Coordinated Control and Management of Distributed battery-based energy Storage Systems for Islanded Microgrids

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COORDINATED CONTROL AND MANAGEMENT OF DISTRIBUTED BATTERY-BASED ENERGY STORAGE SYSTEMS FOR ISLANDED MICROGRIDS

BY
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COORDINATED CONTROL AND MANAGEMENT OF DISTRIBUTED BATTERY-BASED ENERGY STORAGE SYSTEMS FOR ISLANDED MICROGRIDS

Ph.D. Dissertation
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Curriculum Vitae

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Received the B.S degree in Electronic Engineering from the Universidad Distrital F.J.C in 2008, and the M.S. degree in Industrial Automation from the Universidad Nacional de Colombia in 2011, Bogotá, Colombia. He is currently pursuing the Ph.D. degree from the Department of Energy Technology, Aalborg University, Aalborg, Denmark. He is member of the Research Laboratory of Alternative Energy Sources, Universidad Distrital F.J.C. and Microgrid Research Group, Aalborg University. His current research interests include microgrids and power converters control.

Abstract

The integration of variable renewable energy sources such as solar or wind generators has meant a big breakthrough in the development of current societies, not only by reducing the environmental impact caused by conventional sources based on fossil fuels. But also, by helping to support the growing energy demand and enabling the electrification of remote communities, which restricted by technical and economic issues cannot be connected to the utility grid. Due to the uncertainty and variability of the variable renewable energy generators, new technical challenges, as well as prospective solutions, have emerged.

Microgrids have appeared as an alternative for enabling flexible integration of variable renewable energy sources within a local power system in which loads, generators, and energy storage systems operate coordinately, for accomplish specific aims of common interest, such as: (i) supplying the demand relying only on local resources, (ii) ensuring the regulation of the local power system under different operating conditions, (iii) achieve an efficient use of the renewable generation, and (iv) ensuring safe operating conditions for the distributed units. However, due to the non-homogeneous characteristics of the distributed generators and loads, it is not possible to consider unified and homogeneous behaviours for all the distributed units. Because of that, the coordination needs to consider the particularities of each distributed units, such as the kind of its primary energy resource, its limitations, and current operating conditions, as well as the requirements and current operating conditions of the whole microgrid, in order to determine appropriate individual actions of the distributed resources.

The coordination architecture contains the set of rules and control actions, which determine the responsibilities (roles) and the ways of interaction (behaviours), that the distributed resources in a microgrid should follow for ensuring the fulfilment of the common aims. This thesis explores different coordination architectures designed for islanded microgrids based on distributed renewable energy generators and battery-based storage systems. The proposed coordination architectures rely on expert systems, which define the operation of the distributed resources and the whole microgrid within a finite number of operation modes, that ensure the appropriate charging/discharging profiles for energy storage systems based on batteries. Here, centralized and decentralized architectures are explored and implemented by means of deterministic automaton systems, which coordinate the changes of the operation modes at the microgrid derived from the proper stages for charging the storage devices.

The centralized architectures determine the coordinated actions relying on a global perception of the whole microgrid. Because of that, grid-interactive approaches can be easily deployed, in which the distributed units can be operated as dispatchable sources based on simple equilibrium or optimization functions. Alternatively, the coordination of roles among distributed units can be determined by a centralized decision-making unit, emulating the role of a coach in a soccer team. This approach has been widely used for coordinating multi-robot systems such as robot soccer teams. From a metaphoric point of view, this project has addressed the coordination problem of distributed resources in a microgrid like the coordination of a robot soccer team. On the other hand, the proposed decentralized approaches are purely distributed without the use of additional communication infrastructure. In this case, bus signalling strategies are used for coordinating the operation of autonomous distributed generators. Additionally, the proposed architectures allow cooperative operations between the distributed units, in order to achieve appropriate active power sharing and ensure equalization of the state of charge for distributed energy storage systems. This fact, allows among other advantages, managing the distributed energy storage system like a single aggregate system.

The performance of the proposed coordination architectures have been verified experimentally and by means of hardware-in-the-loop simulation in lab-scale prototypes of islanded microgrids, either in dc or ac configurations.

keywords:
Coordination architecture, Distributed Storage and Generation, Decision-Making, Energy Storage Equalization, Finite State Machine, Islanded Microgrids.

Resumé

Integrationen af variable vedvarende energikilder såsom sol eller vindmøller har betydet et stort gennembrud i udviklingen af de nuværende samfund, ikke kun ved at reducere miljøbelastningen forårsaget af konventionelle energikilder baseret på fossile brændsler. Men også, ved at hjælpe til at understøtte den voksende energibehov og muliggør elektrificering af fjerntliggende samfund, som begrænset af tekniske og økonomiske spørgsmål kan ikke forbindes til forsyningsnettet. På grund af den usikkerhed og variabilitet af de variable energi generatorer vedvarende, har nye tekniske udfordringer samt potentielle løsninger opstæet.

Microgrids har optrådt som et alternativ til at muliggøre fleksibel integration af variable vedvarende energikilder inden for et lokalt-power system, hvor belastninger, generatorer og energilagring systemer fungerer sideordnet, for udrette specifikke mål af fælles interesse, såsom: (i) leverer efterspørgslen stoler kun på lokale ressourcer, (ii) at sikre reguleringen af det lokale elsystem under forskellige driftsbetingelser, (iii) opnå en effektiv udnyttelse af vedvarende generation, og (iv) at sikre sikre driftsbetingelser for de distribuerede enheder. Men på grund af de ikke-homogene karakteristika for de distribuerede generatorer og belastninger, er det ikke muligt at overveje ensartede og homogene adfærd for alle de forskellige enheder. På grund af dette, koordineringen skal overveje de særlige hver distribuerede enheder, såsom den form for sin primære energikilde, sine begrænsninger og aktuelle driftsforhold, samt de krav og aktuelle forhold i hele elsystemet drifts, for at fastlægge passende individuelle handlinger distribuerede ressourcer.

Koordineringen arkitekturen indeholder det sæt af regler og kontrolforanstaltninger, der bestemmer det ansvar (roller) og de måder for interaktion (adfærd), at de distribuerede ressourcer i en elsystemet bør følge for at sikre opfyldelsen af de fælles mål. Denne afhandling udforsker forskellige koordinering arkitekturer designet til islanded Microgrids baseret på distribuerede vedvarende energi generatorer og batteri-baserede storage-systemer. De foreslåede koordinering arkitekturer stole på ekspertsystemer, som definerer driften af distribuerede ressourcer og hele elsystemet inden et endeligt antal driftstilstande, at sikre passende opladning/afladning profiler til energilagringssystemer baseret på batterier. Her er centraliserede og decentraliserede arkitekturer udforskes og gennemføres ved hjælp af deterministiske robot systemer, som koordinerer ændringerne i driftstilstande på elsystemet stammer fra de rigtige trin til opladning af lagerenheder.

De centraliserede arkitekturer bestemme de koordinerede aktioner afhængige af en global opfattelse af hele elsystemet. På grund af dette, kan grid-interaktiv tilgange let indsat, hvor de distribuerede enheder kan drives som Afsendte kilder baseret på simple ligevægt eller optimering funktioner. Alternativt koordinering af roller blandt distribuerede enheder, kan bestemmes ved en centraliseret beslutningsproces enhed, efterligne rollen som coach i et fodboldhold. Denne tilgang er ofte blevet brugt til at koordinere med flere robotsystemer såsom robot fodbold hold. Fra et metaforisk set har dette projekt rettet koordineringen problemet med distribuerede ressourcer i en elsystemet som koordinering af en robot fodboldhold. På den anden side, er de foreslåede decentrale tiltag rent distribueres uden brug af ekstra kommunikationsinfrastruktur. I dette tilfælde er bus signalering strategier bruges til at koordinere driften af autonome distribuerede generatorer. Derudover de foreslåede arkitekturer tillader kooperative operationer mellem de forskellige enheder, for at opnå passende aktive magtdeling og sikre udligning af staten beregning for distribuerede energilagringssystemer. Dette faktum, tillader blandt andre fordele, styre distribueret energilagringssystem som en enkelt samlet system.

Udførelsen af de foreslåede koordinering arkitekturer er blevet verificeret eksperimentelt og ved hjælp af hardware-in-the-loop simulering i lab-skala prototyper af islanded Microgrids, enten i dc eller ac konfigurationer.

Nøgleord:
Koordinering arkitektur, Distributed Opbevaring og Generation, beslutningsprocesser, energilagring Udligning, Finite State Machine, Islanded Microgrids.

Thesis Details and Publications

Thesis Title: Coordinated Control and Management of Distributed Battery-Based Energy Storage Systems for Islanded Microgrids.
Ph.D. Student Nelson Leonardo Díaz Aldana.

Supervisor: Prof. Josep M. Guerrero.

Co-supervisor: Prof. Juan C. Vasquez.

1st **Authored Journal Papers:**

- Díaz, N. L., Dragičević, T., Vasquez, J. C., & Guerrero, J. M. (2014). Intelligent Distributed Generation and Storage Units for DC Microgrids - A New Concept on Cooperative Control without Communications Beyond Droop Control. IEEE Transactions on Smart Grid, 5(5), 2476-2485 . DOI: 10.1109/TSG.2014.2341740.

- Díaz, N. L., Guarnizo, J., Mellado, M., Vasquez, J. C., & Guerrero, J. M. (2016). A Robot-Soccer-Coordination Inspired Control Architecture Applied to Islanded Microgrids. IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2016.2572262.

- Díaz, N. L., Luna, A. C., Vasquez, J. C., & Guerrero, J. M. (2016). Centralized Control Architecture for Coordination of Distributed Renewable Generation and Energy Storage in Islanded AC Microgrids. IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2016.2606653.

- Díaz, N. L., Vasquez, J. C., & Guerrero, J. M. A Communication-less Distributed Control Architecture for Islanded Microgrids with Renewable Generation and Storage. This paper has been submitted to IEEE Transactions on Power Electronics.

Co-authored Journal Publications:

- Luna, A. C., Díaz, N. L., Graells, M., Vasquez, J. C., & Guerrero, J. M. (2016). Cooperative Energy Management for a Cluster of Households Prosumers. IEEE Transactions on Consumer Electronics.
- Luna, A. C., Díaz, N. L., Graells, M., Vasquez, J. C., & Guerrero, J. M. (2016). Mixed-Integer-Linear-Programming Based Energy Management System for Hybrid PV-wind-battery Microgrids: Modelling, Design and Experimental Verification. I E E E Transactions on Power Electronics. DOI: 10.1109/TPEL.2016.2581021.

