i on phase ϕ at time t.

Variables

- $(P/Q)_{i,t}^{\phi D}$ — Active/reactive power of demand connected to bus i on phase ϕ.
- $(P/Q)_{i,t}^{\phi EV}$ — Active/reactive power of an EV connected to bus i on phase ϕ.
- $(P/Q)_{i,t}^{\phi G}$ — Active/reactive power of a generating unit connected to bus i on phase ϕ.
- δ_i^{ϕ} — Voltage angle of phase ϕ at bus i.
- $\mid V_i^{\phi} \mid$ — Voltage magnitude of phase ϕ at bus i.

1. Introduction

Fundamental changes occurring in the electric power system promoted by the global sustainability efforts are reshaping the electrical grid operation. With increased penetration of distributed energy resources, there is an additional need for control strategies which allow them to provide various flexibility services, and avoid over-investments for maintaining the grid security [1]. Additionally, since the market share of electric vehicles (EVs) is expected to grow significantly in the following years, even greater system complexity is imposed [2]. Uncontrolled EV charging may result in voltage violations and cable overloading followed by the need for grid reinforcement, but also in increased operational cost such as energy loss cost as the charging period would mostly coincide with the peak consumption time. As an economic alternative, different EV charging strategies can be used for mitigating the adverse effects and supporting the grid.

An extensive amount of research has been made on coordinated EV charging proving that such concept can be used for lowering the impact on the power system and providing ancillary services to the grid [3–5]. A new business entity, namely an EV aggregator, has been widely proposed to coordinate larger EV amounts and offer their services to system operators, mostly via centralised control which is proven to reduce losses, improve voltage stability, and decrease peak loading compared to the uncontrolled case. Various studies use optimal power flow formulation for EV scheduling in order to minimise the charging cost or maximise the EV aggregator revenue [6, 7], but they usually deal with large EV numbers at the transmission level, and completely omit distribution grid constraints. In a smart grid context, obtaining the optimal EV charging schedule requires an adequate grid representation as the result must be feasible in the respective grid with corresponding constraints. Thus, centralised approaches have been used for scheduling EV charging at the distribution level as well. Ref. [8, 9] use linear programming to maximise vehicle charging power while satisfying distribution grid constraints; [10] proposes a rolling multi-period optimisation for minimising the EV charging cost in unbalanced networks; [11, 12] propose formulations for EV load management in balanced conditions; and [13] explores the relationship between losses, load factor and load variance in order to minimise distribution system losses via coordinated EV charging. Moreover, the impact of controlled EV charging has been investigated mainly by modulating the active power, whereas optimal EV reactive power control has not been extensively discussed in the literature. Autonomous reactive power control based on droop control has been investigated in [14, 15], but these approaches assume only reactive power support without any optimal scheduling. Ref. [16] presents a PQ optimisation method for EV (dis)charging, but focuses only on the total charging cost, whereas distribution grid constraints have been completely disregarded. These constraints have been taken into account in [17], but only for balanced distribution systems.

As pointed out in [3], combining several objective functions in EV scheduling has scarcely been touched upon, even though combining both DSO's and EV aggregator's concern is of utter importance. Ref. [18] proposes a multi-objective formulation at the distribution level for minimising operation cost and voltage deviations, but it is applicable only to balanced grids. Since distribution systems are usually unbalanced, and EVs are single-phase connected, the individual EV charging schedules do not have to coincide for all vehicles, especially in heavily unbalanced networks. Hence, use of unbalanced optimal power flow is essential in order to accurately represent the distribution system and the unbalance effect on EV operation schedules.

Even though EV smart charging problem is well studied and numerous approaches are proposed for achieving this behaviour, many existing methods suffer from one or more of the following drawbacks: (1) lack of distribution grid constraints, (2) optimal power flow formulation for balanced distribution grids, (3) no EV reactive power flexibility, and (4) no multi-objective formulation for collaborative day-ahead EV scheduling between the DSO and the EV aggregator. To the authors' knowledge, the existing research has not looked into combining all of the mentioned aspects together. The contributions of this paper are as follows:

- To propose a novel model for obtaining combined EV active and reactive power day-ahead scheduling considering unbalanced distribution grid constraints. By using unbalanced optimal power flow, unbalance impacts are taken into account when scheduling the individual EV in respect to the constraints of the phase it is connected to.

- To propose a novel model with a multi-objective formulation combining two partially competing objectives: minimisation of the DSO's loss cost which represent the local grid efficiency, and the EV aggregator's charging cost which represent the system-wide aspect as the EV aggregator participates in the wholesale electricity market. The methodology provides not only one solution, but a set of solutions from which an optimal schedule can be chosen with a proper balance between the DSO's and EV aggregator's economic concerns.

- To analyse the impact of EV reactive power support both on technical parameters, as well as on the loss cost and the EV charging cost, in case when EVs are the only flexible resource, and when interconnected with scheduling the residential demand response.

2. Methodology

2.1. Assumptions

The assumptions of this paper are described as follows:

- All EVs are under the jurisdiction of a single EV aggregator which knows their connection points. EVs are equipped with smart metering technology, and can be remotely controlled by receiving the active/reactive power charging set point. EV owner allows the aggregator to manage the EV scheduling as long as the vehicle is available for transportation purposes before their scheduled departure time. It is assumed that the EV aggregator uses estimation techniques for predicting EV arrival and departure times to manage the day-ahead scheduling.
- The grid operator has access to the following information: network size, network topology, line specifications and transformer specifications. Smart metering technology with load control capability is assumed to be present in each household, and can be used for rescheduling part of the consumption through demand response program [1, 19].
- DSO and the EV aggregator utilise techniques for forecasting the day-ahead electricity price as well as the consumption which can be forecasted with reasonable accuracy. Therefore, the error associated with the forecast has been disregarded.
- Similarly to available PV inverters, the 4-quadrant EV converter can be enabled to exchange reactive power with the grid without affecting the state-of-charge and consequently user comfort. It is assumed that the EV converter is sized to provide reactive power additionally to the active power charging rate, with no need for prioritizing between them as similar PV inverters are already commercially available due to grid code requirements in several European countries.

2.2. Constraints

In this work, a three-phase grounded four-wire system optimal power flow is formulated based on [20], and implemented as a single non-linear program which can be solved by commercial non-linear solvers such as CONOPT or IPOPT. Within this formulation, the calculated active and reactive power for phase a of branch ij at time t are given as follows:

$$P^a_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^a_{i,t}||Y^{a\phi-n}_{ij}||V^\phi_{i,t}| \cos(\theta^{a\phi}_{ij} + \delta^\phi_{i,t} - \delta^a_{i,t}) - |V^a_{i,t}||Y^{a\phi-n}_{ij}||V^\phi_{j,t}| \cos(\theta^{a\phi}_{ij} + \delta^\phi_{j,t} - \delta^a_{i,t}) \Big) \quad (1)$$

$$Q^a_{ij,t} = \sum_{\phi=a,b,c} \Big(|V^a_{i,t}||Y^{a\phi-n}_{ij}||V^\phi_{j,t}| \sin(\theta^{a\phi}_{ij} + \delta^\phi_{j,t} - \delta^a_{i,t}) - |V^a_{i,t}||Y^{a\phi-n}_{ij}||V^\phi_{i,t}| \sin(\theta^{a\phi}_{ij} + \delta^\phi_{i,t} - \delta^a_{i,t}) \Big) \quad (2)$$

Similar equations can be extracted for calculated active and reactive power of the remaining two phases b and c. The power mismatch equations for each bus are given as follows:

$$\sum_{\substack{j=1 \\ j\neq i}}^{N_j} P^\phi_{ij,t} = \sum_{G=1}^{N_G} P^{\phi G}_{i,t} - \sum_{D=1}^{N_D} P^{\phi Dnew}_{i,t} - \sum_{EV=1}^{N_{EV}} P^{\phi EV}_{i,t} \quad (3)$$

$$\sum_{\substack{j=1 \\ j\neq i}}^{N_j} Q^\phi_{ij,t} = \sum_{G=1}^{N_G} Q^{\phi G}_{i,t} - \sum_{D=1}^{N_D} Q^{\phi Dnew}_{i,t} - \sum_{EV=1}^{N_{EV}} Q^{\phi EV}_{i,t} \quad (4)$$

The voltage dependency of the residential demand is given by:

$$P^{\phi D}_{i,t} = P^{\phi D}_{0,i} \cdot |V^\phi_{i,t}|^\kappa \quad (5)$$

where $P_{0,i}^{\phi D}$ and $Q_{0,i}^{\phi D}$ represent the load's nominal active and reactive power, whereas κ equals to zero for constant power loads, one for constant current loads, and two for constant impedance loads. Furthermore, the residential consumption is assumed to be somewhat flexible, so the load is a controllable variable which may vary within the observed period as follows:

$$\sum_t P_{i,t}^{\phi Dnew} \cdot |V_{i,t}^{\phi}|^{\kappa} = \sum_t P_{0,i}^{\phi D} \cdot |V_{i,t}^{\phi}|^{\kappa} \tag{6}$$

$$(1-\xi_i)P_{0,i}^{\phi D} \leq P_{i,t}^{\phi Dnew} \leq (1+\xi_i)P_{0,i}^{\phi D} \tag{7}$$

where ξ_i is the demand flexibility parameter for bus i. The load's reactive power is then given by:

$$Q_{i,t}^{\phi Dnew} = \tan(\arccos(\varphi_{i,t}^{\phi D})) \cdot P_{i,t}^{\phi Dnew} \cdot |V_{i,t}^{\phi}|^{\kappa} \tag{8}$$

where $\varphi_{i,t}^{\phi D}$ is the residential power factor. The distribution grid voltage and power flow constraints are formulated as follows:

$$V_{i,t,min}^{\phi} \leq |V_{i,t}^{\phi}| \leq V_{i,t,max}^{\phi} \tag{9}$$

$$(P_{ij,t}^{\phi})^2 + (Q_{ij,t}^{\phi})^2 \leq (S_{ij,max}^{\phi})^2 \tag{10}$$

where $S_{ij,max}^{\phi}$ is the maximum apparent power capacity of branch ij. In addition, the MV side of the transformer is assumed to be the slack bus with fixed voltage magnitudes and angles.

The EV characteristics are expressed using the following constraints:

$$SOC_{i,t}^{\phi EV} = SOC_{i,t-1}^{\phi EV} + P_{i,t}^{\phi EV} \cdot \Delta t \cdot \eta_{ch,i}^{\phi EV} \tag{11}$$

$$SOC_{0,i}^{\phi EV} \leq SOC_{i,t}^{\phi EV} \leq SOC_{max}^{EV} \tag{12}$$

$$SOC_{i,t|t=t_{end}-1}^{\phi EV} = SOC_{max}^{EV} \tag{13}$$

$$P_{i,t}^{\phi EV} = P_{0,i,t}^{\phi EV} \cdot |V_{i,t}^{\phi}| \tag{14}$$

$$0 \leq P_{0,i,t}^{\phi EV} \leq P_{max}^{EV} \tag{15}$$

$$-k_{i,t}^{\phi EV} \cdot P_{i,t}^{\phi EV} \leq Q_{i,t}^{\phi EV} \leq k_{i,t}^{\phi EV} \cdot P_{i,t}^{\phi EV} \tag{16}$$

$$Q_{min}^{EV} \leq Q_{i,t}^{\phi EV} \leq Q_{max}^{EV} \tag{17}$$

Equation (11) describes the EV battery state of charge (SOC) dependent on the SOC in the previous time step, EV charging power, and EV charging efficiency. The battery size constraint is given in equation (12), and equation (13) imposes the users' conservative restriction where EVs must be fully charged one hour before the estimated departure time. As represented in equation (14), EVs are modelled as a constant current load with $\kappa = 1$. In addition to EV active power constraints described in equation (15), it is assumed that EVs have the possibility to dynamically modulate the power factor under constraints described in equation (16) and equation (17), where $k_{i,t}^{\phi EV}$ is fixed for each EV converter, e.g., $k_{i,t}^{\phi EV} = 1/3$ for a converter capable of modulating the power factor up to 0.95 $(ind./cap.)$. Therefore, both EV active and reactive power are controllable variables.

2.3. Objective functions

The proposed methodology obtains active and reactive optimal EV scheduling considering two partially competing objective functions which combine both DSO and EV aggregator concerns in one multi-objective framework. First objective is to obtain the minimum operating cost in terms of energy losses [21] which represents one of the main concerns of a future DSO, which obtains a new role of the flexibility operator. The minimisation of energy loss cost F_1 can be formulated as:

$$\min\ F_1 = \sum_t \sum_{l=1}^{N_l} \sum_{\phi=a,b,c} P_{l,t}^{\phi loss} \cdot \Delta t \cdot \lambda_t \tag{18}$$

where $P_{l,t}^{\phi loss}$ are the total losses on phase ϕ of line l, and λ_t is the corresponding electricity price at time t.

The second objective function is minimising the total EV charging cost. It is assumed that all EVs are under the same aggregator with a single charging tariff, so the individual EV owner pays a fixed charging price regardless of the time of day. Then, this function represents the aggregator's main concern as by minimising the total charging cost, it maximises the revenue. The minimisation of EV charging cost F_2 can be formulated as:

$$\min\ F_2 = \sum_t \sum_{EV=1}^{N_{EV}} \sum_{\phi=a,b,c} P_{i,t}^{\phi EV} \cdot \Delta t \cdot \lambda_t \tag{19}$$

Assuming that $F(X)$ is the vector of objective functions, whereas $H(X)$ and $G(H)$ represent equality and inequality constraints respectively, the proposed multi-objective minimisation problem can generally be formulated as follows:

$$\begin{aligned} \text{minimise} \quad & F(X) = [F_1(X), F_2(X)] \\ \text{subject to:} \quad & \{G(X) = 0, H(X) \le 0\} \\ & X = [x_1, ..., x_m] \end{aligned} \tag{20}$$

For solving the multi-objective problem and obtaining the Pareto optimal front, the ϵ-constraint method is used. This involves minimising the primary objective function while expressing the other objective in the form of inequality constraints. The equation (20) can then be reformulated as follows:

$$\begin{aligned} \text{minimise} \quad & F_1(X) \\ \text{subject to:} \quad & \{G(X) = 0, H(X) \le 0\} \\ & F_2(X) \le \epsilon \\ & X = [x_1, ..., x_m] \end{aligned} \tag{21}$$

where ϵ varies from the F_2 maximum to the minimum value.

2.4. Best compromise solution

Once the Pareto optimal front is determined, a range of solutions is available between which the final operating schedule should be chosen. In this method, a fuzzy satisfying set theory is used to choose the best candidate solution. The concept can be described as follows: for each solution X_n in the Pareto optimal front with N_s solutions, a membership function $\mu_k(X_n)$ is defined to show the level of which X_n belongs to the set that minimises the objective function F_k. A linear membership function is used for both objective functions as defined:

$$\forall k \in \{1,2\}\ \mu_k(X_n) = \begin{cases} 0, & F_k(X_n) > F_{kmax} \\ \frac{F_{kmax} - F_k(X_n)}{F_{kmax} - F_{kmin}}, & F_{kmin} \le F_k(X_n) \le F_{kmax} \\ 1, & F_k(X_n) < F_{kmin} \end{cases} \tag{22}$$

where F_{kmin} is the minimum, and F_{kmax} is the maximum value of objective F_k.

The best compromise solution is then determined by the decision maker. A conservative decision maker tries to minimise the maximum dissatisfaction for all objectives [22], i.e., to minimise the dissatisfaction of both the DSO and the EV aggregator. Hence, the final best compromise solution can be found as:

$$\min_{N_S} \left(\max_{k=1}^{2} (\mu_k(X_n)) \right) \tag{23}$$

By using this criteria, it could be interesting for the decision maker to arrange the Pareto solutions in a descending order, and obtain a priority list of possible schedules.

3. Test Case

3.1. Distribution grid characteristics

The proposed methodology is tested on a real semi-urban low-voltage distribution grid located in Zealand, Denmark, which has been modelled based on the information and measurement data provided by the Danish DSO. The described optimisation model has been applied to a feeder which is radially run and connected to the 10 kV MV network through a typical 400 kVA distribution transformer with the assumption that the voltages of the MV slack bus are kept at $1\ p.u.$, so $\pm 10\%\ U_n$ is completely available for LV regulation ($V^{\phi}_{i,t,min} = 0.9\ U_n, V^{\phi}_{i,t,max} = 1.1\ U_n$).

As seen in Fig. 1, the observed feeder has 43 residential houses which are three-phase connected with the nominal phase-to-neutral voltage U_n equal to 230 V. Depending on their location and consumption characteristics, the loads can be categorized in two groups: (1) Hørmarken, indicated as area A, where the houses have district heating and no photovoltaics, and (2) Græsmarken, indicated as area B, where each house is equipped with a photovoltaic installation and a heat pump resulting in high consumption during the heating period. The feeder is composed of 13 line segments between 25 m and 112 m in length, all of the same cable type with X/R ratio equal to 0.37, which corresponds to typical LV grid parameters, e.g., similar to the ones of the CIGRE European LV benchmark network [23]. There are three additional feeders under the same transformer station which have been modelled as an aggregated load due to the lack of data for individual households. All houses in the observed feeder are equipped with smart meters, so individual consumption profiles are based on real metering data with an hourly sampling rate. The consumption values are based on the measured three-phase power flows with no insight into individual phase fractions, so, based on the DSO's experience, it is assumed that the phase unbalance is distributed in 40%:30%:30% ratio. Additionally, the measured data does not contain the reactive power component, so a fixed power factor of $\cos\varphi = 0.95\ (ind.)$ has been considered for all households. The residential demand response flexibility parameter ξ_i is assumed to be 10% for all nodes.

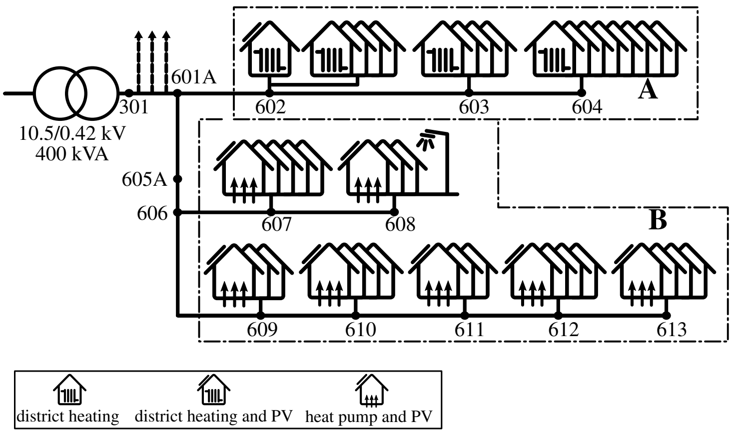

Fig. 1: Schematic overview of the network topology.

A characteristic 24 hour period has been chosen based on the available historic data to represent the extreme case: a winter day with high residential consumption and almost no PV production. One should note the chosen 24 hour period starts from 15/01/2013 12:00 until 16/01/2013 11:00 in order to include the night time since EVs are generally available during the night. However, other time windows can be chosen as well. The corresponding electricity price shown in Fig. 2 has been taken from the NordPool Spot day-ahead electricity market [24].

3.2. Electric vehicle

First of all, it is assumed *Mode 2* charging infrastructure [25] is used for EV charging with a single-phase 16 A connection plug, i.e., 3.7 kW under nominal voltage. For the sake of simplicity, all EVs are assumed to be a Nissan Leaf with a 24 kWh battery and constant EV charging efficiency of 80% [26]. Nevertheless, this assumption does not influence the model's generality as various vehicle types can easily be included. Secondly, there are 15 EVs in total, which are randomly distributed across the observed feeder resulting

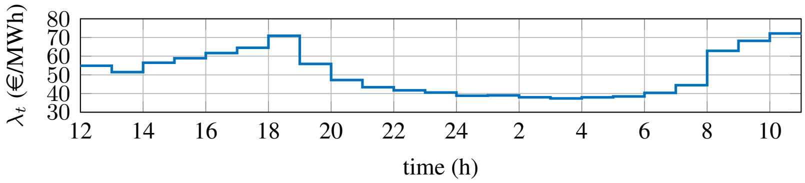

Fig. 2: Electricity price profile for the observed 24 hour period.

in overall 35% penetration rate. In area A, there are 2 vehicles on phase a and 4 on phase b, whereas the distribution in area B is 2 EVs on phase a, 3 on phase b, and 4 on phase c.

The probability of an EV being plugged-in is taken from the Test-en-EV program where 184 vehicles were distributed to 1600 different Danish families over a three year period. According to the data derived from empirical patterns in [27], each vehicle is assigned a random initial SOC, plug-in time and plug-out time as follows:

$$t^{\phi EV}_{start,i} \sim \mathcal{N}(19{:}10h, (39min)^2) \tag{24}$$

$$t^{\phi EV}_{end,i} \sim \mathcal{N}(07{:}50h, (29min)^2) \tag{25}$$

$$SOC^{\phi EV}_{0,i} \sim \mathcal{N}(49\%, (4\%)^2) \tag{26}$$

Then, $t^{\phi EV}_{start,i}$ and $t^{\phi EV}_{end,i}$ are rounded to the closest integer value as the simulation time step is chosen to be 1 hour due to available consumption data. One should note how the initial SOC, arrival and departure time are input parameters which are estimated by the EV aggregator. Therefore, the model generality is not influenced by the choice of normal distribution as other probability distributions can be included as well.

Finally, the EV reactive power limits are assumed to be ± 1.23 kVAr which corresponds to $\cos\phi = 0.95$ $(ind./cap.)$. For comparison, commercially available PV inverters from SMA Solar Technology have the possibility to modulate the reactive power up to $\cos\phi = 0.8$ $(ind./cap.)$. It is also assumed that EVs can provide reactive power support only if they are charging, so they cannot act as constant capacitor banks whenever plugged-in.

3.3. Scenario overview

Five scenarios are defined in order to analyse EV potential for charging cost minimisation and concurrent grid support. First of all, the objective values are obtained for uncontrolled charging case where there is no flexibility available in the grid, and the EVs charge as soon as they are plugged-in until the battery is completely full. This scenario is referred to as scenario I. Afterwards, different degrees of flexibility are added in scenarios II-V as listed in Table 1. The simulations are done using GAMS software with CONOPT solver on a notebook with a 2.6-GHz Intel(R) Core(TM) i7-5600U CPU and 8 GB of RAM, taking in average 6-20 seconds for solving one optimisation problem depending on the conducted scenario.

4. Simulation Results

4.1. Pareto optimal fronts and objective values

The Pareto optimal fronts obtained for different conducted scenarios are given in Fig. 3 with the chosen best compromise solutions emphasised with filled red shape. Foremost, it is obvious that introducing EV reactive power flexibility has beneficial impact on the grid as the Pareto optimal front of scenario III is below the one obtained for scenario II where only EV active power flexibility is available. With addition of demand response in scenarios IV and V, better Pareto fronts are obtained resulting in the best one in for scenario V where the most flexibility is available. Secondly, it is interesting to notice how the maximum EV cost value is increased by adding more flexibility to the system. One of the reasons is the EV reactive power dependency on the EV charging active power. As EV reactive power support influences the losses, but is only available when EV is charging, the minimum loss cost is obtained if part of the charging is shifted to more expensive hours when there is greater need for reactive power support. The objective functions' values for the best compromise solutions of each scenario, and the relative values compared to the uncontrolled charging scenario are given in Table 1, whereas the comparison between the best compromise solution and single-objective optimisations is given in Fig. 4.

It can be seen that modulating EV active and reactive power results in savings both for the DSO and the EV aggregator when compared to the uncontrolled case. The influence of EV reactive power flexibility does not have a significant impact on the EV charging cost, whereas it has positive influence on the loss cost when comparing the best compromise solutions. Therefore, if EV reactive power capability would be obligatory and implemented in grid codes similarly to the ones for PVs, the DSO would have greater benefit while the EV aggregator, and consequently EV users, would not be substantially affected. Interestingly, when comparing the loss cost with the loss amount itself in Table 1, even though the losses are higher in scenario IV than in scenario III, the loss cost is lower as they are concentrated in periods with lower prices. This leads to the conclusion that minimising distribution grid losses themselves may not be the optimal decision for the DSO, and minimising the loss cost, as formulated in this paper, is more appropriate due to variable electricity price.

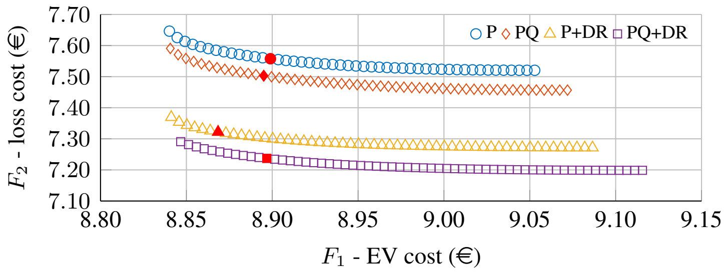

Fig. 3: Obtained Pareto optimal fronts for conducted scenarios II to V.

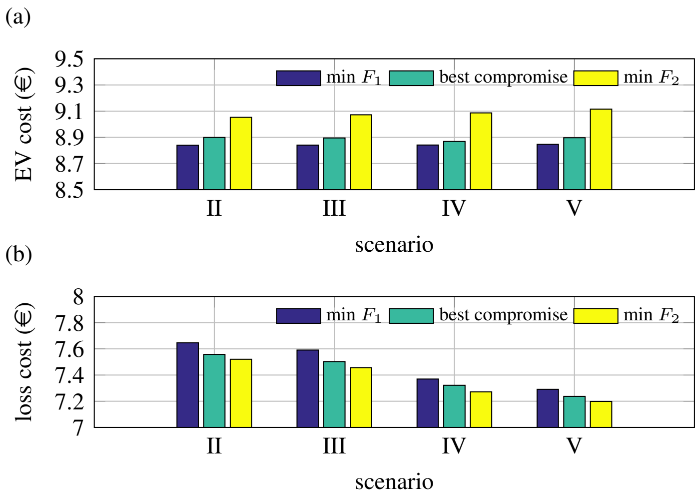

Fig. 4: Comparison between the best compromise solution and single-objective solutions for scenarios II-IV: (a) EV charging cost, and (b) loss cost.

Table 1: Objective Functions' Values for the Best Compromise Solutions of Conducted Scenarios.

Scenario	**EV flexibility**	**Demand response**	**EV charging cost (€)**	**Loss cost (€)**	**Total losses (kWh)**	**Δ EV charging cost (%)**	**Δ loss cost (%)**
I	-	-	12.0386	8.4434	161.2943	-	-
II	P	-	8.8998	7.5571	150.5874	-26.07	-10.50
III	PQ	-	8.8947	7.5033	149.1654	-26.12	-11.13
IV	P	±10%	8.8713	7.3192	150.2265	-26.31	-13.31
V	PQ	±10%	8.8976	7.2367	148.0795	-26.09	-14.29

4.2. Distribution grid parameters

Several relevant grid parameters are reported in this subsection. First of all, Fig. 5 depicts the active power losses for all conducted scenarios. It is easily noticeable the highest losses are in the EV uncontrolled case when EV charging coincides with the peak period. When comparing different flexibility scenarios, two distinctive periods can be singled out. First one is the peak period from 18:00 to 22:00, and the second one is the off-peak period from 2:00 to 6:00. In all conducted scenarios, none of the EVs will charge in the peak period as the electricity price is too high. Hence, the active losses mainly come from the residential consumption which is the reason why the curves coincide for two scenarios without demand response (P and PQ), and for the two with (P+DR and PQ+DR). In the off-peak period when electricity prices are low, EVs are charging and the curves diverge for different scenarios. As EVs provide local reactive power support, total losses are reduced compared to the scenarios without it. The highest losses in the off-peak period are for the scenario where demand response is added to the EV active power flexibility, and they are comparable to the peak losses in scenarios without the demand response. However, even though the loss absolute value is high, the cost is low since electricity prices are lower. One should bear in mind that with higher EV penetrations, the total consumption would be higher, so local EV reactive power support could have greater value as well.

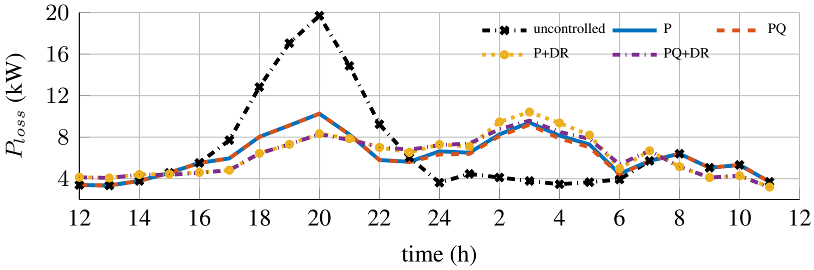

Fig. 5: Total active power losses for the obtained best compromise solutions.

Fig. 6 reports active and reactive power exchange with the MV grid on the most loaded phase a. Similar behaviour has been observed for the remaining two phases, so corresponding curves have been omitted for the sake of clarity. As seen in Fig. 6a, EV charging has been shifted to the off-peak period compared to the uncontrolled case. In addition, part of the residential consumption is shifted to the same off-peak period in the scenarios where demand response is available. The difference between the scenarios with EV reactive power support can be appreciated in Fig. 6b where the reactive power import is lower for the scenarios with EV reactive power capability, since EVs locally support the grid and decrease the need for external reactive power.