Selected Publications in Proceedings with Peer Review:

- Díaz, N. L., Dragičević, T., Vasquez, J. C., & Guerrero, J. M. (2014). Fuzzy-Logic-Based Gain-Scheduling Control for State-of-Charge Balance of Distributed Energy Storage Systems for DC Microgrids. In 2014 IEEE Applied Power Electronics Conference and Exposition (APEC 2014) . Proceedings of a meeting held 16-20 March 2014, Fort Worth, Texas, USA. . (pp. 2171-2176). IEEE Press. (I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings).
- Díaz, N. L., Wu, D., Dragičević, T., Vasquez, J. C., & Guerrero, J. M. (2015). Fuzzy droop control loops adjustment for stored energy balance in distributed energy storage system. In Proceedings of the 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia). (pp. 728 - 735). IEEE Press.
- Díaz, N. L., Wu, D., Dragičević, T., Vasquez, J. C., & Guerrero, J. M. (2015). Stored Energy Balance for Distributed PV-Based Active Generators in an AC Microgrid. In Proceedings of the 2015 IEEE Power & Energy Society General Meeting. (pp. 1-5). IEEE Press.
- Díaz, N. L., Coelho, E. A. A., Vasquez, J. C., & Guerrero, J. M. (2015). Stability Analysis for Isolated AC Microgrids Based on PV-Active Generators. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE). (pp. 4214 - 4221). [7310255] IEEE Press.
- Díaz, N. L., Luna, A. C., Vasquez, J. C., & Guerrero, J. M. (2015). Energy Management System with Equalization Algorithm for Distributed Energy Storage Systems in PV-Active Generator Based Low Voltage DC Microgrids. In Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM). (pp. 293-298). IEEE Press.
- Díaz, N. L., Luna, A. C., Vasquez, J. C., & Guerrero, J. M. (2015). Equalization Algorithm for Distributed Energy Storage Systems in Islanded

AC Microgrids. In Proceedings of the 41th Annual Conference of IEEE Industrial Electronics Society, IECON 2015. (pp. 004661 - 004666). IEEE Press.

This present report combined with some of the above listed scientific papers has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis.

The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

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To God thanks because his times are perfect, and for making a perfect coordination of my life which makes possible this dream to come true.

Nelson Leonardo Díaz Aldana.
Aalborg University, December 13, 2016

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Part I

Introduction

Introduction

1 Energy Storage Systems in Microgrids

A generalized rising of modern living standards, not only for households but also in commercial sectors, buildings, and industry had led to a growing demand for energy resources by the end-users [4]. It is estimated that by 2030 the energy consumption will be double and consequently the CO2 emission can be increased up to a 75% due to the use of conventional energy generation systems based on fossil fuels [5]. In this scenario, the capability, reliability and efficiency of the conventional central generators, connected through long distance transition lines until the end-user, can be seriously compromised. This fact combined with environmental effects caused by CO2 emissions have demanded changes in the way that new energy sources are integrated.

The integration of distributed generation units close to the end-user has emerged as an alternative to counteract the growing demand more efficiently, thanks to the reduction in losses compared to conventional utility infrastructure. On top of that, government policies, combined with personal environmental commitments of private consumers, are promoting the integration of renewable energy sources (RESs) such as wind, hydro, solar and biomass [6]. Particularly, variable RESs such as wind turbines (WT) and solar photovoltaic (PV) generation units are the mainstays in Europe and in the United States for the integration and increasing penetration of renewable energy sources [7,8]. This fact has meant a change of paradigm for energy consumers who envision the possibility of reducing the dependence on the main grid and ensure self-energy consumption, by relying only on their own local energy resources "prosumer" [9]. However, due to the intermittent nature of variable RESs, it is not possible to ensure that the local generators can match the local demand by themselves. Therefore, Energy storage systems (ESSs) are used for smoothing the variability of the renewable energy resource, either by absorbing the excess of generation from RESs or by supplying energy when the generation from RESs is not enough to meet minimum load requirements [10]. Even in large-scale integration of variable RESs, the ESSs are useful for mitigating the impacts caused by variable nature of RESs in operation and plan-

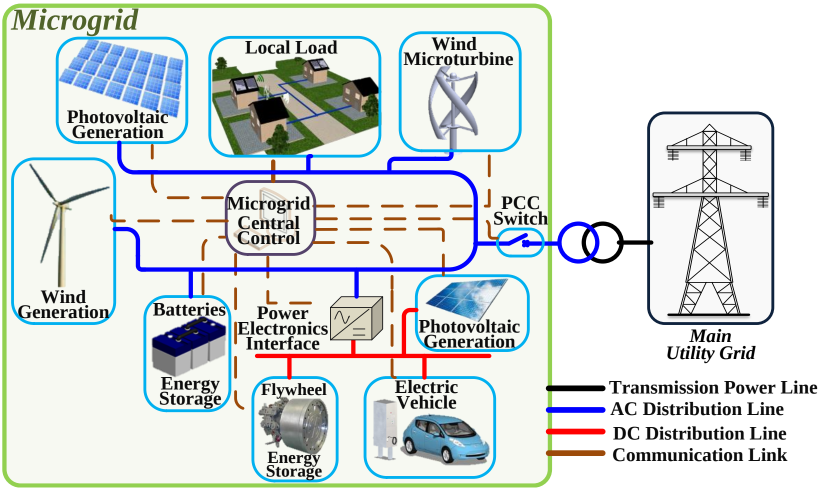


Fig. 1: Microgrid scheme with one point of common coupling with the utility grid.

ning [11].

The local power system composed of loads and distributed energy resources (DER) such as generators and energy storage systems, can be managed and coordinated as a single entity in order to ensure on-site generation and consumption. Here the microgrid (MG) concept emerges to define small-scale power systems based on local resources.

A MG can operate completely in grid-connected or islanded mode and as well as in dual mode by means of seamless transition between them [5]. Typically, the MG is integrated to the main grid by a common coupling point (PCC) connected throughout a static switch, therefore, it can be seen as a unified entity from the point of view of the distribution system as shown in Fig. 1 [12]. Also, a MG can operate, either in ac or dc configurations based on specific requirements of the DERs and loads, or it can be configured as hybrid ac/dc system by means of proper power electronic interfaces [13, 14].

1.1 Grid-Connected and Islanded Operation

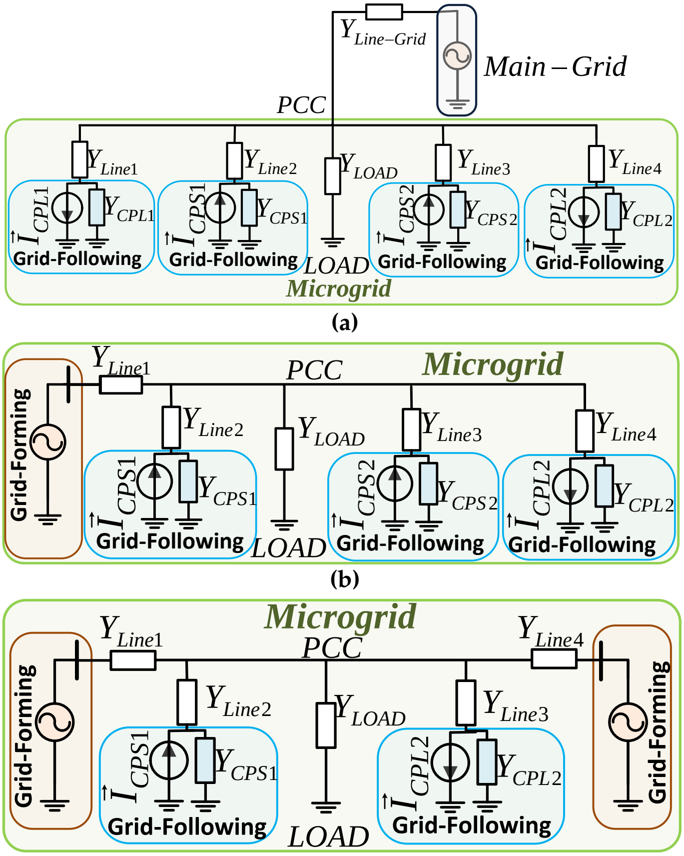
A MG continuously connected to the main grid can import or export energy from or toward the main grid, for balancing supply and demand. Since one of the main objective of a microgrid is ensuring self-consumption and generation based on its own local resources, its interaction with the main grid differ from the traditional approach oriented to maximize the energy exported to the main grid [9]. The conventional strategy relies on the use of ESSs for storing the energy during the time where the generation exceeds the demand and releasing the stored energy when generation is lower than consumption [15]. Because of that, the participation of microgrids on the energy market is commonly limited at the retail level [16].

The increasing penetration of small-scale microgrids based on variable RESs implies additional technical challenges for the Distribution System Operator (DSO). Since the distribution systems will be exposed to more variability in the net load, it is necessary to include additional support schemes in order to ensure appropriate frequency and voltage regulation [17, 18]. The cost derived from the inclusion of new support schemes or even for replacing old infrastructure, in accordance with new requirements, is passed in a grand extent, to the end-consumers through additional surcharges in the retail prices [18, 19].

Apart from that, MGs are mainly connected to the utility grid through the low-voltage (LV) distribution system, therefore, the injection of energy to the main grid may cause significant variation in the voltage magnitude along the LV feeder and consequent deterioration of voltage quality [15]. To solve this problem different actions have been proposed in order to limit the active power feed-in to the main grid such as active power curtailment of generation from RESs [15]. This fact, in addition to recent reductions in feed-in tariffs, has promoted a more independent operation of microgrids [9], [18].

Nevertheless, the MGs may always appeal to the utility grid as a backup solution, in the cases where the storage unit is not able to provide or store more energy, or under unforeseen situations in which one or more of the distributed energy resources (DERs) have to be disconnected [5]. Also, the main grid can behave as an infinite energy buffer in order to balance short-time mismatches between generation and consumption, which are common in power systems with variable RESs [20, 21]. In this way, load demand and power balance can be met all the time regardless of different operating conditions and variability of RESs. As a consequence, the reliability of the local power system is enhanced [22]. Here, the concept of connected island mode appears for defining the growing trend for grid-connected microgrids in which importing/exporting energy with the main grid is avoided as much as possible [23, 24].

Another characteristic of grid-connected MGs is that the main grid behaves as a master unit by defining the references for voltage amplitude and frequency in the PCC. Meanwhile, the DERs are mainly grid-following units synchronized in phase and frequency with the main grid and controlled in current control mode (CCM) for injecting or absorbing active/reactive power (Fig. 2(a)) [25]. This fact, added with the aforementioned backup and buffering support provided by the main grid, facilitates the management of the DERs. The power references for grid-following units can be dispatched by a high-level power management strategy, deployed in the microgrid central control as shown in Fig. 1 or they can be locally calculated according to specific power profiles (i.e. maximum power point tracking (MPPT) in variable



(a) (b) (c)

Fig. 2: Equivalent circuital scheme of MGs: (a) Grid-Connected, (b) Islanded Single Master, (c) Islanded Multi Master.

RESs or regulated process of charge in ESSs). Within the current trend in MGs, the management system aims for minimizing the power exchange with the main grid and maximizing the use of the local energy resources. Also, another pre-defined optimization objectives can be achieved [23–25].

Islanded operation may appear for several reasons such as a fault in the main grid, intentional disconnection due to maintenance needs or when economic and geographic issues do not allow an interconnection with the main grid (i.e. remote areas) [26, 27]. Particularly, islanded microgrids based on variable RESs have been installed worldwide for electrification of remote villages in the developing world [28]. The access to electrical energy means an important advance in the development of poor communities and represents a technological challenge for the deployment of islanded MGs, by considering that still around 17% of the global population remain without access to electricity [29].

However, the management of DERs in islanded microgrids involve additional technical challenges, since the voltage and frequency are not imposed anymore by the main grid and should be generated internally by the DERs. Once the microgrid is disconnected from the main grid, the responsibility of forming the grid in the islanded power system (grid-forming role), should be assumed by at least one of the DERs, which will operate under voltage control mode (VCM) [21,30]. The grid-forming unit will behave as an energy buffer in the islanded power system in order to ensure the power balance and to avoid losing the control over frequency and voltage in the common bus. The grid-forming role can be assumed by a single unit in the islanded MG (single master configuration as shown in Fig. 2(b)), or this role can be shared by multiple DERs (multi-master configuration as shown in Fig. 2(c)) [31].

Since the grid-forming units are responsible for managing the power balance in the islanded microgrid, they should have enough capability and an adequate reserve for injecting or absorbing energy. Because of that, the ESSs are commonly used as the grid-forming units [25], [31]. In general, ESSs can provide fast response in terms of power injection and they can ensure either short-term or long-term balancing and power dispatch.

1.2 Energy Storage Systems in Islanded Microgrids

For microgrids based on small-power variable RESs the energy storage system should be scalable and modular in order to be sized properly in accordance to different characteristics of the distributed generators and load requirements. Additionally, several characteristics such as life-time, cycle life, power rates, energy density, availability, capital cost, etc., should be considered for an adequate selection of the ESSs. In [11] is suggested that supercapacitors, flywheels, super conducting magnetic energy storage (SMES), and batteries are the most suitable storage technologies for applications based on variable RESs. Here is a brief summary about the characteristics of these storage technologies.

- ***Supercapacitors***: They are electrical energy storage systems characterized by high power density (10.000 W/kg), high cycling ($>$ 100.000) and long-life (8-10 years). They are preferred for fast cycling applications because the can be charged and discharged faster than others ESSs. However, they have low energy density, which makes them not suitable for long-term balancing [32]. On the contrary, they are ideal for providing a fast power injection, which is useful for smoothing transient responses and sudden power shortage caused by changes in the operation mode of the microgrid or due to the variability of RESs. They are also useful in cases when the load needs high instantaneous current (i.e for starting an electric motor). They are commonly used connected directly to de dc-link of the variable RESs operating as an energy buffer for smoothing and filtering the generation from variable RESs. However, supercapacitors have larger cost per kW than many others electric energy storage technologies [11], [21], [33].

- ***Flywheels***: They are mechanical ESSs based on a rotating mass, which stores kinetic energy in accordance to changes in the rotational velocity of the mass and releases the stored energy via an electric motor. They are characterized by long life (15 to 20 years), high cycling (10.000 to 100.000), high power density and small energy density. They can provide very high peak power, therefore they can be used for mitigating the fast ramping of variable RESs and for fast charging of electric vehicles [34]. The main disadvantage is the highest cost per kWh, because of that, they have had a small penetration in the market [11], [33].

- ***Super Conducting Magnetic Energy Storage (SMES)***: It is a device that storage energy in form of a magnetic field created by a direct current flowing through a superconducting coil. SMESs are relatively new technology, characterized by long life (>20 years), high cycling (>10.000), high power density with a very fast dynamic response, but also small energy density. For the integration of variable RESs, the SMESs can be used in the same applications than supercapacitors and flywheels. SMESs have demonstrated to be effective for short duration power quality applications and reactive power support. However, they can be extremely expensive due to the cooling system required for keeping the superconductivity of the coil [11], [33].

- ***Batteries***: They are devices that convert chemical energy into electrical energy by means of an internal chemical reaction. Batteries are categorized between primary and secondary batteries. The primary batteries can be used only once and they can not be recharged. Meanwhile, in secondary batteries, the electrochemical reaction can be reversed and the batteries can be recharged [35]. Therefore, secondary batteries are ideal for applications with variable RESs since they can be charged and discharged for smoothing the uncertain generation profiles of RESs. In general, secondary or rechargeable batteries are characterized by high energy density -compared with the devices previously introduced- and good capability in terms of fast power injection [21], [33]. Therefore, batteries can be considered for medium to long-term applications, capable of supporting a load from minutes to hours [32], [36], which makes them desirable for Uninterruptible Power Supply systems or for islanded MGs. One of the main drawbacks of batteries is that they have relatively low durability in terms of cycle life, compared with the storage technologies aforementioned [37]. A wide range of rechargeable batteries technologies can be utilized in conjunction with variable RESs [15]. Their main differences lay on the manufacturing technology and materials.

- *Lead-Acid Batteries*: They are characterized by their low cost, high reliability and efficiency. However, they have poor cycle-life (500-2.000) and short lifetime (5-15 years) compared with other technologies. There are basically two types of Lead-acid batteries: vented and valve regulated lead-acid (VRLA). Vented batteries are less expensive and have larger cycle-life than VRLA batteries, but, they require periodic maintenance and special conditions for transportation and installation. On the contrary, VRLA batteries are designed to be maintenance-free, they are smaller and lighter than vented batteries. Additionally, VRLA batteries can be installed and transported without considering vertical orientation, which allows an easy transportation, installation, and storage. These characteristics, make VRLA batteries more suitable for applications in remote areas [38]. Among other applications Lead-acid batteries are commonly used in automotive applications, data centers, telecommunications systems, UPS and another emergency and standby power systems.
- *Nickel-Based Batteries*: There are mainly three types of Nickel-based batteries, which differ one to the other by the material used for the negative electrode; cadmium hydroxide (NiCd), metal alloy (NiMH) and zinc hydroxide (NiZn). They are characterized by a higher energy density and in some of them a larger cycle-life than Lead-acid batteries but at the expense of higher cost (up to 10 times). Additionally, the efficiency of Nickel-based batteries is lower than the efficiency of Lead-acid batteries. Among the nickel-based batteries, NiCd is the most used for industry applications especially for UPS [11], [36]. However, due to environmental issues caused by the toxic cadmium, the use of NiCd has been declined or even banned in some countries [11]. This problem of using toxic metals has been solved with the use of NiMH batteries, however, the cycle-life of NiMH batteries is smaller (comparable with the cycle-life of Lead-acid batteries). The main disadvantage of Nickel-based batteries for the integration with variable RESs is the memory effect [11]. The memory effect means that the battery loses capacity when it is not fully discharged [35].
- *Sodium-Sulphur Batteries (NaS)*: This is a promising emerging technology in the last decade. NaS batteries are characterized by high efficiency and higher power density. They are economically and environmentally feasible because they are made of inexpensive

and non-toxic materials [36]. Their main drawback is that the should be operated at high temperatures (300 to 350 degrees Celsius) which imply additional costs [11]. Therefore, this technology is more suitable for large-scale stationary applications and not for small-scale power systems such as microgrids [33], [36].

– *Lithium-ion Batteries*: This is an outstanding technology compared with the others technologies in terms of many of its different features such as higher energy and power density than Nickel-based and Lead-acid batteries, higher efficiency than Nickel-based, and higher cycle life than Lead-acid batteries. Additionally, Li-Ion batteries do not have the problems with the memory effect, have low self-discharge and are less toxic than Lead-acid and NiCd. The main drawback of Li-Ion batteries is their high cost and the limited reserves of lithium-ion [11]. Additionally, Li-Ion batteries are very strict on their limit of charge, they cannot be overcharged because safety will be seriously compromised.

– *Flow Batteries*: This technology is characterized for storing at least one of its liquid electrolytes on external tanks, from where the electrolytes is pumped to a reactor in order to obtain electric current from a reversible chemical reaction. The most popular technologies are the Zinc-Bromine (ZBR) batteries and the Vanadium redox batteries (VRB). One of the main advantages of this kind of batteries is that the stored energy is decoupled from the rated power capacity, since the rated power depends on the size of the reactor while the energy density depends on of the size of the auxiliary tanks [33]. This fact makes the flow batteries more flexible and easy to fit and customize for a wide range of applications. One of the main problems with this technology is its low energy density, therefore, it is required a large amount of space for applications that require long-term support.

For small power systems where the ESSs play an important role, the key element is the autonomy level provided by the ESSs. Based only on technical reasons Lithium-ion batteries have the best performance in terms of lifetime, energy density, power density, self-discharge, efficiency and become the best candidate for small to medium power applications such as islanded MGs based on variable RESs. However, whether the cost is a sensitive issue to consider (for instance in remote villages in developing countries) Lead-acid batteries and particularly VRLA batteries have the best compromise between performance and cost [15], [37]. Because of that, Lead-acid batteries still dominate the market for applications in islanded power systems and remote villages, since in addition to reduced costs they also offer good availability and easy transportation [26], [29], [38].

Given the above points, ESSs based on batteries, and more specifically Lead-acid and Lithium-ion batteries will be considered in this work for applications in islanded MGs by considering specific limitations for charging within a safe operating window.

1.3 Charge/Discharge Characteristic of Batteries

The name "battery" is often used for the basic unit where the electrochemical reaction takes place. To be more precise, the basic unit is the cell, and a battery by itself is composed of a group of cells connected in series or parallel depending on the desired voltage and capacity [35]. In general, a basic electrochemical cell is composed of two electrodes, one positive (cathode) and one negative (anode), which are plunged into an electrolyte. The process of charge and discharge implies movement of ions between cathode and anode. During the process of discharge, the anode provides electrons and suffer oxidation, while the cathode receives the electrons and it is reduced. The process of charge reverses the movement of ions, which is facilitated by the electrolyte [36]. Because of the changes in the electrochemical reactions, the voltage of the cell and its internal resistance will vary during the process of charge and discharge. This fact is due mainly to three factors such as: (i) the state of charge (SoC), which is an indication of the amount of energy stored in the cell, (ii) the current flowing through the cell, and (iii) the temperature. The variations in the voltage of the cell differ from one technology to other depending on the material used in the manufacturing process of the cell. Therefore, different and particular signatures of the voltage vs. SoC can be found for all the electrochemical batteries (i.e. the discharge signature in Li-Ion is flatter than the Lead acid signature) [39]. Fig. 3 shows a typical voltage vs. SoC curve for an electrochemical battery.