Table 2 reports the average, minimum and maximum voltage value across the observed feeder for different scenarios at the off-peak time 3:00 when all EVs are charging, whereas Fig. 7 shows the minimum phase a voltage across the grid for the observed time period. Even though minimising voltage deviations is not formulated as an objective function, the overall voltages increase with introduction of EV reactive power flexibility as their capacitive behaviour supports the grid. As seen in Table 2, the exception is phase b where minimum voltages get somewhat lower, due to reasons explained in subsection 4.3. However, if the voltage would decrease below the minimum acceptable limit, the corresponding solution would be infeasible, and the EV behaviour would be modified in order to satisfy all the constraints.

Table 2: Average, minimum and maximum feeder voltage values (p.u.) for conducted scenarios.

Time	**Scenario**	$\mathbf{V_{average}(p.u.)}$			$\mathbf{V_{min}(p.u.)}$			$\mathbf{V_{max}(p.u.)}$		
		a	b	c	a	b	c	a	b	c
	I	0.966	0.951	0.994	0.982	0.976	0.996	0.982	0.975	0.996
	II	0.959	0.942	0.994	0.964	0.954	0.995	0.973	0.956	0.995
t=3:00	III	0.962	0.946	0.995	0.964	0.953	0.996	0.973	0.960	0.996
	IV	0.953	0.934	0.993	0.965	0.955	0.995	0.973	0.956	0.995
	V	0.958	0.941	0.994	0.965	0.954	0.995	0.973	0.960	0.996

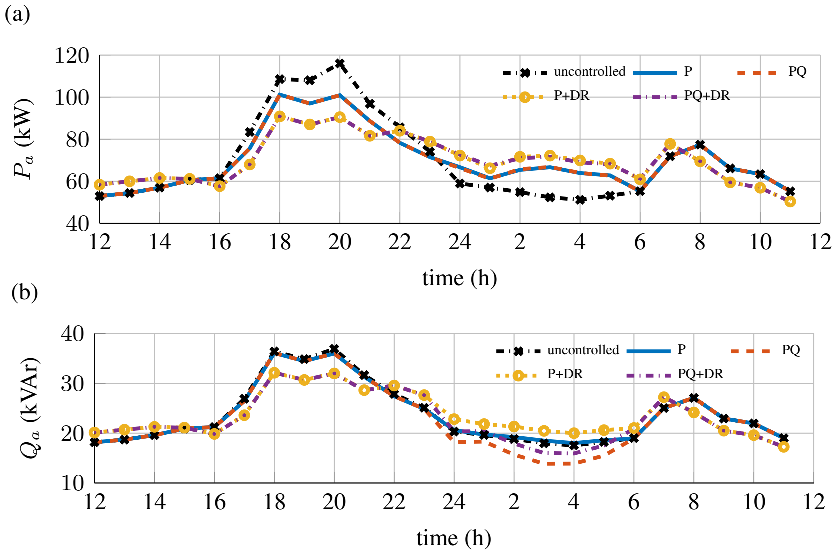

Fig. 6: Interaction between the MV and the observed LV feeder: (a) active power, and (b) reactive power of phase a for the best compromise solutions.

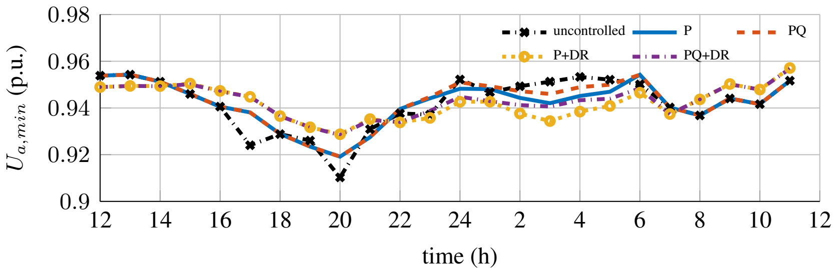

Fig. 7: Minimum phase a voltage values over the observed period for all conducted scenarios.

4.3. Individual EV patterns

Fig. 8 depicts several individual EV profiles for scenario V with demand response and EV PQ flexibility. It is obvious that EVs do not have identical schedules, neither for active nor for reactive power. As expected and seen in Fig. 8a, all EVs are charging during the night when electricity prices are lower in order to minimise the EV aggregator's cost, resulting in lower peak load and reduced need for grid reinforcement. However, what is interesting to observe is the EV reactive power behaviour shown in Fig. 8b. Even though one would expect only capacitive EV behaviour, inductive behaviour is observed for some vehicles connected in area A. The reason behind are high unbalances in area A, so several EVs behave inductively and try to bring the voltages closer together to reduce the unbalances, and consequently overall losses.

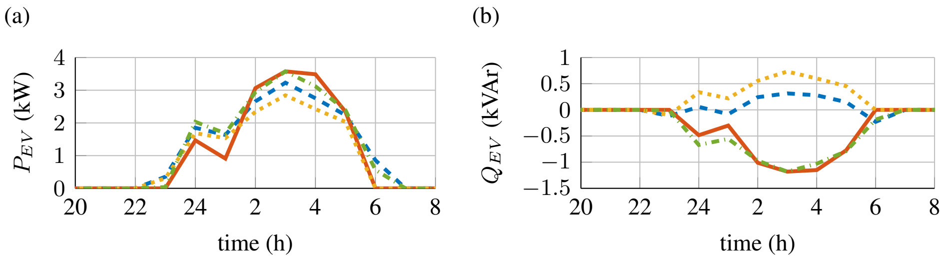

Fig. 8: (a) Active power, and (b) reactive power profiles for selected EVs in scenario V.

4.4. Sensitivity analysis

Sensitivity analysis has been conducted for several parameters in scenario V as shown in Fig. 9. First of all, the impact of EV charging efficiency is analysed by changing the value from 75% to 90% in 5% steps. Secondly, the impact of maximum EV charging rate has been analysed for three specific rates, i.e. 16 A, 32 A and 63 A, which equal to 3.7 kW, 7.4 kW and 14.5 kW under nominal voltage. Finally, the impact of DR is analysed by changing the demand flexibility parameter from 0% to 15% in 5% steps. It can be observed that the maximum EV charging power has an influence only on the maximum loss cost, whereas the maximum EV cost remains the same, since the minimum losses are obtained for more spread-out EV charging schedules which are not impacted by the maximum charging rate. However, the higher is the charging rate, the larger is the loss cost in the best compromise solution, as the DSO is willing to pay more compared to the alternative. On the other hand, EV charging efficiency has an impact both on the EV charging cost, and the DSO loss cost. The higher is the efficiency, the greater are the benefits for both entities. Finally, demand response flexibility has a positive impact on the loss cost, but could potentially increase the maximum EV aggregator's cost. Nevertheless, for a fixed EV cost, the loss cost are reduced as more demand flexibility is introduced.

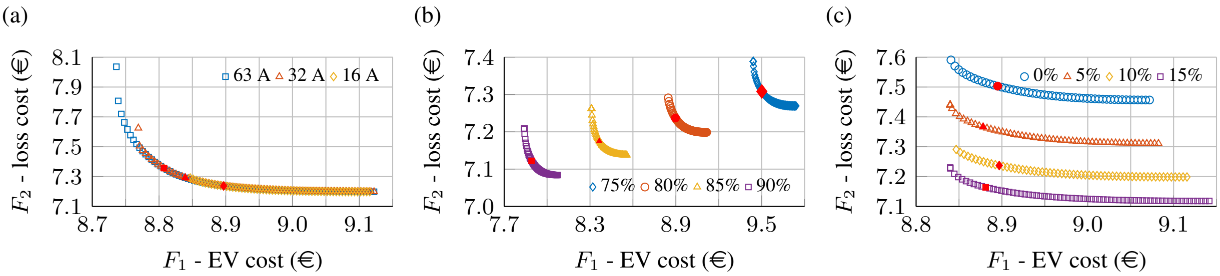

Fig. 9: Impact of (a) maximum EV charging rate, (b) EV charging efficiency, and (c) demand flexibility on Pareto optimal front in scenario V.

5. Conclusion

This paper presents a multi-objective methodology for optimal active and reactive EV scheduling in unbalanced distribution networks. Two objective functions have been used in resource scheduling, namely minimisation of loss cost which represents the DSO's economic concern, and minimisation of EV charging cost which represents the EV aggregator's main concern. After obtaining a Pareto front, a fuzzy set approach is used to select the best compromise solution, i.e., to minimise the maximum dissatisfaction of both parties. In addition, the impact of EV reactive power capability is investigated, both on the objective functions' values, as well as on the grid technical constraints.

The method was tested on a real distribution network with 35% EV penetration rate. The multi-objective approach was able to obtain the Pareto front with a range of possible solutions, whereas the fuzzy set approach gives a good compromise between the both considered objectives. Due to grid unbalances, individual EV schedules differ depending on their connection point and available demand response. It was observed that EV reactive power support can provide benefits for the DSO while not significantly affecting the EV aggregator's cost. By introducing such a capability in grid codes, EVs would be able to provide local grid support resulting in overall improved voltages, decreased losses and less need for reactive power from the external grid.

For future work, the authors' would like to incorporate demand forecast errors which would affect the EV day-ahead scheduling, as well as to extend the presented model with EV control in discrete current steps according to contemporary standard IEC 61851. Moreover, future work includes extending the model with application to distribution network planning [28, 29] purposes as well as to real-time operation [30].

Acknowledgment

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Pub. G. Enhancing the role of electric vehicles in the power grid: Field validation of multiple ancillary services

Enhancing the Role of Electric Vehicles in the Power Grid: Field Validation of Multiple Ancillary Services

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***Abstract*—With increased penetration of distributed energy resources and electric vehicles (EVs), different EV integration strategies can be used for mitigating various adverse effects, and supporting the grid. However, the research regarding EV smart charging has mostly remained on simulations, whereas the experimental validation has rarely been touched upon. This paper focuses mainly on evaluating the technical feasibility of a series-produced EV to provide flexibility in real distribution grids. The implemented controller uses contemporary and widely supported standards for limiting the EV charging rate, which essentially means it is applicable to any EV complying with IEC 61851 and SAE J1772 standards. The field test validation is conducted in a real Danish distribution grid with a Nissan Leaf providing three ancillary services through unidirectional AC charging, namely congestion management, local voltage support, and primary frequency regulation. Several performance parameters, such as EV response time and accuracy, are assessed and benchmarked with current requirements. Ultimately, the paper aims to strengthen the applied research within the EV integration domain through validating smart grid concepts on original standard-compliant equipment.**

***Index Terms*—ancillary services, electric vehicle, power distribution control, power system testing, smart charging**

I. Introduction

FUNDAMENTAL changes occurring in the electric power system promoted by the global sustainability efforts have started to reshape the grid operation. With increased penetration of distributed energy resources, such as photovoltaic installations (PVs) and various electric vehicles (EVs) [1], [2], there is an increased need for control strategies which would allow them to provide flexibility services. EVs seem to be one of the eminent resources for providing various services due to their defining properties: (1) they are a large load compared to other residential loads, (2) they have quick-response with potential bi-directional power flow capabilities, and (3) they are available most of the time with high degree of flexibility [3], [4]. Significant amount of research has been done to address the arising EV challenges as well as to capture their benefits [5], [6].

Overall, the literature pointed out that EVs can have high potential in providing regulation services to the transmission system operator (TSO), especially primary frequency regulation, due to their rapid response. Ref. [7] concluded that EV participation in regulation markets offers a substantial earning potential to the EV owners, whereas [8]–[10] showed that EVs with different droop controls can be effective in primary frequency control, likewise in larger systems and isolated microgrids. On the other hand, considering that residential EV charging highly impacts the local grid, different strategies are proposed for EVs providing flexibility to the distribution system operator (DSO), namely congestion management and voltage regulation [11], [12]. It is shown across a variety of studies that centralized EV control reduces losses, improves voltage stability and performs peak shaving or congestion control [13]–[15]. On the other hand, decentralized control based only on local measurements provides similar results [16]. Additionally, more and more countries, among which Germany and Italy, request small inverter-interfaced PVs to provide reactive power. Similarly, since EVs are also inverter-based, their electronic equipment could potentially enable reactive power exchange with the grid without affecting the active power flow, provided the inverter is properly sized [17], [18].

Even though the identified literature analysed different EV control strategies, it mostly remained on simulations, whereas the experimental validation is rarely touched upon. Ref. [19] tested the developed smart charging algorithm on a commercial EV, but focused only on minimising the charging cost, not on providing any ancillary services. In general, when dealing with ancillary services, the literature assumes an ideal EV response to the control signal, and omits response latencies and inaccuracies which may greatly impact the results. The importance of hardware-in-the-loop for evaluating the ancillary service provision of inverter-interfaced DERs is discussed in [20]. The works described in [21] experimentally tested proposed frequency control, but the EV was represented by a custom-made set of Li-Ion batteries whose behaviour differs from commercial EVs. On the other hand, [22] uses series-produced EVs for experimental validation, but only for frequency control, and in laboratory environment. Thus, an extensive experimental activity is required to prove the feasibility of different EV controls with contemporary technology and series-produced cars outside the laboratory environment.

The main contributions of this manuscript can be summarized as follows:

- Validating the developed EV smart charging controller for providing multiple ancillary services, i.e.,

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congestion management, local voltage support, and frequency-controlled normal operation reserve (primary frequency regulation).
- Assessing the technical feasibility of such a controller with currently available technology and series produced vehicle. Implemented controller uses contemporary standards for limiting the EV charging rate, which essentially means it can be used with all EVs compliant with IEC 61851 [23] and SAE J1772 [24] amounting to 7563 only in Denmark at the end of 2015 [25]. Assuming 50% service participation rate with ± 5 A flexibility per vehicle, this results in approximately ± 4 MW of available system flexibility.
- Conducting a field validation in a real distribution grid with no controllability over other residential units, and limited amount of measurement equipment.
- Investigating issues which may arise when dealing with the practical implementation of EVs providing ancillary services, i.e. several performance parameters such as vehicle responsiveness and accuracy to compare the fulfilment with the existing requirements.

The paper is structured as follows. Section I presented the contemporary standards and literature survey regarding the tested services. Further on, Section II presents the implemented control strategy. The description of the experimental field setup, the performed test activities, and the parameters for result evaluation are given in Section III. Finally, the results are presented and discussed in Section IV followed by the conclusions in Section V.

II. EV SMART CHARGING CONTROLLER

A. *Control logic for various ancillary services*

To validate the technical feasibility of contemporary EVs providing various ancillary services, a universal smart charging controller was developed, which is applicable to any EV compliant with IEC 61851 and SAE J1772. This controller can be used for performing centralised EV control such as congestion management and primary frequency control, or as an autonomous controller implemented directly in the Electric Vehicle Supply Equipment (EVSE) for local voltage regulation.

The control logic itself is based on droop control whose characteristics have been inspired by the corresponding service requirements, and the current EV capabilities. The droop control is a well-established control scheme commonly used in the power system domain due to its simplicity, which makes it a viable solution for EV flexibility provision. As shown in [9], [10], [26], [27], EVs equipped with a droop control can provide primary frequency regulation, and maintain the system frequency, both in the case of centralised and decentralised strategies likewise in an islanded mode or when grid connected. Moreover, it has been shown that droop control can be efficiently applied to EVs providing voltage regulation and congestion management [16], [28], [29] in order to support the local distribution grid. When utilising decentralised droop control for local support, the control performance is guaranteed as long as the physical properties

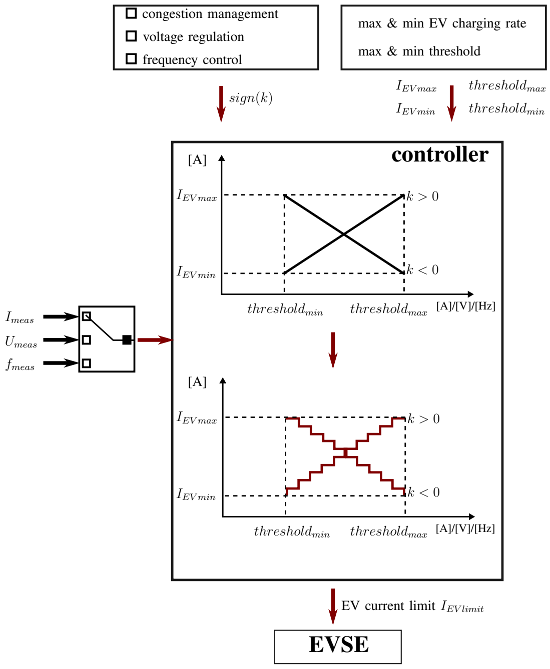

Fig. 1: Schematic overview of controller's input parameters for droop characteristics construction.

of the system do not change which is usually the case with radial distribution grids.

In the developed controller, one can easily switch between the services by choosing the measurement to which the EV is responding, and changing the droop characteristics as desired. As shown in Fig. 1, the specified input parameters construct the ideal, and the effective EV droop characteristics which is dependent on the current EV capabilities. The necessary input parameters are: (1) the *type of service* which defines the droop characteristic sign ($sign(k)$) and the input measurement (MV-LV transformer loading I_{meas}, local phase-to-neutral voltage U_{meas} or system frequency f_{meas}), (2) *the minimum* (I_{EVmin}) *and the maximum EV charging current* (I_{EVmax}), and (3) *the minimum* ($threshold_{min}$) *and the maximum threshold* ($threshold_{max}$) for the chosen service.

First of all, according to contemporary standards [23], [24], all EVs must be able to limit their charging rate between the minimum charging current of 6 A and the maximum one, which is the EVSE rated current. These values are the ones used in the controller if not specified otherwise. The same standards also require that the charging rate is limited in discrete 1 A steps, whereas the response to intermediate currents is not guaranteed. Hence, the effective EV droop characteristic cannot be linear like the ideal theoretical one due to the described practical limitations. The defined minimum (I_{EVmin}) and the maximum EV charging currents (I_{EVmax}) specify the band within which the EV charging rate $I_{EVlimit}$ can be controlled for all services as follows:

$$\begin{gathered} I_{EVmin} \leq I_{EVlimit} \leq I_{EVmax} \\ I_{EVlimit} \in \mathbb{N} \end{gathered} \tag{1}$$

For a typical 16 A single-phase EVSE, 11 current steps are available in total (i.e., 6 A, 7 A, ..., 16 A). In case the grid components are not sized for the maximum charging rate, e.g. if residential fuses are 13 A, the maximum rate can be limited within the controller. Naturally, this results in a lower EV current span available for flexibility provision. Moreover, in case an aggregator would like to realize an ideal linear behaviour for a specific service, it would be necessary to have a sufficient amount of EVs so that, once aggregated, they show an equivalent linear response. Nevertheless, the number of current steps does not influence the EV performance evaluation in terms of response time and accuracy.

Secondly, depending on the specified service, the controller responds to the different measurement data as explained in II-B. Regardless of the chosen service, the range $threshold_{min} - threshold_{max}$, within which the EV provides flexibility, has to be defined. This range is either the transformer loading, the voltage, or the frequency range. The set thresholds are arbitrarily chosen, and can be either constant or varying depending on the time of the day and the specific grid circumstances. It is up to the system operator to determine the most suitable thresholds depending on the distribution grid characteristics. Since the thresholds are defined within the control logic, they can also be dynamically changed if an adaptive droop characteristic is required, or if the droop characteristic is to be periodically updated to include the EV SOC target. The process of threshold choice can be automatised with estimation techniques, but designing an adaptive control logic was not the main focus point of this paper, so the thresholds are set to fixed values. Similarly as derived in [28], here the EV charging rate is a linear characteristic of the input measurement data, and can generally be calculated as the multiplication between the droop gain, and the difference between the measured and the nominal value (i.e., current, voltage or frequency). Hence, once the thresholds are defined, the droop slope k is calculated as follows:

$$k = \frac{I_{EVmin} - I_{EVmax}}{threshold_{min} - threshold_{max}} \quad (2)$$

One should note that the droop characteristic will be positive in case of voltage and frequency regulation, i.e., the EV charging rate linearly increases if the voltage or the frequency increases, whereas it is the opposite for congestion management where the EV charging rate linearly decreases if the transformer current increases. Therefore, the EV charging current limit I_{calc} is calculated according to equation (3) for voltage regulation, equation (4) for frequency control, and equation (5) for the congestion management. Since the set EV charging limit must be an integer value due to the practical limitations set by the standards, the calculated current is rounded up.

$$I_{calc} = \lceil +k \cdot (U_{meas} - threshold_{max}) + I_{EVmax} \rceil \quad (3)$$

$$I_{calc} = \lceil +k \cdot (f_{meas} - threshold_{max}) + I_{EVmax} \rceil \quad (4)$$

$$I_{calc} = \lceil -k \cdot (I_{meas} - threshold_{min}) + I_{EVmax} \rceil \quad (5)$$

Then, the EV charging limit $I_{EVlimit}$ is set as:

$$I_{EVlimit} = \begin{cases} I_{calc}, & I_{EVmin} \leq I_{calc} \leq I_{EVmax} \\ I_{EVmax}, & I_{calc} > I_{EVmax} \\ I_{EVmin}, & I_{calc} <_{EVmin} \end{cases} \quad (6)$$

The specific input parameters chosen for the experimental validation will be explained in Section III.

The droop control logic is chosen due to its simplicity which makes it cheap and applicable on wide range of computing devices. However, the developed controller can be extended for other control strategies as well, e.g., multi-agent systems [30], [31], where the EV charging limit is calculated based on different input signals such as the market price, as well as for a more complex droop control strategies which include the user preferences [32]. Naturally, for a more complex control logic, the overall performance could decrease due to a longer computational time. Experimental investigation of such strategies has been left for future work.

B. Communication architecture

The communication architecture for the implemented smart charging controller is shown in Fig. 2.

Depending on the chosen service, input for the control logic comes from a different measurement device. The Smart Grid Unit (SGU) installed at the transformer substation sends the single-phase current measurements I_{meas} via the Internet, similarly to the DEIF MTR-3 device which measures the system frequency f_{meas}. These devices could be replaced with any measurement device capable of sending the data via the Internet. On the other hand, the local phase-to-neutral voltage measurement U_{meas} comes from the DEIF MIC-2 device installed in the EVSE, which is connected to the control logic by Ethernet using the MODBUS protocol. The actual measurements are polled using the corresponding data poller subroutines within the controller. The control logic actuates the EV charging power by setting the appropriate current limit in the EVSE controller located within the EVSE, whereas the EV itself is connected to the EVSE using the IEC 61851 standard. According to this standard, the EV listens to the EVSE communication line (called the Control Pilot line), in the form of a Pulse Width Modulation (PWM) signal whose duty cycle indicates the maximum EV charging limit.

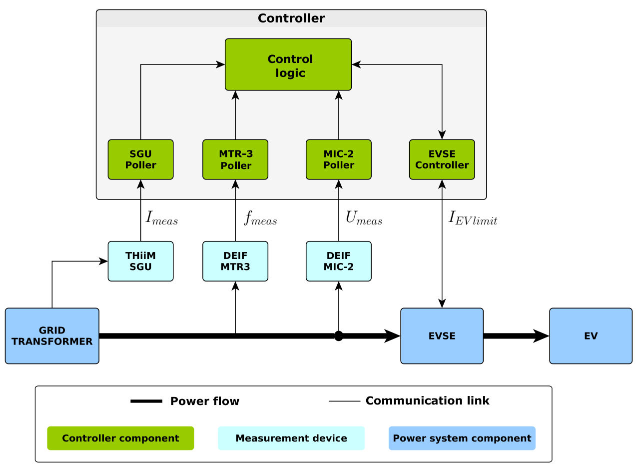

Fig. 2: Communication architecture diagram for the tested smart charging controller.

The described architecture can easily be extended to more EVs, both for centralised and decentralised algorithms. In case of a centralised strategy, the control logic would just be connected to several others EVSEs which would allow the control of large EV amounts. On the other hand, the shown architecture would be implemented within each individual EVSE in case of decentralised control, or in systems based on autonomous agents. Since the developed controller is based only on contemporary standards and equipment, it can easily be integrated in the current power system under the smart grid concept.

III. Experimental Field Test

The field test was conducted in a 400 V distribution feeder located in the suburban area of southern Zealand, Denmark, whose topology is depicted in Fig. 3. This feeder is radially run and connected to the MV network through a typical 400 kVA transformer. It consists of 43 residential houses with a three-phase grid connection, and a common neutral conductor grounded at the transformer substation. There are three additional feeders under the same transformer station with approximately the same number of houses per feeder. For the conducted field trials, the EV was connected to a standard Schuko plug in a residential house located towards the end of the feeder at phase c of node 612. As depicted in Fig. 3, the field test setup consists of the following components:

- series produced EV (Nissan Leaf) with 24 kWh Li-Ion battery and single-phase 16 A (230 V) connection,
- EVSE with PhoenixContact controller for limiting the EV charging current,
- ThiiM Smart Grid Unit (SGU) for transformer current measurements (located at the transformer substation) with 0.1 A accuracy and 30 second sampling rate,
- DEIF MIC-2 for local phase-to-neutral voltage measurements and EV current measurement with 0.5% accuracy and 1 second sampling rate,
- DEIF MTR-3 for frequency measurements (located at Risø Campus, Technical University of Denmark) with 10 mHz accuracy and 1 second sampling rate, and
- notebook with Internet connection for receiving the measurements and running the control logic.

Moreover, one should note that none of the other residential loads were controlled, so the consumption variability comes solely from the users themselves.

The three used droop characteristics are shown in Fig. 4, respectively for congestion management, voltage regulation, and frequency-controlled normal (FCN) operation reserve. Since the field experiment was conducted in a real residential house whose fuses are not sized for such a heavy load, the maximum EV charging rate was set to 12 A which resulted in seven possible charging current for all services, seen as six steps in Fig. 4. The thresholds for each service have been chosen as follows: (1) $I_{min} = 90$ A and $I_{max} = 120$ A for congestion management, (2) $U_{min} = 0.96\ U_n$ and $U_{max} = 0.98\ U_n$ for voltage support, and (3) $f_{min} = 49.9$ Hz and $f_{max} = 50.1$ Hz for frequency-controlled normal operation reserve.

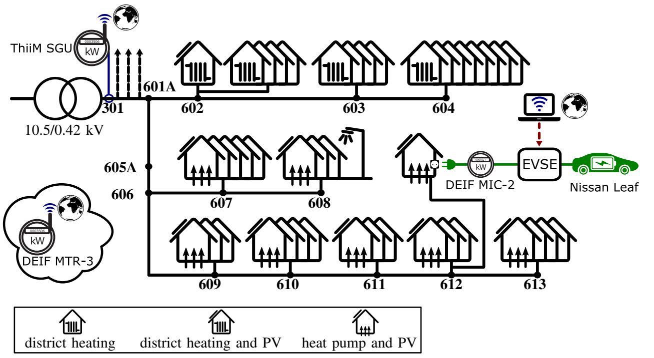

Fig. 3: Schematic overview of the conducted field test and corresponding grid's topology.

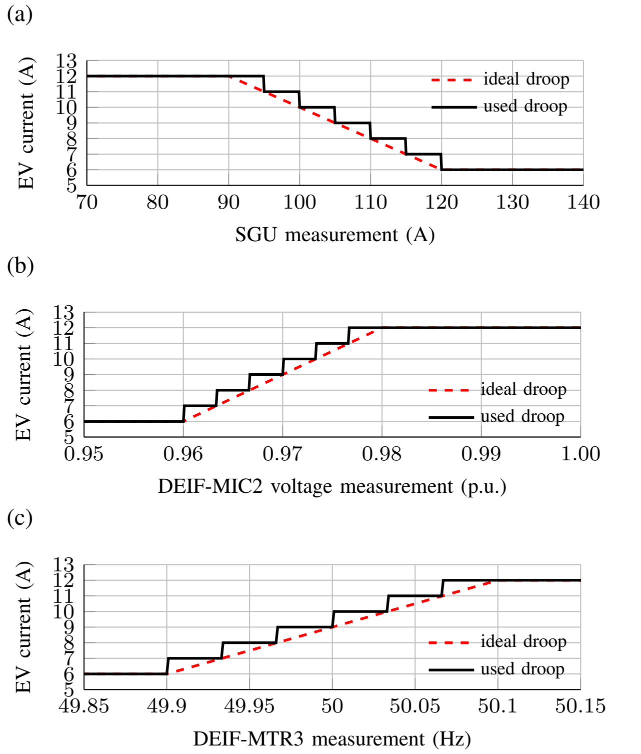

Fig. 4: Implemented droop characteristics for: (a) transformer congestion management, (b) local phase-to-neutral voltage support, and (c) frequency-controlled normal operation reserve.

A. Evaluation criteria

The conducted test scenarios, whose results are reported in the following section, are respectively: (1) congestion management, (2) local phase-to-neutral voltage support, and (3) frequency-controlled normal reserve in the Nordic synchronous area. Several trials have been conducted for each test scenario, but only selected ones will be reported in detail in Section IV. Regarding the result evaluation for congestion management and voltage support, there are no defined requirements for measurement equipment or response times as such services still do not exist in practise. However, one can assume that if the EV satisfies frequency control requirements, it would also satisfy the future ones for DSO services, as the overloading and voltage issues are of much slower nature. FCN requirements only define that all reserve must be supplied within 150 seconds, so for what concerns this manuscript, the EV response time is benchmarked to frequency-controlled disturbance reserve where 50% of the response must be provided within 5 seconds and the remaining 50% within additional 25 seconds [33]. The EV performance for each conducted trial is evaluated by assessing several distinctive parameters:

- time difference between the input measurement signal and the set EV current charging limit which will be referred to as *control delay*,
- time difference between the set EV charging limit and the measured EV current which will be referred to as *EV response time*,
- time difference between the input measurement signal and the measured EV current which will be referred to as *overall delay*, and
- magnitude difference between the set EV charging limit and the measured EV current which will be referred to as *EV accuracy*.