An ideal battery will have a charge/discharge curve extremely flat, however, in real batteries, the curve will have a non-linear behaviour as is shown in Fig. 3. When the batteries are approaching their states of full charge or full discharge their internal resistance tends to increase due to the polarization of the active materials, as a consequence, the curve shows a more sloping profile [35]. Beyond certain values, the batteries cannot continue storing or delivering energy at the risk of being degraded or being under unsafe operating conditions. A battery can operate within a safe operation region in which the voltage signature is almost linear. The range of safe operation window may involve potential differences from Li-Ion to Lead-acid, but a safe SoC window is typically established between 20 % to 90 % [15], [38], [40]. These values roughly correspond to the points where the voltage signature exhibits a well-defined knee as can be seen in Fig 3. However, the SoC value could be not the best option in order to define the operation limits, since the voltage signature is also affected by the battery current and temperature. When the

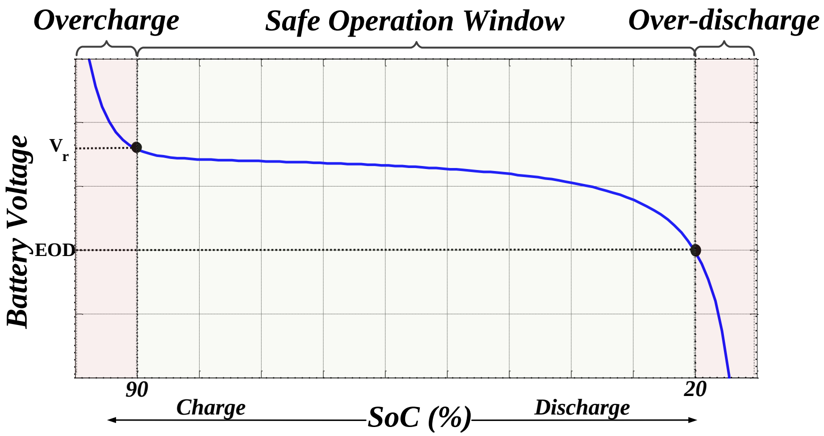


Fig. 3: Charge/Discharge curve of a Cell.

Table 1: Summary Table of Typical Voltage Values per Cell

	Charge Cut-off Voltage	Cell Voltage Nominal	Discharge Cut-off Voltage
Lead-acid	2.4 V	2 V	1.75 V
Li-Ion	4.20 V	4.2 V	2.5-3.0 V

battery is being charged the current flow causes an increment in the voltage and when the battery is being discharged the current causes a drop in the voltage. Additionally, the temperature affects the internal resistance of the cell [39].

Particularly, Lead-acid and Lithium-ion batteries are voltage-limiting devices whose threshold values are determined specifically by the manufacturers. Table 1 summarizes typical values defined by the manufacturers for the charge and discharge cut-off values for both Li-Ion and Lead-acid cells. The maximum value that a cell is allowed to reach is commonly known as the regulation voltage (V_r) and the minimum value is known as the end of discharge value (EOD) or low-voltage disconnect (LVD), since beyond this point the load has to be disconnected from the battery in order to avoid further discharge [38]. Despite the similarities between Lead-acid and LI-Ion batteries, there are some particular requirements that should be taken into account in the process of charge, in order to enhance the performance and lifespan of the batteries.

Charging Lead-acid

Lead acid batteries require a process of charge of at least two stages (commonly three), since either overcharge and undercharge may compromise the lifespan and performance of the battery [41]. As stated in [38] "Appropri-

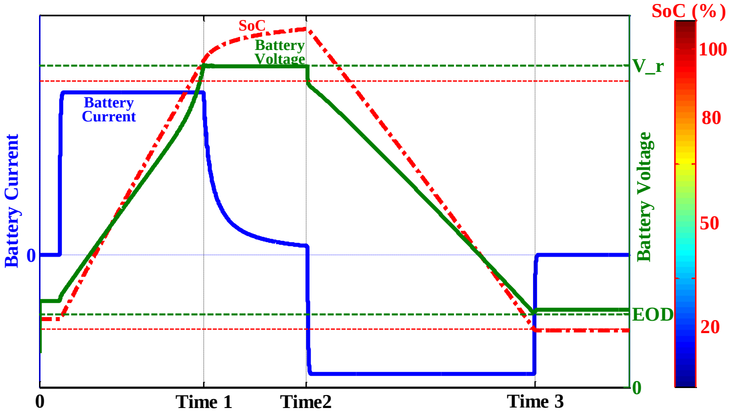


Fig. 4: Charging/Discharging Characteristic of Lead-acid batteries.

ate charging is critically important to the life and performance of lead-acid batteries, especially VRLA batteries”.

For applications within an islanded MG based on variable RESs the two stages are: 1). A current-limited stage in which the battery as part of an ESSs operating in the grid-forming role will absorb the surplus of energy in the local grid. 2). A constant-voltage stage in which the battery voltage should be kept constant by means of a topping charge in which the battery current will begin to taper, while the battery continues being charged until saturation [38], [41–43]. The second stage should start once the battery voltage reaches the regulation value V_r.

A third stage denoted as float charge is recommended for Lead-acid batteries when they remain on standby for long periods (more than 48 hours) [35]. This stage basically compensates the self-discharge of a lead-acid battery and keeps the SoC [41]. This stage can be omitted when the battery is not going to be in standby for long periods as usually happen in remote power systems (islanded MGs), where one or two charge cycles occur in a day [29], [43]. Fig. 4 shows the expected charging profile for a Lead-acid battery.

In Fig. 4, from **0** to **Time 1** the charger operates in stage 1 until the battery voltage reaches the regulation value (V_r) at **Time 1**. From **Time 1** to **Time 2** the charger operates in stage 2.

To sum up, in the process of charge there are important factors recommended by the manufacturers that should be taken into account for ensuring a proper performance and avoiding limiting the life of Lead-acid batteries as is stated in the references [35], [38], [41–43].

- In the first stage of charge it is ensured about an 80 % of the total charge, while the second stage complements the remaining charge.

- It is important to fully charge the battery between discharge cycles in order to maximize the capacity and avoid fast degradation.
- The topping charge (constant-voltage charging) is the most effective method for ensuring full charge of Lead-acid batteries.
- Since the Lead-acid batteries are voltage-limiting devices, the manufacturers recommend a charge controller with a constant set-point (the voltage regulation V_r), which is determined by the manufacturers.
- A seamless transition is required between the current-limited stage and the constant-voltage stage.
- Since the process of charge is inefficient it is necessary to charge the battery with more that 100 % of SoC (105 % to 110 %).

Charging Lithium-ion

Lithium ion batteries are also voltage-limiting devices but unlike the Lead-acid batteries, the voltage per cell is higher as can be seen in Table 1. On top of that, Lithium-ion batteries are less tolerant to accept overcharge than Lead-acid batteries, since they are very strict in their maximum voltage limits. Any operation beyond the limit compromises seriously their safety [41]. In counterpart, Lithium-ion batteries do not need to be fully charged. In fact, a partial charge is more recommended that full charge, and as a consequence, the saturation stage can be discarded. Furthermore, any reduction in the peak charge voltage can be reflected in a larger cycle-life. However, this decision is always a trade-off, because the voltage reduction reduces the capacity.

Since the saturation stage is not required, the controller for the charger can be simpler in comparison with the charge control of Lead-acid batteries. Actually, it is recommended to cut-off the battery current and keep the battery voltage in the regulation value as short time as possible. This fact causes that the battery voltage begins to droop, and the voltage stress is reduced [41]. Fig. 5 shows the charging curve that can be applied to Lithium-ion batteries, by taking into account the aforementioned considerations.

In Fig. 5, at **Time 1** the battery voltage reaches its maximum limit (V_r) and the battery current is cut-off. The following list summarizes some of the main features to take into account for charging Li-Ion batteries.

- They cannot be operated beyond the regulation value.
- Partial charge is better than full charge.
- Partial charge does not cause additional degradation.
- A constant-voltage controller is not required.

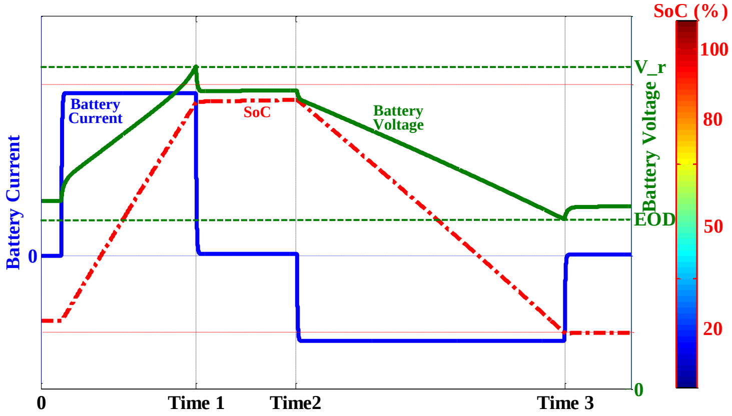


Fig. 5: Charging/Discharging Characteristic of Lithium-ion batteries.

- A smaller regulation voltage means less stress and longer life but is reflected in the battery capacity.

Discharging

In addition to a proper charge procedure, over-discharge should be avoided for preventing degradation of the storage unit. For both Lead-acid or Li-ion, deep discharge wears the battery down. Because of that, the depth of discharge (DoD) of a battery should be limited to safe valued (DoD(%)=100-SoC(%)). For Li-Ion and Lead-acid batteries, it is acceptable a maximum DoD of 80 %, beyond that limit the operation of the battery is not recommended because of wear. Similarly, the SOC or the DoD values are not the best indications to end up the discharge of the batteries. As aforementioned, the voltage signature can also be affected by other parameters such as the current and temperature. Therefore, the EOD should be the value to be taken into account to cut-off the battery discharge current. The EOD should be decided based on the manufacturer's guidance and the battery control should also incorporate proper actions to avoid deeper discharge [38]. To illustrate, Figs. 4 and 5 show the expected behaviours for a deep discharge cycle (from **Time 2** to **Time 3**). At **Time 3**, the batteries reach their corresponding EOD value and the battery current is cut-off for avoiding further discharge.

1.4 Aggregated or Distributed ESSs-Motivation

One of the biggest discussions about the deployment of ESSs is whether they should be distributed or aggregated. The traditional approach relies on a holistic vision of the power system where the power balance service provided by the ESSs benefits the power system as a whole. Therefore, any

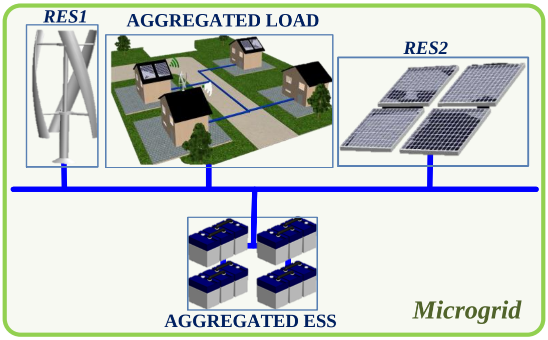


Fig. 6: Microgrid with aggregated ESSs an loads.

unbalance between generation and consumption caused by the variability of RESs can be managed by a single or a small number of larger ESSs (Fig. 6). The aggregated approach is characterized by simplified schemes of control and coordination with other distributed generators and loads. Also the aggregated approach ensures an efficient integration of variable RESs [17], [44]. However, aggregated approaches are frequently limited by the space, due to the requirement of bulked installations. On top of that, they are not easily scalable and reconfigurable for the integration of additional generation units and increasing load requirements.

On the other hand, distributed approach dominates the current trend in the integration of ESSs. They are characterized by small size distributed storage units, which offer a flexible integration in terms of location restrictions, since they can be connected either near generation or near consumption based on optimal considerations [33], [45], [46]. Also, they are flexible in terms of easy dimensioning for various size requirements. Apart from that, distributed ESSs are scalable and typically require reduced cost associated with additional integration, replacement, maintenance and operation [11].

For the integration of distributed RESs, it is commonly suggested that the storage units should be located on the same node and operated in conjunction to individual RESs and local loads. In this way, it is possible to enhance the voltage and power quality at the point of common connection [11], [44]. On top of that, the ESSs can be optimally sized for particular conditions of generation and consumption, in which the couple formed by an ESS and a RES (ESS+RES) can behave either as a baseload generator with constant output power or a load-following generator looking for ensuring on-site generation and consumption [47]. Here, is where the concept of the active generator has emerged as an alternative in which the integration of variable energy resource is considered together with its own storage system and load control in order to ensure a more stable power generation profile from RESs [48–50].

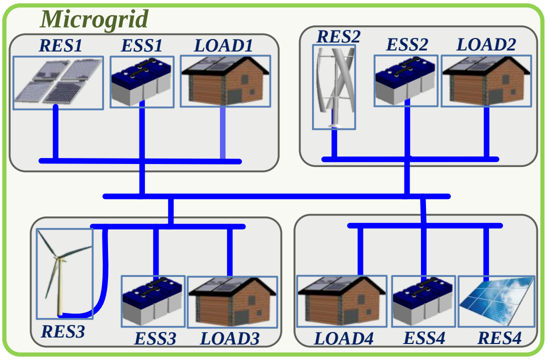


Fig. 7: Microgrid based on distributed active generators.

Fig. 7 shows a typical configuration of a MG based on active generators in which the variable nature of each RES is smoothed by its own ESS. An active generator can participate as a dispatchable source within a MG or alternatively participate in the common bus regulation and supporting the power balance of the whole microgrid.

The main drawback of a fully distributed approach based on active generators is, in fact, the elimination of the benefits derived from an aggregated operation such as a more efficient use of the distributed resources [17]. To be more precise, by considering individual and different consumption and generation profiles, if the active generator (RES+ESS) is configured for supporting only local consumption, it is possible to have the case in which simultaneously an ESS could be being charged while other could be being discharged and the power generation from one RES could be being wasted at the time it is required by another load.

In light of the above, it is desirable to combine the flexibility, scalability and optimal sizing provided by a distributed approach with the efficient use of the distributed resources derived from an aggregated approach. For that reason, an appropriated management and coordination strategy that allows distributed resources and loads cooperate between them, and behave as an aggregated unit can be the best option for achieving high flexibility and an efficient operation in a microgrid based on distributed ESSs (Fig. 8).

Alternatively, the coordination of the distributed resources can ensure a reliable operation of the islanded MG by means of specific control actions in each of the distributed units, which consider not only its own particular operating conditions but also the limitations and operating conditions of the other DERs and the whole MG [51]. Simple actions such as reducing or increasing the generation or adjusting the load demand in order to keep the power balance can be addressed for a proper coordination. Likewise, changing the operation mode for assuming the regulation of the common

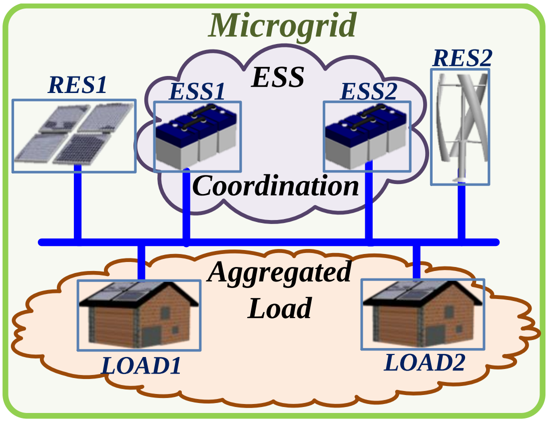


Fig. 8: Microgrid based on distributed resources with coordinated operation.

bus whenever needed can also be considered as cooperative control actions.

2 Coordination of Islanded Microgrids Based on Distributed RESs and ESSs-Motivation

2.1 Operation of an Islanded Microgrid Based on RESs and ESSs

An islanded MG is a complex system composed of heterogeneous DERs which are integrated by means of power electronics interfaces with their own local controllers (LC) as is shown in the simplified scheme of Fig. 9a. The role that each distributed unit assumes determines its control mode and the way in which it behaves determines its level of interaction with other units inside the MG.

Two main roles (control modes) can be defined for the operation of distributed generators in a islanded MG; grid-forming or grid-following. The grid-forming units are mainly responsible for controlling the voltage and frequency, while the grid-following units are mainly responsible for injecting or absorbing active/reactive power. The role of a distributed generator can be assumed by means of grid-interactive or grid-noninteractive behaviours (control methods) as proposed in [25]. A grid-interactive behaviour means that the distributed generator participates actively in the regulation and control of the whole MG, while a grid-noninteractive operation means that the distributed generator only takes care of its own particular control objectives regardless the operation of the whole MG. The role of a distributed generator takes an important place in the coordination of the MG, while the behaviour

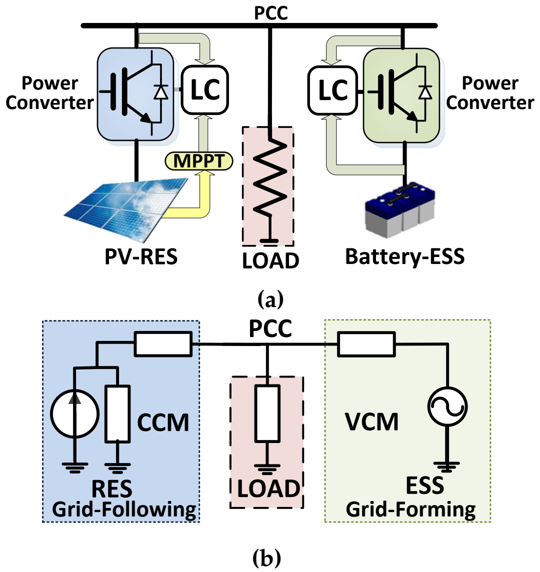


Fig. 9: MG based on ESSs and RESs: (a) Basic scheme, (b) Equivalent circuit.

determines the level of cooperation of the distributed generator in the MG.

For instance, when the ESSs are operated under a partial state of charge (PSoC), they can assume the grid-forming role with a grid-interactive behaviour, since they are able to absorb or supply power in order to compensate any unbalance between generation and consumption, while they are regulating the common bus. Because of this feature, provided by the storage systems, they are commonly assigned to be the master units, being responsible for forming bus in the islanded power system (Fig. 9b) [31, 52]. Meanwhile, it is expected to obtain from RESs the maximum amount of available energy in order to make an efficient use of the renewable resource. Because of that, the operation of variable RESs, such as WT and PV, is preferred under a maximum point tracking algorithm (MPPT) [53–55]. RESs operating under MPPT are a clear example of grid-following units with a grid-noninteractive behaviour, since the amount of power fed to power system grid depends more on weather conditions rather than on particular requirements of the local power system [25].

The operation of an islanded MG under a partial-state-of-charge (PSoC) is also a management strategy that has been commonly addressed in order to maintain the operation mode of the MG as shown in Fig. 9b and avoid the use of additional coordination actions [52]. However, the PSoC strategy requires the use of batteries with oversized capacity for keeping the SoC value as far as possible from the safe operation limits (Fig. 3). As a consequence, the initial capital cost of the battery is increased. On top of that, when this strategy is applied to Lead-acid batteries, they will require the periodic schedule of full charge cycles (saturation), for avoiding the degradation of the Lead-acid batteries. Apart from the cost, the saturation of the battery by itself is not a problem, but this procedure implies that the battery should be put out of service for at least 12 hours and up to 48 hours depending on the capacity of the battery. What is more, in remote villages is not possible to ensure that the amount of energy required for fully charge a large battery is available [41]. One alternative for avoiding a periodic fully saturated charge is the use of Lithium-Ion batteries, which can be operated with partial charge without any problem, but the cost of the battery becomes a bigger problem in cost sensitive application such as remote villages, by considering that the prices of Lithium-ion batteries is more than double the cost of Lead-acid batteries.

Even for an optimally sized MGs, the PSoC operation mode cannot always be ensured due to the unpredictable nature of variable RESs [56]. It is possible to have the case in which the storage unit gets fully charged and the generation is bigger than consumption, or conversely, the case in which the amount of power generation is not able to satisfy the load requirements and then the ESSs could be fully discharged. The appropriate use of the energy storage system takes a significant relevance for islanded MGs with ESSs based on batteries, since the well-being and lifespan of batteries rely on specific and precise constraints for charging and discharging as was exposed before. This is not a minor issue by regarding the cost associated with early replacement and maintenance of batteries [57, 58]. In light of the above, a basic set of rules can be defined to summarize the main aims to be taken into account for a reliable operation of an islanded MG based on batteries and RESs.

1. The power balance and regulation of the local power system should be ensured under all the operating conditions.
2. Overcharge and deep discharge should be avoided by considering specific characteristics of the storage technology.
3. The RESs are more likely to operate under MPPT algorithms in order to obtain from them their maximum energy.
4. The load should be fed whenever possible.

With respect the aforementioned goals, the first two are of strictly enforced, while the last two are more flexible and could be sacrificed at the expense of accomplishing the first two. In other words, actions as active power curtailment of the generation from RESs and load-shedding can be considered within a coordination strategy in order to ensure a reliable and safe operation of the power system [59–61].

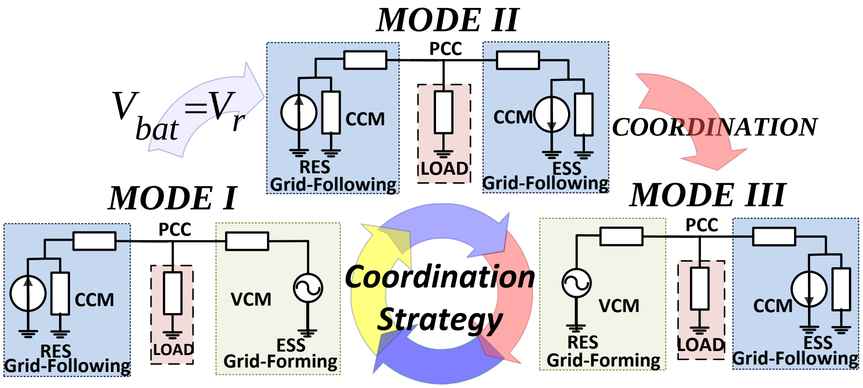


Fig. 10: Transition between operation modes for proper charge of Lead-acid batteries in a MG.

Particular consideration for the operation with Lead-acid Batteries

Since Lead-acid batteries require a saturation stage for the charging process, it is needed a change in the control mode of the ESS once the battery voltage (V_{bat}) reaches the regulation value V_r. For that reason, the ESS needs to change its control mode from VCM to CCM in order to regulate the amount of current drawn by the battery and keep the battery voltage in the regulation value. This change in the control mode implies also a change in the role of the ESSs and the way they are interacting in the microgrid. In this stage, the ESSs will become grid-following units with a noninteractive operation, since the ESSs leave the tasks related to the regulation of the common bus and the power balance of the microgrid to assume the regulation of the battery voltage.