The evaluated control delay includes the EV charging limit computation time, the communication delay between the control logic and the EVSE controller as well as the time needed for the EVSE controller to change the PWM signal, including the respective measurement delays. The aim is to assess the controller's overall responsiveness and accuracy compared to the ideal droop controllers commonly used in the simulation studies, i.e., the one where the EV responds with no accuracy error and with a negligible response time.

IV. Results

A. Congestion management

The first tested ancillary service is congestion management where the EV is responding to the total feeder current measurement of its respective phase. Fig. 5 shows the measured input, and outputs for one conducted 30-min trial.

First of all, Fig. 5a depicts the total feeder current measurement where two current dips are obvious. These dips correspond to faulty measurements, or more precisely skipped measurement samples which are not an unusual occurrences for measurement units. Since the used measurement device has a 30 second sampling rate, skipped samples result in zero value for half a minute. Secondly, Fig. 5b shows how the EV has the inverse proportional behaviour from the input measurement signal. More precisely, when the feeder current is close to the upper threshold, the EV charges at lower rates, and vice versa. For the skipped measurements, the controller will assume the EV can be charged at maximum rate which may not correspond to reality. However, for validating purposes of this manuscript, the faulty measurements were not seen as an issue, so the resilience to them has not been investigated in detail. A reasonable solution for overcoming these issues could be remaining the previous EV charging limit, which has been left for future work. Finally, it is clear how the measured EV current is not identical to the set charging limit. The shapes of the two curves coincide almost completely, but

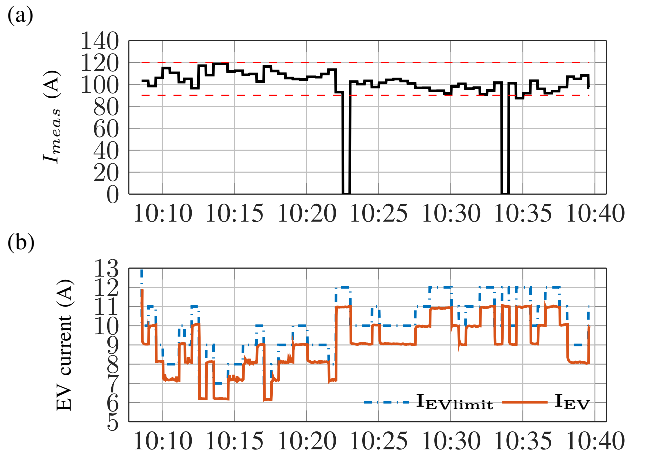

Fig. 5: (a) Measured total feeder current at the transformer station, and (b) set EV charging limit and measured EV response current for the congestion management trial.

there is a consistent offset in their magnitudes. Hence, one can expect that control delay and EV response time are within few seconds, whereas the EV accuracy is not close to the ideal one. The specific values for these parameters are reported in IV-D.

Furthermore, in case of a large EV number, the validated controller can be scaled up and utilised by an aggregator for centralised control. In that case, the whole control logic would be implemented on the aggregator's side, whereas each EVSE would just receive the charging limit as a reference.

B. Local voltage support

The second tested ancillary service is providing local voltage support, and partially mitigating the EV self-induced low voltages. Contrary to the congestion management trial, the EV here responds proportionally to the voltage of the phase where it is connected to. In fact, as shown in Fig. 6, the EV charging rate is lower if the measured voltage is low in order not to additionally burden the grid.

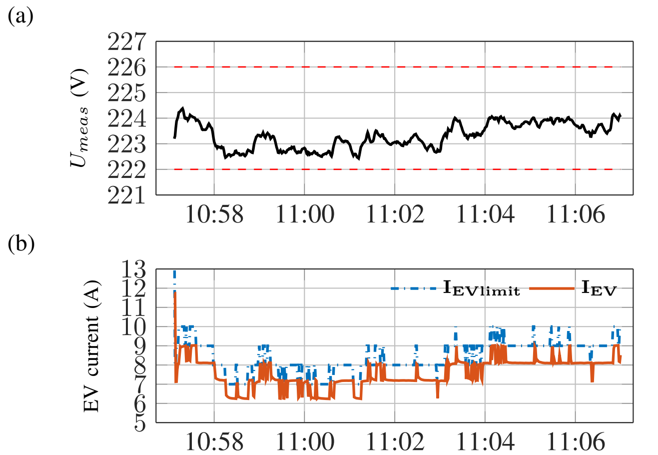

Fig. 6: (a) Measured local phase-to-neutral voltage U_{cn}, and (b) set EV charging limit and measured EV response current for voltage support trial.

Since the validation was conducted on a cold winter day, the residential consumption was relatively high due to heating purposes, resulting in overall low voltages. The measured voltage does not cross the set thresholds, so the EV does not charge at its maximum or minimum rate. Still, since the voltage is not constant, the EV charge is modulated according to the specified droop characteristic. One should note how the chosen droop characteristic is quite steep, and the whole EV flexibility range is utilised within 0.02 U_n in order to stress the EV by changing the charging limit more often. As the voltage measurements are sampled every second, small voltage deviations result in fast set point changes which can be observed as spikes in Fig. 6, both in the set charging limit, as well as in the measured EV current. Nevertheless, the two curves almost perfectly coincide, and the EV response is not jeopardized by fast changes in the charging limit signal. The accuracy remains similar as in the congestion management trial, which will be discussed later on.

In case of large local EV penetrations, this controller can be used for autonomous voltage support by implementing it within the EVSE, which is already equipped with voltage measurements, and thus reducing ICT costs needed for centralised strategies. For such autonomous control, the service provision can easily be scaled up to larger EV numbers, but once chosen voltage limits could not be remotely changed unless additional communication is implemented. However, specific EVSEs could be given different voltage thresholds by the DSO depending on their connection points, or otherwise, the voltage thresholds could be set to $\pm 10\%$ U_n according to EN50160 requirements [34].

C. Frequency-controlled normal operation reserve

The third and final tested ancillary service is providing FCN reserve, whose results are given in Fig. 7. Since the frequency is constantly below 50 Hz in the observed period, the EV is not modulating the charging rate very often. However, the EV behaviour, both in terms of response time and accuracy, is similar to the one observed in the previous trials.

Utilising decentralised droop controls for providing FCN reserve is a common practice today for large power plants which are equipped with fine frequency meters. Yet, it is highly unlikely to expect the same strategy to be used for EVs since it would imply that each EVSE is equipped with costly high precision frequency measurement device approved by the TSO. Therefore, centralised control concept has been tested in this work, where the frequency measurement is routed via the Internet from a device located 40 km away at the Technical University of Denmark. Then, only the calculated EV charging limit is sent to the EVSE. However, the tested controller can be utilised for both centralised and decentralised frequency control strategy, since it can be modified to receive local measurements if available, similarly to the voltage support trial.

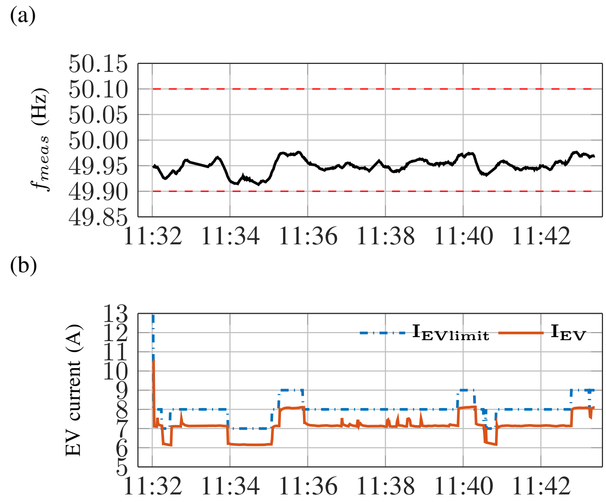

Fig. 7: (a) Measured frequency, and (b) set EV charging limit and measured EV response current for frequency-controlled normal reserve trial.

D. Result overview and further discussion

Fig. 8 depicts the relationships between the measured feeder and the measured EV current for one congestion management trial and several overall delays, with the applied droop characteristic highlighted in red. It is clear that the points are more scattered in case of one and three seconds delay, while they are closer to the applied characteristic in case of two seconds delay. Additionally, there is a clear "undershoot" phenomenon in the EV response, as already mentioned in Section IV.

As a measure of the linear dependence degree between two variables, Pearson product-moment (PPM) correlation coefficient is used. This factor ranges between -1 and +1

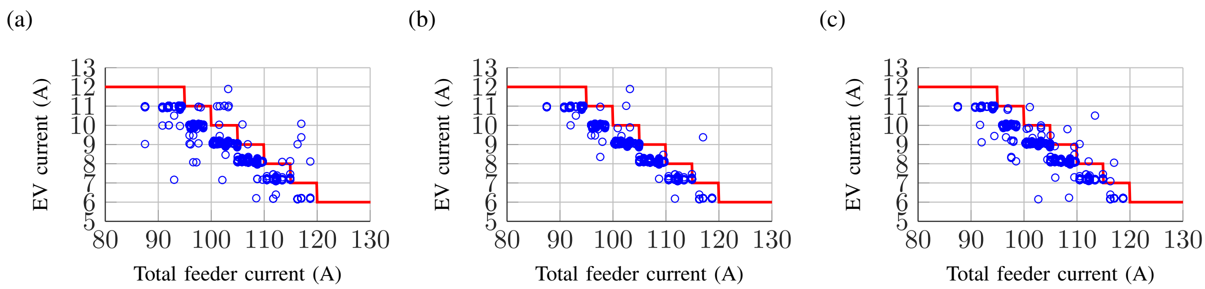

Fig. 8: Relationship between the measured feeder current and the measured EV response current for congestion management field test in case of (a) one second overall delay, (b) two second overall delay, and (c) three second overall delay.

inclusive, where +1 is the perfect positive correlation (increase in the first variable means increase in the second, and vice versa), and -1 is the perfect negative correlation (increase in the first variable means decrease in the second, and vice versa). Detailed PPM correlation coefficients for all tested ancillary services are reported in Table I as follows:

1) Correlation between the respective input measurement signal, and the EV charging limit set by the controller, used for evaluating the average *control delay*.
2) Correlation between the EV charging limit set by the controller, and the measured EV current, used for evaluating the average *EV response time*.
3) Correlation between the respective input measurement signal, and the measured EV current, used for evaluating the average *overall delay*.

All correlations coefficients are obtained for the data sets excluding the skipped measurement samples.

Several conclusions can be derived from Table I. First of all, the correlation between the input measurement signal $\{I, U, f\}_{meas}$ and the set EV charging limit $I_{EVlimit}$ is the highest for one second delay in all conducted trials, leading to the conclusion that the average control delay is one second. Secondly, even though the highest correlation between the set EV charging limit $I_{EVlimit}$ and the measured EV current I_{EV} is for one second delay in almost all of the trials, it is also comparable for two second delay in the congestion management trials which could be due to the input measurement sampling rate of 30 seconds. In the voltage and frequency trials, where the input signal is sampled every second, the correlation is clearly the highest for one second delay. Therefore, it can be deducted that the average EV response time is one second. Finally, the correlation between the input measurement signal $\{I, U, f\}_{meas}$ and the measured EV response current I_{EV}, which includes all communication and measurement delays, is the highest for two seconds delay, but also comparable for three seconds delay.

Since time is the most critical aspect when providing frequency control, the correlation for different overall delays is shown in Fig. 9 for the FCN reserve trial. It is clear there is no correlation for long time delays, and that the EV response is much faster than the requested 25 seconds. Moreover,

TABLE I: PPM correlation coefficients between input measurements, set EV charging limit and measured EV current for all the tested ancillary services and different Δt delays.

	Signals	Δt = 0s	Δt = 1s	Δt = 2s	Δt = 3s
congestion	$I_{meas} - I_{EVlimit}$	-0.9630	***-0.9768***	-0.9635	-0.9497
management	$I_{EVlimit} - I_{EV}$	0.9758	***0.9913***	0.9904	0.9728
trial 01	$I_{meas} - I_{EV}$	-0.9463	-0.9616	***-0.9754***	-0.9713
congestion	$I_{meas} - I_{EVlimit}$	-0.8758	***-0.8782***	-0.8747	-0.8711
management	$I_{EVlimit} - I_{EV}$	0.9873	0.9935	***0.9938***	0.9875
trial 02	$I_{meas} - I_{EV}$	-0.8688	-0.8728	***-0.8758***	-0.8741
voltage	$U_{meas} - I_{EVlimit}$	0.8412	***0.9119***	0.8950	0.8737
support	$I_{EVlimit} - I_{EV}$	0.8374	***0.9557***	0.8605	0.7806
trial 01	$U_{meas} - I_{EV}$	0.8315	0.8820	***0.9261***	0.9185
voltage	$U_{meas} - I_{EVlimit}$	0.7546	***0.8843***	0.8805	0.8760
suport	$I_{EVlimit} - I_{EV}$	0.9023	***0.9260***	0.8076	0.7779
trial 02	$U_{meas} - I_{EV}$	0.8356	0.8575	***0.8830***	0.8788
FCN	$f_{meas} - I_{EVlimit}$	0.7514	***0.8879***	0.8823	0.8730
reserve	$I_{EVlimit} - I_{EV}$	0.8893	***0.9377***	0.8191	0.7975
trial 01	$f_{meas} - I_{EV}$	0.8189	0.8574	***0.8944***	0.8909

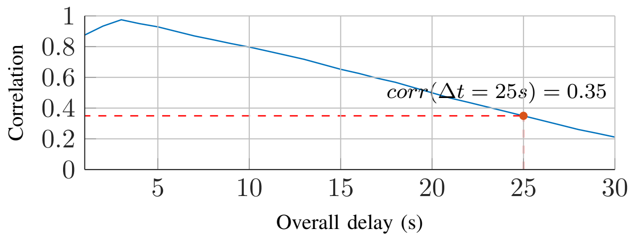

Fig. 9: PPM correlation between the input frequency measurement, and the measured EV current for different overall delays.

TABLE II: Average difference between the set charging limit and the measured EV current - "undershooting" phenomenon.