Any change in the operation mode of each unit is reflected in a change in the topological operation of the whole MG as can be seen in Fig. 10, where the MG changes from (MODE I) to (MODE II) [62,63]. In (MODE II) there is not regulation of the common bus, then a coordination action must be enabled to assign responsibility for regulating the common bus to another unit with enough capacity. In the case of the MG shown in Fig. 9 the grid-forming role can be assumed by the RESs as can be seen in the (MODE III) of Fig. 10. The main task of a coordination strategy will be to ensure a seamless transition between operation modes by considering particular operating conditions of each distributed unit and the whole MG.

Particular consideration for the operation with Lithium-ion Batteries

Lithium-ion batteries are also a voltage limiting device in which the process of charge should be terminated once the battery voltage reaches a cut-off value. Unlike the process of charging Lead-acid batteries, the Li-Ion batteries

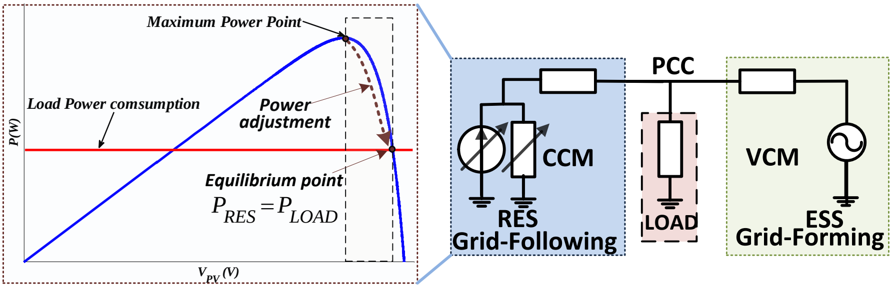


Fig. 11: Active Power curtailment of generation from RES for avoiding overcharge of the ESS.

do not need the stage of topping charge (saturation). Indeed, it is recommended to avoid the saturation stage for reducing the stress of the battery and also operation under partial charge is preferred for preserving the lifespan of the batteries [41].

For avoiding overcharge, the battery current should be set to zero once the voltage limit is reached. In this case, a similar strategy to the one explained before based on changes in operation modes for Lead-acid batteries can be used, but by setting the reference of the battery current at zero.

Since the saturation stage can be avoided, it is no necessary to change the operation mode of the ESSs. Alternatively, the power generation of the other distributed units can be adjusted until the power balance in the system is achieved and the power drawn for the ESSs becomes equal to zero. To clarify this scenario, the RESs can keep its role of grid-following unit, since the ESSs would continue as the grid-forming unit, but the behaviour of the RESs can change for grid-noninteractive operation (MPPT operation) to a grid-interactive operation (off-MPPT mode) in which the power injected to the MG can be dispatched or adjusted. This behaviour is illustrated in Fig. 11 for the MG shown in Fig. 9a. The main task of a coordination strategy will be to ensure a proper coordination and changes in the behaviour of the RESs by considering the amount of available power and the power requirements of the whole MG.

The strategy presented in Fig. 11 can also be deployed in MG with Lead-acid batteries. However, periodic cycles of saturated charge should be scheduled.

2.2 Coordination Architecture

The coordination architecture for distributed resources in an islanded microgrid corresponds to the set of actions, roles, and behaviours that the distributed resources should assume in order to ensure the fulfilment of common aims. The roles and responsibilities of the distributed resources are assigned based on their particular operating conditions, capabilities, and limitations and based on a collective perspective in which the requirements and operating conditions of the whole microgrid should be considered [64].

The coordination architecture can be deployed by means of decision-making (DM) mechanism, which execute automatically a computer program for adapting the operation of the distributed resources in accordance with changing circumstances. The DM uses the information obtained from the environment (operating conditions of the whole MG and particular operating conditions of each distributed unit), to make the decisions and request specific actions from the distributed resources [65]. The decision-making process is performed by an inference engine, which contains assertions and conditions about the expected operation of the microgrid. From a metaphorical point of view, this is equivalent to the process performed by an expert human being. Because of that, a knowledge-based or expert system can be considered for managing the complexity of a MG and define the coordination architecture from a higher level of abstraction.

Decision-Making based on Expert Systems

An expert system is composed of a knowledge base and an inference engine. The knowledge base contains facts to be considered for a proper operation of a MG. This is all the information concerning the common aims of the MG and the particular limitation and requirements of the DERs (i.e. the constraints and requirements for charging/discharging battery-based ESSs). On the other hand, the inference engine contains all the information about the conditions and actions that should be performed by the DM units, which usually can be represented by means of IF-THEN rules (i.e. If the voltage in an ESSs based on VRLA batteries has reached the regulation value THEN the ESSs should operate in CCM).

From the approach proposed in this project, the different stages for charging and discharging properly the ESSs based on batteries will determine the different operation modes and the coordination of the whole MG. In this sense, all the knowledge and information exposed before, which is summarized in subsection 2.1 will define the conception of the expert system responsible for the coordination of the microgrid.

A stable and safe operation of a microgrid can be defined within a limited set of operation modes. The microgrid and the DERs inside the MG can continue doing the same action or performing the same role until the operating conditions make them change [3]. For instance, in a first stage the ESSs may operate within the safe operation window (Fig. 3) and keep the grid-forming role in a continuous way. However, if the maximum and minimum limits of charge are reached, it is required to define some coordinated actions which lead to changes in the operation mode of the MG for avoiding overcharge or over-discharge and keep the power balance in the MG. The MG can continue operating at this stage until there is a change in its operating conditions. In this sense, finite state machines can provide a simple and intuitive mechanism for the deployment of the coordination architecture based on DM units, since the operation mode of the DERs and the whole microgrid can be bounded within a finite number of operation modes, which are mainly determined by the different stages for a proper charge of ESSs based on batteries [65], [3].

The use of finite state machines allows to keep the operation of the MG within a known set of states, and the transitions between operation modes for a proper coordination can be defined in accordance with a simple and intuitive rule base, which considers the different stages for charging battery-based ESSs. This fact allows to addressing the coordination problem of the islanded MG from a higher level of abstraction by means of simple rules as an expert does and in this way hide details that are not important for coordination purposes. For instance, by assuming that the distributed resources operate properly in accordance with their roles and control operation modes, and the coordinated actions can be managed properly at each unit. Nevertheless, it is important to understand how the controllers at the levels of abstraction immediately above and below operate in order to ensure a proper integration of the coordination strategy [66]. In the particular case of a MG composed by distributed generators, it is important to be acquainted about the control loops and the whole control structures involved in the MG in order to ensure a proper matching between coordination commands and control signals.

Coordination Within a Hierarchical Control Frame for Microgrids

In order to standardize the control of microgrid and managing its complexity from different levels of abstraction, a hierarchical control approach has been defined in four levels typically [13], [51].

The first level deals with inner control loops responsible for regulating current and/or voltage based on local measurements and ensuring the local stability of the power electronic interface. The inner control defines the role of the distributed generation in the MG (grid-forming or grid-following) [67]. The second level is termed as primary control which is also a local stage that allows power electronics converters to operate independently but at the same time may allow a cooperative interaction between them. A good example of primary controllers enabling cooperative operations in MGs are the droop control loops, which allows the parallel connected grid-forming unit to share autonomously the power balance in the local grid at the expenses of sacrificing the voltage and frequency regulation [68]. The third level (secondary control) ensures accurate regulation of the global system variables by restoring any deviation caused by the primary controllers (i.e. common bus voltage/frequency, reactive power sharing, power quality in certain points of the microgrid, etc.) [69–71]. Finally, the tertiary control commonly operates as an energy management system (EMS) who defines power references for dispatchable sources by considering an optimized power flow between the MG and the main grid and based on specific interests related to efficiency and economic operation of the MG [72]. Commonly, secondary and tertiary control require global information to perform their task, because of that they require the deployment of additional communication infrastructure.

The definition of the of the hierarchical levels is more related to specific tasks and the bandwidth of each control level, rather than the way in which the task are performed. That is, the tasks can be performed by a central controller, can be decentralized among all the distributed units, or they can be based on hybrid centralized/decentralized solutions [73].

Currently, the dominant trend is the decentralized approach, especially for tasks which require a higher speed (wider bandwidth) such as the inner control loops and the primary controllers. Because of that, the decentralized or even hybrid approach is becoming almost mandatory in order to reduce the dependence of high bandwidth communication [73–75].

Since the inner control defines the role of the distributed resources (control modes) and the primary control allows a cooperative interaction between units (i.e. droop control loops) these two levels should be considered for the definition of a coordinated strategy. By acting on the first level it is possible to modify the role of each DER in the microgrid. Meanwhile acting on the second stage will allow defining cooperative behaviours for the achievement of particular purposes. A coordination architecture based on roles and behaviours may operate independently and in parallel to the secondary and tertiary control layers as is shown in [24,76].

Any, coordination actions or cooperative behaviour (including adaptive adjustment of primary controllers) can be performed either by centralized or distributed DM mechanism. While, centralized architectures, as shown in Fig. 12a, are preferred for small-scale and local area power system with reliable communication systems [2, 76]. Decentralized and specifically distributed approaches, as shown in Fig. 12b, are preferred in applications that require high degrees of scalability and reconfiguration and for MG implemented over wide areas where additional communication infrastructure is not always suitable [3,75,77].

Background in Coordination Strategies for Microgrids

Different coordination strategies have been proposed for managing the complexity in the operation of islanded microgrids. Approaches based on central control units take advantages of the global perception of the MG, which is provided by a dedicated communication network with all the distributed

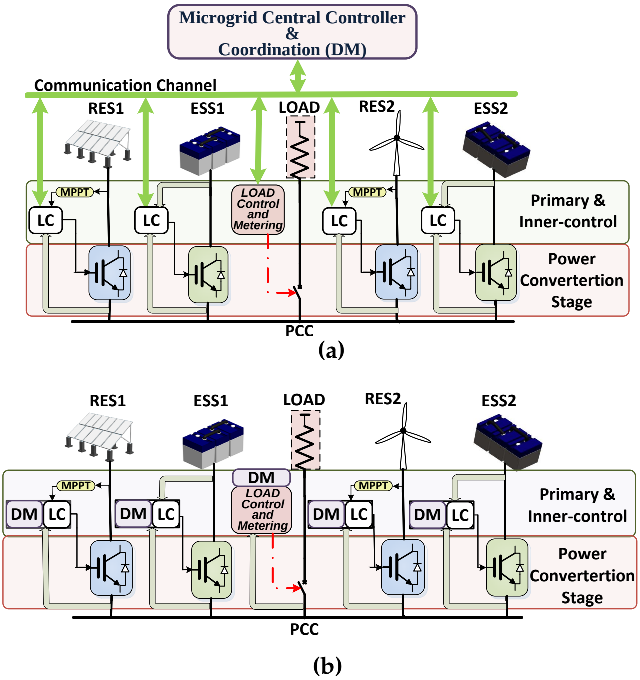


Fig. 12: Islanded MG control schemes: (a) Centralized, (b) Distributed.

units, in order to provide a stable, multi-objective, and optimized coordination [31, 78, 79]. In [60] the coordination is managed by a secondary central controller which adjust the power generation from dispatchable microsources in order to ensure the power balance in the islanded system. Meanwhile, a single ESS based on batteries is responsible for forming the power grid and compensating any transitory mismatch between generation and consumption. As a result, the operation of the ESS is kept within a partial SoC value ($\approx 50\%$).