EV limit	congestion management trial 01	congestion management trial 02	voltage support trial 01	voltage support trial 02	FCN reserve trial 01	all combined
6 A	-	-0.21 A	-	-	-	-0.21 A
7 A	-0.75 A	-0.78 A	-0.68 A	-	-0.82 A	-0.76 A
8 A	-0.81 A	-0.69 A	-0.79 A	-	-0.84 A	-0.81 A
9 A	-0.89 A	-0.86 A	-0.89 A	-0.89 A	-0.93 A	-0.89 A
10 A	-0.95 A	-0.89 A	-1.14 A	-1.01 A	-	-0.95 A
11 A	-1.01 A	-0.94 A	-	-1.25 A	-	-0.99 A
12 A	-1.04 A	-1.04 A	-	-	-	-1.04 A

by analysing the obtained data, it has been observed that the maximum occurring overall delay equals to four seconds including all Internet communication and measurement delays, which would categorise EVs as a fast reserve. Unless EVs provide a very fast reserve such as the inertial response, there is currently no need for additional requirements to improve the EV response time.

On the contrary, the issue which may occur is not the EV response time, but its accuracy. As aforementioned, the tested EV has far beyond an ideal response, since an "undershooting" phenomenon occurs. The average difference between the set charging limit $I_{EVlimit}$ and the measured current I_{EV} is given in Table II. Interestingly, the higher the set charging limit is, the more does the EV "undershoot", leading up to over 1 A difference for the 12 A charging limit. There could be several reasons to explain this phenomenon. First of all, contemporary standards define that EVs must be able to respond to the charging limit, and guarantee that the EV is charging below it. However, one must emphasize that they do not define what is the acceptable deviation from the set limit, so EVs are not manufactured to respond as close as possible to it. Secondly, the EV battery management system is highly dependent on many factors, and the authors believe one of the factors is the outside temperature. In fact, in occasion of previous experiments in laboratory environment [22], the "undershooting" phenomenon was lower than for the conducted field test performed on a winter day with temperatures below 0°C. Thirdly, the battery management system may also be influenced by the battery state of charge (SOC) and previous driving behaviour. Unfortunately, these hypotheses cannot be thoroughly investigated as the information from the battery management system itself is not broadly available.

As a final remark, modulating the EV active power influences the SOC and consequently user comfort and, in the worst case, the EV would constantly charge at the minimum 6 A. According to [35], the average EV plug-in time is 13 h, whereas the initial SOC equals to around 50%. Assuming the battery size of 24 kWh, the EV charging time would increase from around 3.5 hours at a 16 A charging rate to around 8.5 hours at a 6 A rate, which is still well below the average plug-in time of 13 hours. However, due to many uncertainties, the authors are aware that EV owners may not allow active power modulation due to fear of not having the EV available for transportation purposes. In that case, the same principle could be used for modulating the EV reactive power which does not influence the SOC. However, current EVs are not equipped with reactive power control, so future work includes applying this controller for modulating the power factor when EVs will be capable of it.

V. Conclusion

This paper focused on validating the technical feasibility of a series-produced EV to provide flexibility in real distribution grids. It presents a droop controller which uses contemporary standards and can be used with all series-produced EVs complying with international standards IEC 61851 and SAE J1772. The conducted field validation tested three ancillary services: congestion management, local voltage support and frequency-controlled normal operating reserve. Overall, the field validation proved that providing ancillary services by EVs is technically feasible already today with existing commercial EVs without any Vehicle-to-Grid capability, and with a very fast response time. The overall delay, including all communication and measurement delays, was 2-3 seconds in average, and never exceeded 4 seconds. However, an "undershooting" phenomenon in current magnitude was noticed when limiting the EV charging rate which may arise as a greater problem than the response time. This difference varied depending on the set charging limit, but can amount to more than 1 A.

There is much room for improvement in EV integration, and the authors have identified several points. First of all, the EV charging systems should not be designed only to guarantee the charging current below a certain limit, but also to be as close as possible to the preferred limit. Considering the available 1 A granularity, an "undershooting" of 1 A can be considered unacceptable as it corresponds to a lower charging set point. Secondly, the overall delay is currently more than enough for the distribution grid services, but it could be additionally shortened by optimising control, communication and EV charging system. This could be of particular value for several services, such as frequency control or provision of virtual inertia. Finally, the granularity of 1 A may not be good enough for using EVs for smart grid purposes, since 1 A amounts to 10% of EV's available flexibility. Considering that EVs are high loads and have a significant grid impact, lower granularity would provide a higher flexibility degree with potentially less influence on the EV owners. More precisely, it would allow EVs to charge at an intermediate rate low enough to mitigate the grid adverse effects, but as high as possible to charge the vehicle faster.

Since EVs could be a valuable asset for all power system entities, the authors' believe that additional standards are needed to address the identified issues, and oblige the EV manufactures to optimise their systems. Future work includes the extension of the field testing to several vehicles to assess the coordination issues, as well as extending the controller logic to more advanced distributed approaches.

Acknowledgment

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Pub. H. Management of power quality issues in low-voltage networks using electric vehicles: Experimental validation

Management of Power Quality Issues in Low Voltage Networks using Electric Vehicles: Experimental Validation

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***Abstract*—As Electric Vehicles (EVs) are becoming more wide spread, their high power consumption presents challenges for the residential low voltage networks, especially when connected to long feeders with unevenly distributed loads. However, if intelligently integrated, EVs can also partially solve the existing and future power quality problems. One of the main aspects of the power quality relates to voltage quality. The aim of this work is to experimentally analyse whether series-produced EVs, adhering to contemporary standard and without relying on any V2G capability, can mitigate line voltage drops and voltage unbalances by a local smart charging algorithm based on a droop controller. In order to validate this capability, a low-voltage grid with a share of renewable resources is recreated in SYSLAB PowerLabDK. The experimental results demonstrate the advantages of the intelligent EV charging in improving the power quality of a highly unbalanced grid.**

***Index Terms*—Electric vehicles, power distribution testing, power quality, unbalanced distribution grids, voltage control.**

I. INTRODUCTION

DISTRIBUTION system operators (DSOs) have historically designed and operated their networks in order to follow a predicted demand with uni-direction power flows only. Nowadays, due to increased share of renewable energy resources, DSOs are confronted with changes in the low-voltage grid operation with even greater system complexity imposed by electric vehicle (EV) integration [1], [2]. Danish Energy Association predicts 47,000 EVs in Denmark by 2020 in a moderate penetration scenario [3], meaning that distribution networks will have to cope with overall voltage degradation, especially in unbalanced systems where voltage quality is already decreased. Unlike in other European countries, the three-phase connection in Denmark is not reserved only for industrial consumers, but is also available for residential customers. Therefore, Distribution System Operators (DSOs) experience high voltage unbalances due to the lack of regulation for per phase load connection [4]. Uncontrolled EV charging in such grids may result in large power quality deterioration, i.e., higher voltage unbalances [5], and the rise of neutral-to-ground voltage due to single-phase charging [6].

As an economic alternative to grid reinforcement, different EV charging strategies can be used for supporting the grid and enhancing both the efficiency and the reliability of the distribution system [7]. An extensive amount of research shows that intelligent integration, namely smart EV charging, can be used for lowering the impact on the power system or providing different ancillary services [8]–[14]. In order to integrate electric vehicles in the distribution grid, both centralised and decentralised charging strategies have been explored [15]–[17]. It has been found that centralised algorithms lead to the least cost solution and are easily extended to a hierarchical scheme, but they require great communication infrastructure for information exchange. On the other hand, decentralised control provided similar results to the centralised one without the complex communication infrastructure.

A decentralised voltage dependent charging strategy, which requires only local voltage measurements, can be used for mitigating the low EV-induced voltages [18], [19]. That is, EV charging power can be modulated in accordance to local voltage measurements in order to compensate the voltage unbalances and improve the overall power quality [20], [21]. However, technical challenges may arise and DSOs may be sceptical about the possibility of the distributed demand participating in the grid regulation. Therefore an extensive experimental activity is required for proving the feasibility of these solutions.

A. Objectives

As stated in [22], electric power quality is a term that refers to maintaining the near sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency. Thus power quality is often used to express voltage quality, current quality, reliability of service, etc. While frequency regulation is a system wide service, experimentally addressed in previous work [23], this paper is focusing on the other main aspect of power quality in LV networks i.e. voltage quality. To the authors' knowledge, most of the literature focuses on modelling the EV voltage support, whereas the experimental validation is rarely touched upon. Therefore, this work mainly focuses on the experimental evaluation of the real EV's ability to reduce voltage unbalances by modulating their charging current according to local voltage measurements. This autonomous control could partially solve voltage quality issues without the need for grid upgrades or costly communication infrastructure,

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therefore enabling the integration of higher EV numbers in the existing power network. The experiment is carried out with commercially available vehicles without any Vehicle-to-Grid (V2G) capability, but with the possibility to modulate the charging current in steps according to the predefined droop control. Several scenarios differing in load unbalances and implemented droop controller have been tested in order to assess the influence of EV smart charging on improving power quality in the low voltage grid.

The paper is organised as follows. Section II briefly recalls the standards regarding the voltage power quality and the motivation for implemented voltage control. In Section III, the applied methodology and experimental setup are presented in details with a description of conducted scenarios. Finally, the results are discussed in Section IV followed by the conclusion in Section V.

II. Voltage control

The modern three-phase distribution systems supply a great diversity of customers imposing a permanent unbalanced running state. Contrary to other disturbances in the power system for which the performance is evident for the ordinary customers, voltage unbalance belongs to those disturbances whose perceptible effects are produced in the long run. Unsymmetrical consumption and production lead to voltage and current unbalances which imply greater system power losses, interference with the protection systems, components' performance degradation and overheating possibly to the point-of-burnout. Further on, the main effects of unbalanced voltages are mostly noticeable on the three-phase components e.g., transformers, synchronous machines and induction motors which are designed and manufactured so that all three phase windings are carefully balanced with respect to the number of turns, winding placement, and winding resistance [24]. Essentially, the unbalanced voltages are equivalent to the introduction of a negative sequence component with an opposite rotation to the one of the balanced voltages, resulting in reduced net torque and speed, as well as torque pulsations. In addition, large negative sequence currents introduce a complex problem in selecting the proper overloading protection. Particularly since devices selected for one set of unbalanced conditions may be inadequate for others.

To ensure that electric appliances are operated in a safe manner, the European standard EN50160 [25] defines acceptable limits for several grid parameters. More precisely, the standard defines the limits for Root Mean Square (RMS) phase-to-neutral voltage magnitude $|U_{pn}|$ and the Voltage Unbalance Factor (VUF) as follows:

$$0.9\ U_{nom} \leq |U_{pn}| \leq 1.1\ U_{nom} \tag{1}$$

$$VUF \leq 2\%, \tag{2}$$

for $> 95\%$ of all weekly 10 minute intervals, and

$$0.85\ U_{nom} \leq |U_{pn}| \leq 0.9\ U_{nom}, \tag{3}$$

for $< 5\%$ of all weekly 10 minute intervals. In addition, the standard defines the VUF as:

$$VUF[\%] = \frac{|U_{inverse}|}{|U_{direct}|} \times 100. \tag{4}$$

where $|U_{direct}|$, and $|U_{inverse}|$ are the direct (positive) and the inverse (negative) voltage symmetrical component respectively. Since the definition described in (4) involves voltage magnitudes and angles, i.e., complex algebra for calculating the positive and negative components, equations (5) and (6) give a good approximation while avoiding the use of complex algebra [26].

$$VUF[\%] = \frac{max\{\Delta|U_a^i|, \Delta|U_b^i|, \Delta|U_c^i|\}}{|U_{avg}^i|} \times 100 \tag{5}$$

$$|U_{avg}| = \frac{|U_{an}^i| + |U_{bn}^i| + |U_{cn}^i|}{3}, \tag{6}$$

where $\Delta|U_a|, \Delta|U_b|, \Delta|U_c|$ are deviations of the respective phase-to-neutral voltage magnitudes from the average phase-to-neutral voltage magnitude $|U_{avg}|$, for the observed time window i. These equations will be used later on for assessing the voltage unbalances in the tested study case.

A. Voltage controller implemented in the EVs

Generally droop controllers are used in power systems for distributing the regulation services among multiple machines regardless of the service purpose: frequency with active power control, voltage with reactive power control or voltage with active power control, etc. The chosen droop controller has been adjusted to the application needs by choosing the thresholds corresponding to the acceptable voltage limits. Three different threshold pairs have been tested, with two different proportional slope/gain values.

The used droop controllers have been inspired by the aforementioned standard. Firstly, an upper threshold for the droop controlled voltage is set to 0.95 U_{nom}, above which EVs charge at the maximum current I_{max} of 16 A. Secondly, they can either charge at minimum current I_{min} of 6 A or stop the charging process if the voltage drops below 0.9 U_{nom}, corresponding respectively to the *real droop 1* and *real droop 2* seen in Fig. 1a. The values in-between the EV charging limits would ideally be linear according to the voltage measurement. However, the current controller has the minimum charging current limit of 6 A and the steps of 1 A as defined in the IEC 61851 [27]. Therefore using a typical 3.7 kW EV charger, there are 10 current steps in total. In the implemented controller, these steps are equally distributed between 0.9 and 0.95 U_{nom}. In addition, a steeper droop control corresponding to *real droop 3* in Fig. 1b has also been tested. Similarly to the first droop control, this control also has 10 current steps equally distributed between the charging limits, but the lower voltage limit is set to 0.925 U_{nom}.

Defining an exact droop value for EVs or loads in general, may not be straightforward as it may not be clear what is the nominal power of the load. In this case, it has been considered that the available range of regulating power (i.e., 2.3 kW) is equal to the EV's nominal power instead of the overall EV charging power which amounts to 3.7 kW. The following parameters have been defined for the described droop controls, i.e., (7) for the droop control seen in Fig. 1a and (8) for the droop control seen in Fig. 1b:

$$\begin{cases} \Delta U = 11.5V; U_{nom} = 230V \\ \Delta P = 2.3kW; P_{nom} = 2.3kW \\ k_{droop} = \frac{\Delta U / U_{nom}}{\Delta P / P_{nom}} = 5\% \end{cases} \quad (7)$$

$$\begin{cases} \Delta U = 5.75V; U_{nom} = 230V \\ \Delta P = 2.3kW; P_{nom} = 2.3kW \\ k_{droop} = \frac{\Delta U / U_{nom}}{\Delta P / P_{nom}} = 2.5\% \end{cases} \quad (8)$$

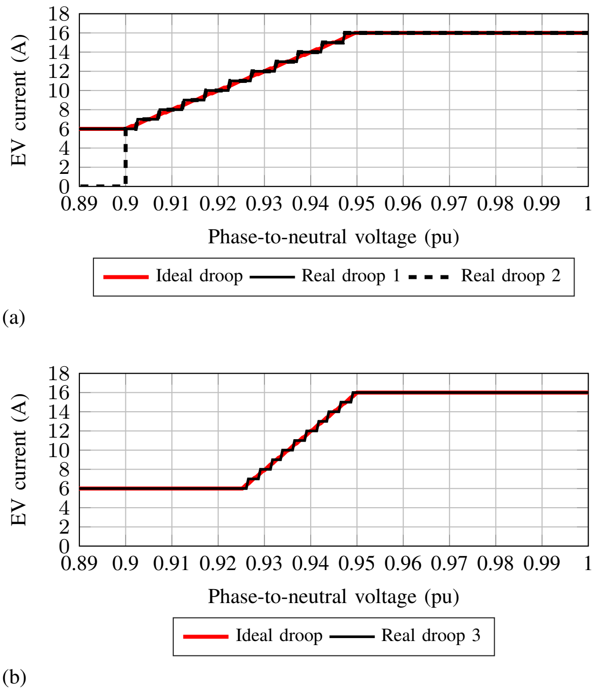

Fig. 1: Implemented droop controls: (a) k=5%, and (b) k=2.5%

Droop controller calculates the EV charging current limit I_{droop} using the following formula:

$$I_{droop} = \frac{(U_{meas} - U_{nom}) * (I_{max} - I_{min})}{(U_{nom} * k_{droop})} + I_{base} \quad (9)$$

where U_{meas} is the actual voltage measurement and I_{base} is a base EV charging current when voltage is at the nominal value and corresponds to 11A.

$$I_{EV} = \begin{cases} I_{droop}, & I_{min} \leq I_{droop} \leq I_{max} \\ I_{max}, & I_{droop} > I_{max} \\ I_{min}, & I_{droop} < I_{min} \end{cases} \quad (10)$$

I_{max} value represents the available power connection current rating at the consumer site, which is typically 16A, and can be further upgraded to 32A or higher. While I_{min} is chosen from lower charging current limit from IEC 61851 standard.

III. Methodology and Experimental Procedure

To validate the previously described controller in real EV charging processes, typical low voltage distribution feeder has been recreated in a laboratory environment. The feeder is grid connected through a typical MV/LV 200 kVA distribution transformer, whereas the EVs are connected in the end of the feeder next to the resistive load, representing a common home charging setup. Additionally, the feeder includes a set of renewable sources such as a wind turbine along with a controllable resistive load capable of modulating the consumption independently per phase.

The EV voltage support can theoretically be done by modulating the active and/or the reactive power. However, since the reactive power control is currently not available in commercial EVs, this experiment focuses on active power control for voltage support. Each electric vehicle supply equipment (EVSE) is equipped with a local smart charging controller which adjusts the EV charging power according to the droop control described in II-A. Since the controller is independent for each vehicle, the charging current is calculated based only on local voltage measurement meaning that the EVs connected to different phases will react differently. Therefore, the vehicles connected to heavy loaded phases will provide more voltage support due to lower measured voltages resulting in being a less burden to the already unbalanced grid.

A. Experimental setup

The experiments are performed in SYSLAB (part of PowerLabDK) which is a flexible laboratory for distributed energy resources consisted of real power components parallelled with communication infrastructure and control nodes in a dedicated network. The complete test setup is distributed over the Risø Campus of Technical University of Denmark. The studied experimental setup is depicted in Fig. 2 and Fig. 3. As seen in the figures, the setup consists of the following components:

- 3 commercially available EVs (Nissan Leaf) with single phase 16 A (230 V) charger and 24 kWh Li-Ion battery.
- 2-blade wind turbine Gaia with rated power P_n = 11 kW.
- 45 kW resistive load (15 kW per phase) controllable per single-phase in 1 kW steps.
- set of Al 240 mm^2 underground cables approximately 1.95 km in length with AC resistance at 45^oC $R_{AC} = 0.14\Omega/km$ and series reactance $X = 0.078\Omega/km$
- 75 m of Cu 16 mm^2 cable with AC resistance at 45^oC $R_{AC} = 1.26\Omega/km$ and series reactance $X = 0.076\Omega/km$
- 10/0.4 kV, 200 kVA transformer.

The wind turbine connected to the test grid, although not significantly large as active power source, provides stochastic active and reactive power variation to the system. Additionally, it makes the test grid closer to a possible realistic distribution grid with more diverse components than just pure resistive loads.

From the line parameters above, the X/R ratio is calculated to highlight the impedance characteristic of the grid: X/R equals to 0.43. The X/R ratio of the test system is quite low i.e., in the range of the typical LV system and is comparable to CIGRE network [28] as well as other benchmark systems.

Therefore, active power modulation is the most effective way to control voltage levels although reactive power control could also be effective to a certain extent as shown in reference [11].

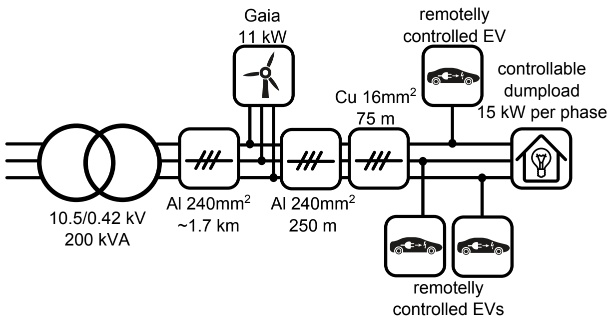

Fig. 2: Schematic overview of the experimental setup

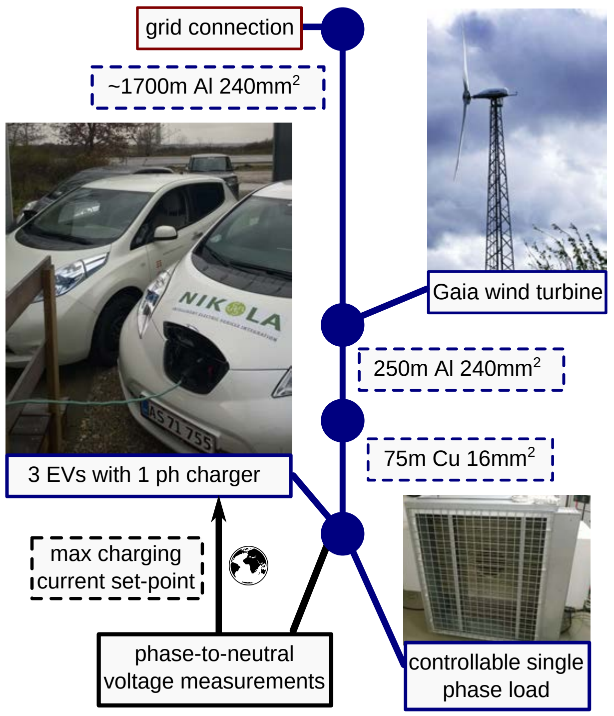

Fig. 3: Experimental setup for the voltage unbalance testing

The EV chargers are not equipped with Vehicle-to-Grid capability, but unidirectional charging rate can be remotely enabled and modulated between 6 A and 16 A with 1 A steps.

B. EV control algorithm

To enable EV smart charging, a control loop has to be established. The control loop typical consists of three components connected to the system: measurement device, controller and actuator. In this work, the measurement equipment providing the input for the controller is DEIF MIC-2 multi-instrument meter with 0.5% accuracy and 1 second sampling rate. The actuator that transfers the control signal to the system under control is Nissan Leaf EV with controllable charging current. The controller is designed as a simple, yet robust droop control algorithm, as described in II-A, and integrated to the following control loop:

1) Phase-to-neutral voltage is measured locally at each EVSE on second basis
2) The EV smart charging controller receives and evaluates:
   - Phase-to-neutral voltages at the connection point
   - The actual charging rate
3) The controller sends a control signal to the Electric Vehicle Supply Equipment (EVSE) for adjusting the EV charging current limit.

The control architecture, with the entire control loop, is shown in Fig. 4.

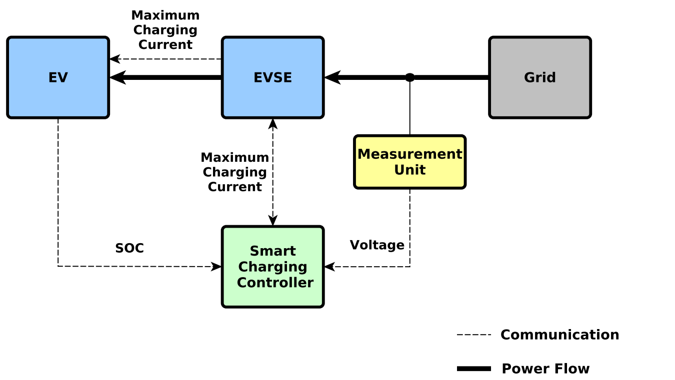

Fig. 4: Information and control flow for the smart charging of each vehicle

In this approach, the flexibility in the EV charging power could be exploited to preserve stable phase-to-neutral voltages while maintaining the user comfort since the EV is primarily used for transportation functions. The phase-to-neutral voltages are measured locally at the (EVSE) using the built-in power meter, which are then compared to the nominal voltage and chosen thresholds. Since the primary goal of this validation is proving that the controlled EV charging can improve the power quality, smart charging function for reaching the target State of Charge (SOC) by the scheduled time of departure has been omitted and left for future work.

C. Experimental procedure and result evaluation

The experiments are intended to test the EV capability to modulate the charge level according to the voltage measurements in order to provide voltage support and partially mitigate the voltage unbalances. The per-phase controllable load is used to represent a realistic variable household consumption, creating voltage unbalances due to different load fractions per phase.

Several test-cases will be analysed to evaluate the power quality in such a system. The full overview of conducted test scenarios is shown in Table I. The scenarios could be grouped into four main groups:

1) Uncontrolled charging scenario with no EV charging control - test scenario I.
2) Controlled charging scenario with 5% droop and minimum charging current of 6 A - test scenarios II to IV.

3) Controlled charging scenario with 5% droop and minimum charging current of 0 A - test scenarios V - VII.
4) Controlled charging scenario with 2.5% droop and minimum charging current of 6 A - test scenario VIII.

For each test scenario the single-phase load is increased from 0 up to 43 A in 5 steps.

The system performance is evaluated by measuring relevant phase-to-neutral voltages as well as VUFs. This analysis allows the investigation of issues arising when dealing with practical implementation of voltage support, such as communication latency, power and voltage measurement inaccuracies, and coordination of more sources. Additionally, it should be noted that the experimental setup is only using communication and control equipment that follows existing industry standards. Hence, tested control algorithms can be applied to any real grid operation, ensuring the interoperability and minimal integration effort.

IV. Results

To demonstrate the differences between uncontrolled and controlled EV charging, test scenarios shown in Table I were executed. Following subsections present the most relevant findings for each of the conducted scenarios.

A. Voltage quality using uncontrolled EV charging

Firstly, the setup is tested using the most occurring situation nowadays - uncontrolled EV charging, while the resistive load at the end of the feeder, representing the domestic consumption, is gradually increasing. Measured voltages at the EVSE, load increase steps and corresponding EV charging currents can be seen in Fig. 5.

Clearly, such voltage quality is unsatisfactory as phase-to-neutral voltages drop below 0.9 U_n on all phases for the maximum load step. Meanwhile, the EVs are steadily charging at the maximum current regardless of the grid status since there is no implemented control. It should be noted that one of the EVs is charging at 17 A even though the same 16 A rated current applies to all of the cars. This shows how even the same EV models differing only in the production year can have different impact on the power quality. Similar findings will be discussed later on for controlled charging scenarios. In addition, one can notice how the load steps are not completely synchronised for all three phases which will also apply to later on scenarios. The reason lies in the lack of automatic control, i.e., the steps had to be manually input into the device. However, this fact does not influence the EV behaviour.

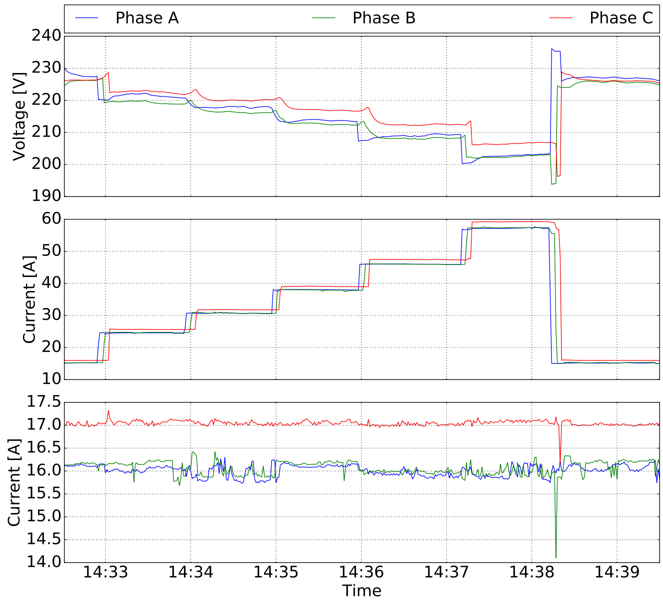

Fig. 5: Voltage and load current measurements for EV uncontrolled charging - test scenario I

B. Voltage quality using EV droop control

Firstly, the droop controller with a 5% droop and minimum charging current of 6 A, shown as *real droop 1* in Fig. 1a, is applied to the EV charging. Measured voltage at the EVSE, load increase steps and corresponding EV charging currents can be seen in Fig. 6, whereas Fig. 7 shows the correlation between the measured phase-to-neutral voltage and the measured EV response for each of the phases. The correlation plot closely resembles the droop characteristic shown in Fig. 1a.

It can be observed that the EVs already start responding at the second load step since the voltage exceeds the droop control boundary of 0.95 U_n. Even for the maximum loading, the voltages are kept above 0.9 U_n as EVs are reducing the charging currents to a minimum value of 6 A. Another interesting phenomena to notice is that the phase-to-neutral voltage on the unloaded phase is rising when the load is increased on the other phases. That is due to a floating, not grounded, neutral line, which introduces a greater voltage unbalance.