On the other hand, distributed approaches use the values of the voltage and frequency in the islanded power grid for enabling a kind of communication between distributed units without the use of dedicated communication channels. For ac microgrids the most common approaches use multi-segments adaptive power/frequency curves such as in [80–84]. In [80–82] the interaction between battery-based ESSs and a RESs is determined by the transition between voltage control mode and power control mode (PCM) in the primary controllers. To do that, the droop control loops include integral actions instead of simple droop with proportional loops, which allow the units to activate a PCM operation under specific circumstances defined by the coordination strategy. For instance, in [80,81] the power/frequency curves are defined based on the relation between generation and consumption, rather that the safe SoC limits. Unlike, the work presented in [82] determines the transitions between PCM and VCM based on SoC threshold values. In [83, 84], there are not changes in control modes, since the ESS will always operate in VCM as grid-forming units. Once the threshold values are reached, the ESS generates a change in the pattern of frequency, which is recognized by the RESs and it is used as information for adjusting the power generation bellow the maximum power point. Similar approaches but adjusting the voltage in the common bus have been proposed for dc MGs such as in [85].

The coordination problem in islanded microgrids based on variable RESs and ESS based on batteries is still open to research, since the coordination methods which consider complete charge profiles for ESS has been seldom discussed. On top of that, little work so far has been found for the coordination of distributed ESSs in islanded microgrids. The proposal in this work tries to consider the limitations and charging requirements for ESSs based on batteries and how the charging process can harmonize with a reliable operation of the microgrid even for microgrids with distributed ESSs.

2.3 Cooperative Behaviours

While a pure coordination approach is responsible for arranging the roles and control modes of the distributed resources in a microgrid, a cooperative approach will determine the degree of participation and efforts provided by the distributed resources in order to achieve goals of common interest. Cooperative behaviours can be defined either in grid-forming units or in grid-following units operating under grid-interactive control methods. A clear example is the use of adaptive droop control loops for adjusting the amount of power shared for each grid-forming unit, in order to achieve common goals by considering particular capacities of each unit [2, 3, 76, 86]. Additionally, grid-following units can also perform cooperative behaviours by adjusting the amount of power injected or absorbed, in order to balance the power of the whole microgrid [2].

Two kinds of cooperative behaviours are defined in this project. The first one is oriented to the equalization of the state of charge of distributed energy storage systems, and the second one is the adjustment of the power delivered by RESs in a proportional ratio to their maximum power availability.

SoC equalization

Within a battery string, it is impossible to ensure that all the cells behave identically due to differences in the manufacturing process. Because of that, some cells can be overcharged while others can be uncharged during the charging process. As a consequence, some cells in a battery array may operate out of the safe operation window shown in Fig. 3. This fact causes uneven degradation of the cells what in turn is reflected in a faster degradation of the whole battery array [87]. In order to overcome this problem, the battery manufacturers offer some kind of cell balancing or circuits which perform the SoC equalization process [38], [41].

The same principle of SoC equalization between cells in a battery array can be applied for distributed energy storage systems based on batteries. In this case, advantages such as avoiding the uneven degradation of the battery arrays can be extrapolated for a distributed battery-based ESSs.

The SOC equalization problem between distributed energy storage systems has been widely addressed recently in the literature by means of adjustments in the power-sharing control loops. Some strategies are based on purely distributed approaches which use adaptive curves such as in [77, 88, 89], others rely on centralized approaches such as in [90, 91], and some others approaches rely on decentralized software agents which achieve the SoC equalization based on average consensus algorithms such as in [92–95]. The vast majority of the aforementioned approaches fall into the error of considering the SoC equalization as an independent issue, without any contextualization for their applicability in a real MG. This issue has rarely been considered as part of a complete coordination strategy for MGs.

When the SoC equalization is integrated as a cooperative behaviour into a coordination strategy, some additional advantages become evident, which enhanced the overall behaviour of a coordinated MG as is proposed in [1–3, 30, 76, 86, 96]. Among others, Fig. 13 illustrates some of the main advantages of performing the SoC equalization as part of a coordination strategy. The following list summarizes the main advantages.

- Unification of the discharge/charge profiles, which allows dealing with the distributed ESSs as a single ESS [2]. Fig. 14 shows a clear example in which the SoC profiles of distributed ESSs with different capacities (5 and 10 Ah) behave like the SoC profile of an aggregated ESS with a total capacity of 10 Ah.
- Avoids uneven degradation of the distributed energy storages caused by unequal stress factors:
    - Cycle Depth as can be seen in Fig. 15.
    - DoD as can be seen in Figs. 13 and 15.
    - Charging/Discharging rate as can be seen in Fig. 16. for instance in an islanded MG composed by two distributed ESSs one of them changes to a topping charge stage and the other assumes completely the power balance in the islanded MG.
- Overall reduction in the DoD, which is reflected in larger cycle-life for the whole distributed ESSs.

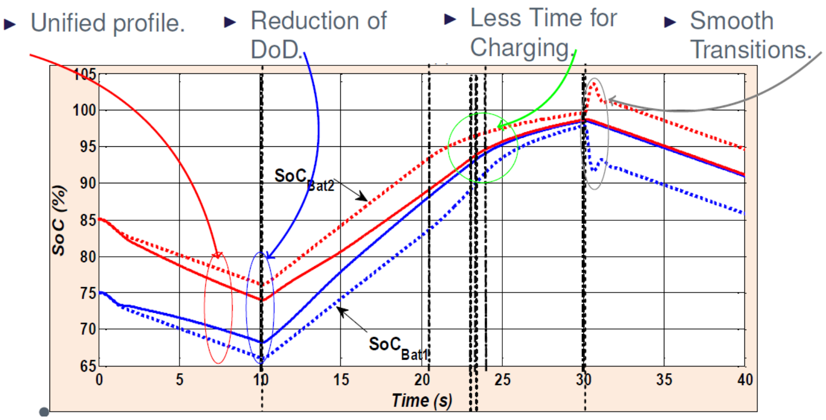


Fig. 13: Comparative curve between SoC profiles with and without equalization [1]. Dashed lines show the SoC profiles without equalization and the continuous lines shows the SoC profile by performing the SoC equalization.

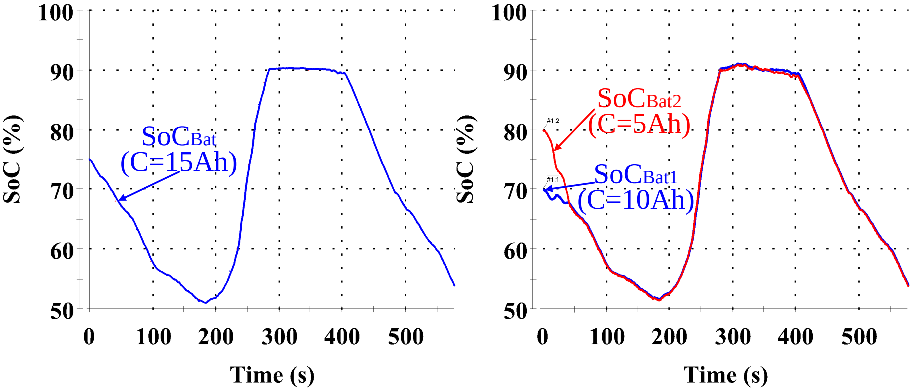
- Faster overall charge of the distributed ESSs.
- Smooth transition between operation modes for the MG [1].
- Simultaneous changes between stages of charge, which is reflected in and easier operation and definition of the coordination strategy.

Proportional Active Power Curtailment

Another fact to be considered as a cooperative behaviour is the operation of RESs as grid-interactive units in the case when the generation is larger than consumption and the energy storage system is not able to store more energy. Therefore, the generation from RESs should be adjusted to match the power consumption as is shown in Fig. 17. This action allows to keep the power balance and avoid that the batteries get overcharged. Here, the problem to solve is determining the power-sharing proportion of each RES.

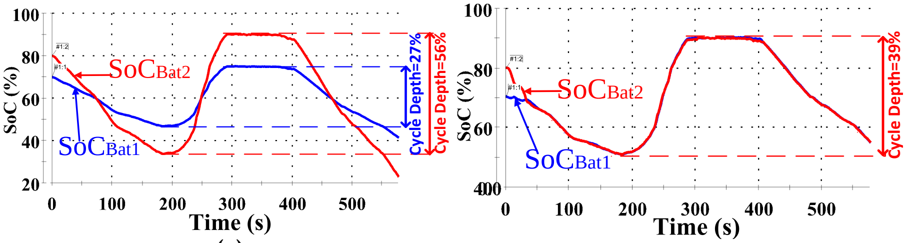
By considering variable RESs, an equal power sharing is not always the best option, since the generation capacity of each unit may vary from one to other. A possible solution is to adjust the power contribution of each unit as a fraction of its maximum available power ($P_{RES} = \beta P_{RES} MPPT$), where ($0 \leq \beta \leq 1$).

The coordination strategies proposed in this project include cooperative approaches, in which the basic criteria for determining the amount of power shared of each RES is based on a proportional relation with its maximum



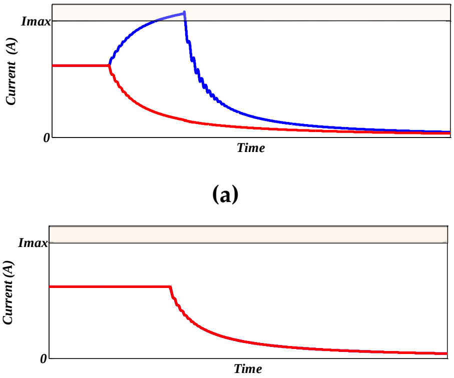
(a) (b)

Fig. 14: SoC profiles for an islanded MG with: (a) aggregated ESS with a capacity of 15 Ah, (b) distributed ESSs with capacities of 10 Ah and 5 Ah and SoC equalization. The figures were obtained from the work presented in [2].



(a) (b)

Fig. 15: Comparison of cycle depth for an islanded MG: (a) without SoC equalization (b) with SoC equalization. The figures were obtained from the work presented in [2].



(a)

(b)

Fig. 16: Comparison between charging current behaviours in distributed ESSs: (a) without SoC equalization (b) with SoC equalization. The figures wer obtained from the work presented in [3].