TABLE I: Overview of conducted scenarios

Scenario	I	II	III	IV	V	VI	VII	VIII
Load	3 phase	3 phase	2 phase	1 phase	3 phase	2 phase	1 phase	3 phase
Droop Control	-	5%	5%	5%	5%	5%	5%	2.5%
Min EV Current	16A	6A	6A	6A	0A	0A	0A	6A
Maximum load current on phase a [A]	43	43	43	0	43	43	0	43
Maximum load current on phase b [A]	43	43	43	0	43	43	0	43
Maximum load current on phase c [A]	43	43	0	43	43	0	43	43

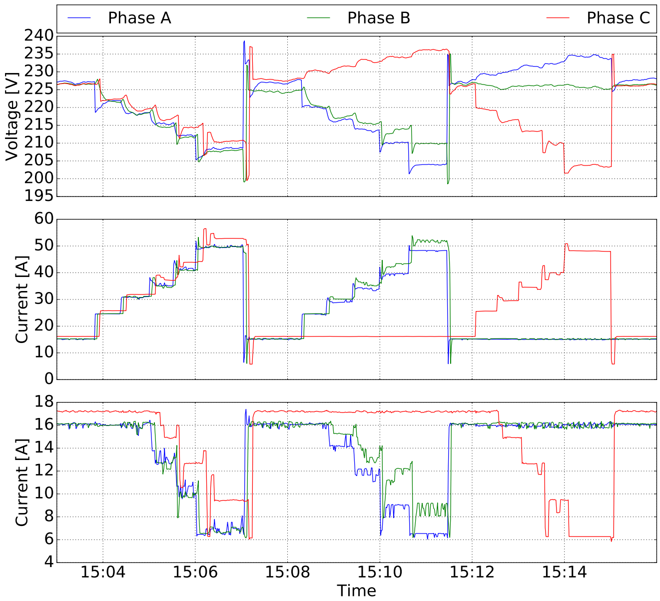

Fig. 6: Voltage, load and charging current measurements for EV smart charging test scenarios: II - 15:03 to 15:08, III - 15:08 to 15:12 and IV - 15:12 to 15:16

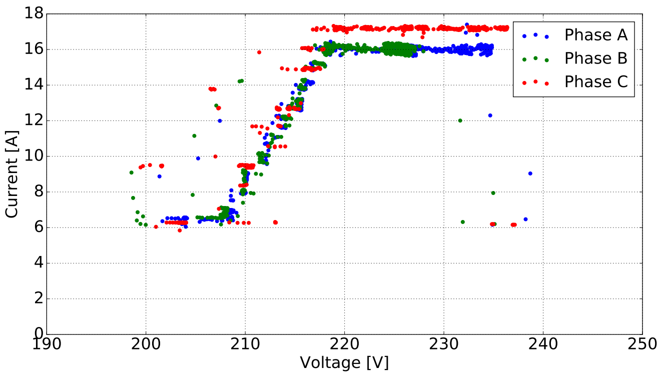

Fig. 7: Correlation plot between measured phase-to-neutral voltage and EV current for test scenarios II to V

C. Voltage quality using EV droop control with stopping the charge

Controlled EV charging according to IEC61851 also has the ability to stop and restart the charging of the vehicle. This function could potentially further improve the power quality in the system as the load from the EV could temporarily be removed. Therefore, the same droop controller with 5% slope, but minimum charging current of 0 A is studied. The modification of the droop curve is done as shown in Fig. 1a as *real droop 2*.

Similarly to previous scenarios, Fig. 8 shows the measured voltage at the EVSE, load increase steps and corresponding EV charging currents.

Fig. 9 presents the correlation between the controller's input voltage and the measured EV response. The relation pattern is partly resembling the curve shown on Fig. 1a as *real droop 2*. Although, unlike in the droop curve two clear drops at 6 and

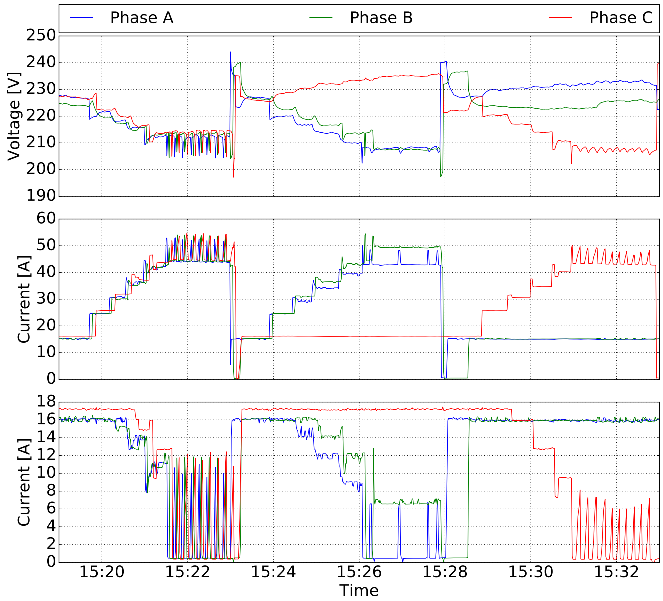

Fig. 8: Voltage, load and charging current measurements for EV smart charging test scenarios: V - 15:19 to 15:24, VI - 15:24 to 15:28 and VII 15:28 to 15:33

10 A are present. The second drop appears due to controller induced oscillation explained further.

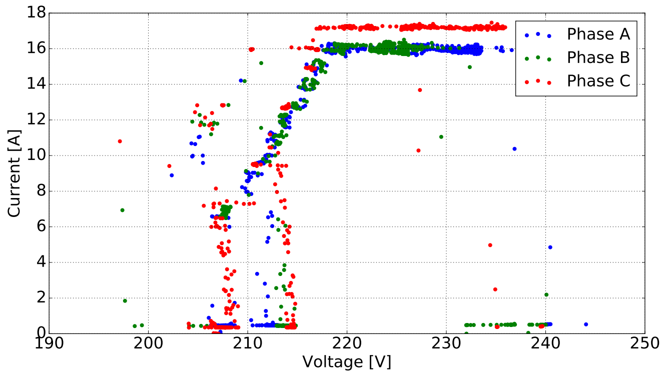

Fig. 9: Correlation plot between measured voltage and EV current for test scenarios V to VII

Fig. 8 shows that the system response is almost identical to the test scenarios II to IV, besides in the maximum loading case. At that point, one can notice oscillations in test scenario V and VII which occur due to the brief voltage dip for the last load step. This step briefly puts the voltage under 0.9 U_n, which triggers the controller to stop the charging of the EVs. As the EVs stop charging, the voltages rise to about 0.93 U_n, which makes the controller restart the EV charging since the voltage is now high enough. The restarting process takes about 8 seconds. However, as the EVs restart the charging, the voltage briefly dips under 0.9 U_n again making the controller to stop the charging. This instability repeats as long as the voltage level stays close to 0.9 U_n. In scenario VI, EV on phase a stably mitigates the voltage unbalance by stopping the charge. At the same time, EV on phase b also stabilises the charging current at 7 A, right at the lower limit of stopping the charge. The aforementioned oscillation issues could be solved by modifying the controller to detect the voltage transients and only react for the steady state voltage measurements. However, this has been omitted from the conducted study and left for future work.

D. *Voltage quality using EV droop control with steeper droop characteristic*

The droop control has then been modified, making it more steep as shown in Fig. 1b. As for the previous scenarios, measured voltage at the EVSE, load increase steps and corresponding EV charging currents can be seen in Fig. 10, whereas the correlation is depicted in Fig. 11. As the droop curve used in this scenario is more steep, minor oscillations are present on phase c due to a slower response of the EV on this phase.

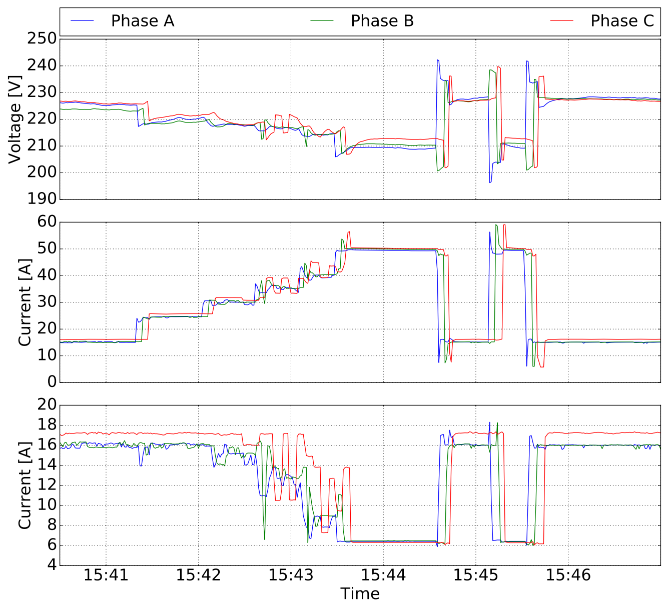

Fig. 10: Voltage, load and charging current measurements for EV smart charging - test scenario VIII

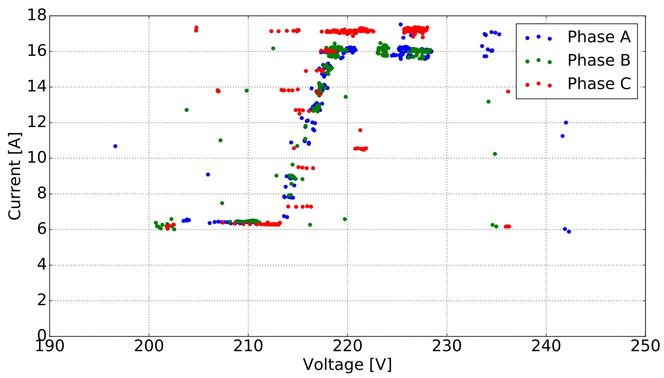

Fig. 11: Correlation plot between measured voltage and EV current for test scenario VIII

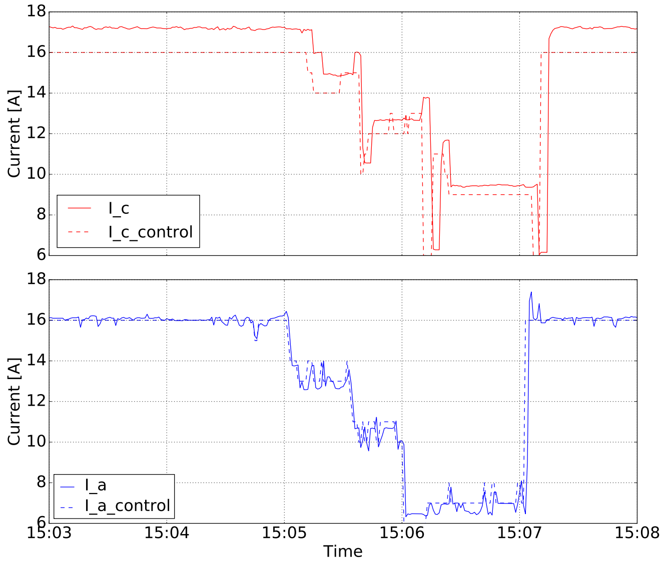

Fig. 12: Sample charging current control signal and measured value for EV smart charging - test scenario II

Moreover, Fig. 12 illustrates the difference between the control and the actual EV charging current. The EVs on phase a and b respond to the control signal in 1 to 2 seconds, while EV on phase c takes 4 to 5 seconds. The difference is due to a older production year for the EV connected to phase c. It is also important to note that the control signal sent to the EV is merely an upper limit for the charging current. Hence, the actual charging current of the vehicle should be below the set limit. However, EV on phase c is violating the set charging current limit by 1 A. It is an atypical behaviour possibly caused by a recent charger firmware update.

E. *Result overview*

According to EN50160, the voltage quality is typically assessed over a week with 10 minutes average intervals. However, the main reason to focus on a shorter period of time in this paper, is to evaluate the performance of the controller. The limited 10 minute intervals show the system response to the load event and control actions taken, in this period the voltage in the system stabilizes to new steady states, therefore this experimental time window can be extrapolated to longer time periods. Additionally, vehicles are solving the problem partly caused by themselves thus, it is reasonable to experience less voltage problems if EVs are not charging.

The setup was tested in 8 test scenarios with the result summary shown in Table II. Maximum VUF is calculated from the values observed at the maximum feeder loading. Steady state voltage values in the maximum load case are also shown for each test scenario. Finally, the voltage drops between the grid and EV connection points at the maximum load case are shown.

Firstly, one should note that smart charging when all 3 phases are evenly loaded (test scenarios I, II, V and VIII) improves the VUF. Secondly, VUF in heavily unbalanced scenarios is much beyond the standard limit for scenarios III,

TABLE II: Maximum VUF, steady state voltage values and voltage drop from grid connection to the EV connection point

Scenario	I	II	III	IV	V	VI	VII	VIII
Load	3 phase	3 phase	2 phase	1 phase	3 phase	2 phase	1 phase	3 phase
Droop Control	-	5%	5%	5%	5%	5%	5%	2.5%
Min EV Current	16A	6A	6A	6A	0A	0A	0A	6A
$\mathbf{VUF_{max}}[\%]$	1.3	0.8	9.0	7.9	0.6	8.4	6.4	1.0
$\mathbf{U_{an_{maxloadss}}}[\mathbf{V}]$	202.8	208.4	203.6	234.5	212.5	208.0	233.0	209.0
$\mathbf{U_{bn_{maxloadss}}}[\mathbf{V}]$	202.6	207.9	209.6	225.7	213.5	207.5	225.0	210.5
$\mathbf{U_{cn_{maxloadss}}}[\mathbf{V}]$	206.6	210.5	235.9	203.5	214.0	235.0	208.5	212.6
$\mathbf{\Delta U_{an}}[\mathbf{V}]$	33.0	27.4	32.1	1.6	23.5	27.8	3.0	27.0
$\mathbf{\Delta U_{bn}}[\mathbf{V}]$	30.3	25.1	23.1	7.3	20.7	25.4	7.2	22.6
$\mathbf{\Delta U_{cn}}[\mathbf{V}]$	28.3	24.4	-1.2	31.3	19.7	-0.1	27.5	22.3

IV, VI and VII. H ere, the controller tries to minimise the unbalance by setting EV charging current to the minimum value specified for each scenario. However, vehicles alone can not eliminate the unbalance in the case of maximum loading, since controllable EVs represent only 17 % of the total load. This flexibility could be extended to 25 % if the charging is stopped. It should be noted that values of smart charging scenarios V, and VII were calculated from the measurements of the steady states between the oscillations. Nevertheless, greater controllable power amount results in significant improvements in power quality for scenarios V to VII.

V. Conclusion

This work presented a method for improving the power quality of a low voltage network by intelligently controlling EV charging current. The validation showed how uncontrolled EV charging can significantly reduce the power quality of low voltage networks, especially in unbalanced networks with long feeder lines. It is shown that EV smart charging, even with a simple decentralised autonomous droop controller, can solve some of the power quality issues. The improvements include reduced voltage drops at the long feeder branches and potentially reduced VUFs in the cases of unbalanced loading. However, EVs should be integrated carefully, as shown in scenarios V and VII, since large power steps at the nodes with poor voltage quality could introduce even more severe problems like large voltage oscillations. Mitigating such problems requires more sophisticated control which accounts for transient voltage drops or introduces input filters. Nevertheless, it has been shown that local smart charging controllers can improve power quality in the distribution systems even in extreme cases. Consequently, this allows the integration of higher EV amount in the distribution grids without the need for unplanned and costly grid reinforcements. As the controller and the supporting infrastructure is made from standardised components, such control schemes could potentially be integrated in the EVSE with minimal development effort which makes such solution economically attractive.

Further research will continue to investigate the effects of the EV charging on the power quality by expanding the list of test scenarios, implementing more sophisticated control algorithms and exploring the effects on other power quality indicators, such as total harmonic distortion. Another topic not touched upon in this work is the user comfort. While controllable charging provides improvements in the power quality, it could potentially inconvenience the vehicle owner by not providing required state of charge level when EV is needed. This issue should be addressed as a part of the smart charging algorithm allowing the user to have a conveniently charged vehicle while still providing the voltage support service when EV is charging.

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