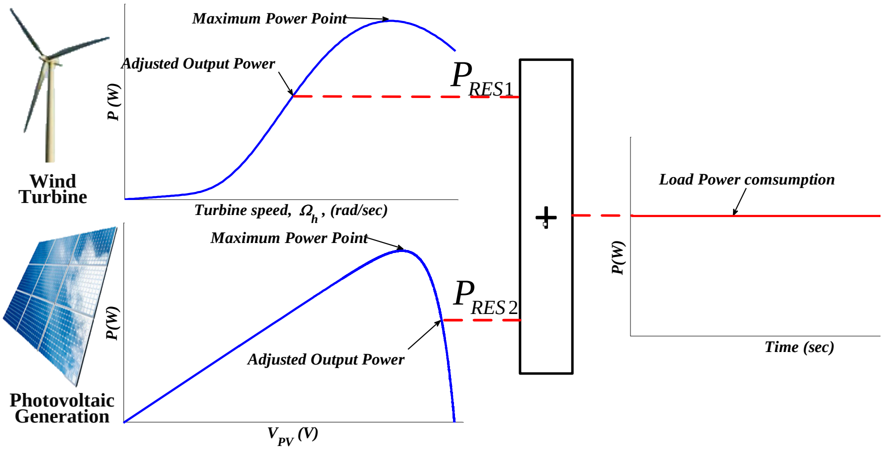


Fig. 17: Operation of RESs as gird-interactive units (off-MPPT mode). Here, the power generation is adjusted to match the power consumption.

power point. That is, the power generator with more power available will contribute with more power than the others and so on [2,3,76,96].

Another possibility is to determine the sharing proportion of each unit based on improving the overall system efficiency in the energy conversion process. It is well known that the efficiency of the power conversion stage is reduced when it operates at low power rates [97]. Therefore, the sharing proportion can be determined by optimal overall system efficiency as is proposed in [98]. This strategy has not been considered in this thesis but can be considered as a part of future work.

3 Thesis Contribution

This thesis addresses the coordination of distributed generation units for small-scale islanded microgrids based on variable renewable energy sources and battery-based energy storage systems. The coordination strategies look for ensuring the reliable and safe operation of the islanded power system by assigning specific responsibilities and actions to the distributed resources in accordance with their particular limitations and capabilities.

The coordination strategies proposed in this thesis are based on specific requirements and characteristics for charging and discharging battery-based energy storage systems. In this sense, three basic stages for the operation of the ESSs are considered as the base for the definition of coordinated actions within the islanded microgrid: (i) The ESS is operating under a partial SoC, therefore, it is able to be charged or discharged in accordance with the requirement of the microgrid. (ii) The ESS reaches its maximum limit for storing energy, therefore, the generation should be adjusted for ensuring the power balance in the microgrid. Meanwhile, proper charge profiles are ensured based on particular requirements of the battery-based ESS. (iii) The ESS reaches its limit for delivering energy to the microgrid, therefore, the load consumption of the microgrid should be adjusted in order to avoid further discharge of the storage unit beyond safe operating limits.

Given the above points, the operation of the microgrid can be considered within a finite number of operation modes or states in a system level, which are determined by specific combinations of operation modes of the distributed resource [3]. As a consequence, the coordination strategies are deployed by means of decision-making units based on finite state machines, which can easily synthesize the required charge profiles for battery- based ESSs.

Finite state machines are probably the most used tool for coordinating multi-robot systems, since they provide a simple way of managing the complexity of the system. This thesis adopts concepts used for coordination architecture of multi-robot systems such as robot soccer teams. The terms of roles and behaviours have been adopted for specifying the control modes, and level of interaction of each distributed unit in the operation of the microgrid respectively. In fact, a coordination architecture based on a metaphoric adaptation of coordination strategies previously proposed for robot-soccer scenarios has been proposed in this thesis.

For ensuring a stable operation of the islanded microgrid under the different stages or operation modes considered within the coordination architecture, a small-signal stability analysis has been performed for islanded ac microgrids by considering different combinations of operation modes at the distributed energy resources. The proposed analysis considers the effect of constant power loads and constant power sources in the dynamic performance of a microgrid and allows to determine the values of the droop coefficients for enabling the power sharing between grid-forming units based on stability constraints.

Thanks to the stability analysis, it is possible to determine safe ranges for adjusting the values in the droop coefficients, which enables the implementation of adaptive power sharing functions. The adaptive functions allow differentiating the amount of power shared by each unit in accordance with its capacity or based on the level of cooperation determined by the cooperative strategy. This fact enables the definition of cooperative behaviours by means of adaptive functions within the coordination strategy such as: (i) SoC equalization. (ii) uniformity in the SoC profiles between distributed battery-based ESSs. (iii) proportional power contribution from variable RESs.

The use of cooperative behaviours for achieving SoC equalization and the uniformity in the SoC profiles allow treating distributed storage systems like a single aggregated storage system, from the point of view of coordination strategy. This because the processes of charging and discharging are carried out almost simultaneously. This fact allows an easy definition of unified actions for coordination in the microgrid and is reflected in uniform degradation and stress for the distributed ESSs.

Expert systems have been used not only for defining the rules and conditions for the finite state machines in the decision-making mechanisms. Additionally, knowledge-based fuzzy inference systems have been proposed for obtaining the adaptive functions which allow the SoC equalization in distributed coordination strategies. The fuzzy system provides an intuitive and qualitative way of defining the adaptive curves for cooperative behaviour, for instance, the adjustment of the droop control loops in accordance to particular operating conditions in each unit. Since the fuzzy system is based on qualitative knowledge, it can be easily adapted for ac or dc microgrids. What is more, a fuzzy inference system is able to manage different control objectives simultaneously as is shown in [86].

In this thesis different centralized and distributed strategies have been proposed for a proper coordination of islanded microgrids based on variable RESs and distributed battery-based ESSs. The proposed architectures can be easily adapted for ac and dc microgrids since the principle of the architecture is based on qualitative knowledge.

The proposed coordination architectures have been validated by either: simulations or experiments. A hardware-in-the-loop (HiL) platform based on Simulink models and dSPACE are chosen as the simulation environment for dc MGs. Experimental setups in the microgrid laboratory are used to verify the coordination architectures in islanded ac microgrids.

4 Thesis Objectives

The research objectives of this project are listed below:

- To investigate the feasibility and advantages of integrating different distributed energy storage systems in combination with distributed renewable energy sources for small-scale islanded microgrids.
- To define suitable power conversion stages and inner control loops for integrating battery-based distributed energy storage devices to islanded microgrids.
- To propose control strategies for coordinated operation of distributed energy storage systems based on batteries and variable renewable energy sources in islanded ac and dc microgrids.
- To develop centralized and decentralized control strategies as well as energy management algorithms for achieving stored energy balance

among distributed energy storage units.

- To develop different scalable and expandable coordination strategies for islanded microgrids based on distributed energy storage systems and variable renewable energy sources, taking into consideration both the storage and the grid side (energy storage limitation and microgrid stability).
- To integrate the coordination strategies to the hierarchical control structure for microgrids.
- To develop coordination and management algorithms according to the power limitation of each power electronics converter and capacity of charge of each energy storage unit. The proposed strategies will consider the particular characteristics of each ESS and their requirements for the proper process of charge/discharge.

5 Thesis Outline

This thesis is organized as follows:

***Chapter II*:** presents the first paper, published in IEEE Transactions on Smart Grid. This paper proposes a distributed coordination strategy for a low voltage islanded dc microgrid, which considers changes between operation modes in the distributed energy resources for ensuring appropriate charge profiles for distributed energy storage systems based on lead-acid batteries. The proposed coordination strategy rely on a multi-objective fuzzy logic based adaptive function for adjusting the value of the virtual resistance in the droop control loops in order to balance the stored energy between distributed battery-based energy storage systems, and at the same time reduce the voltage deviation at the common dc bus. The units are self-controlled by using local variables only, hence, the microgrid can operate without relying on communication systems. Results from hardware in the loop (HiL) show the feasibility of the proposed method. The proposed coordination strategy is tested in the microgrid laboratory with dSPACE based HiL setups.

***Chapter III*:** contains the second paper, presented in IEEE Energy Conversion Congress and Exposition (ECCE) 2015. This paper proposes a small-signal stability analysis for the use of adaptive droop control loops in islanded ac microgrid composed of distributed energy storage systems and variable renewable energy sources. The performed analysis considers different stages and topological circuit operation modes of the microgrid, for providing the appropriate charge profiles to distributed energy storage systems based on lead-acid batteries in ac microgrids. The proposed analysis allows the adequate selection of values and range for adjusting the droop coefficients based on adaptive functions, in order to ensure the stability of the microgrid under different topological operation modes.

Chapter IV**:** presents the third paper, which has been submitted to IEEE Transactions on Power Electronics. This paper proposes a distributed architecture for assigning roles to distributed units in islanded ac microgrids. The distributed units are self-controlled and coordinated by means of distributed decision-making units which rely only on limited information about the global state of the microgrid, provided by a bus-signalling method without the use of additional communication channels. The proposed strategy considers different stages for charging properly storage units based on lead-acid batteries and includes a distributed method based on a fuzzy inference system for equalization of the state of charge (SoC) between distributed energy storage systems. The SoC equalization allows a smooth and uniform transition between charging stages for the distributed ESSs. The proposed control strategy is tested experimentally in the microgrid laboratory.

Chapter V**:** presents the fourth paper, accepted for publication in the IEEE Transactions on Power Electronics. This paper proposes a centralized control architecture based on tactics, roles, and behaviours for a coordinated operation of islanded ac microgrids. The architecture is inspired by a robot-soccer coordination strategy, which is used from a metaphoric point of view in order to structure the coordination of the distributed energy resources for ensuring a reliable operation of the islanded system and appropriate charge profiles for distributed energy storage systems based on lead-acid batteries. The proposed architecture takes advantages of the global perception provided by the centralized control agent to allow greater flexibility in operating modes and transitions between different operating conditions. The proposed control strategy is tested experimentally in the microgrid laboratory.

Chapter VI**:** presents the fifth paper, presented at the IEEE First International Conference on DC Microgrids (ICDCM) 2015. This paper presents a centralized strategy for equalizing the state of charge of distributed energy storage systems in an islanded dc microgrid. On top of that, the proposed strategy allows uniform SoC profiles between distributed battery-based ESSs based on a proportional power sharing in accordance with the capacity of each storage system. The proposed strategy is based on a simple algorithm denoted as equalization algorithm, which modifies the charge or discharge rate by weighting the virtual resistor of local droop control loops at each distributed energy storage system. The proposed strategy can be used as an additional function within a coordination strategy Hardware in the loop results show the feasibility of the proposed method. The proposed coordination strategy is tested in the microgrid laboratory with dSPACE based HiL setups.

***Chapter VII*:** contains the sixth paper, accepted for publication in the IEEE Transactions on Power Electronics. This paper adapts the equalization method presented in the previous section to be implemented in an islanded ac microgrid. The equalization method is incorporated within a complete coordination strategy, which relies on a central control unit which works as a supervisory stage for avoiding overcharge or over-discharge on battery-based ESSs. The proposed strategy provides a more suitable charge profile for Li-Ion batteries. Experimental results validate the proposed coordination strategy.

***Chapter VIII*:** contains the conclusion and summarizes the main contributions. Additionally, this part presents perspectives for future research.

Part II

Paper 1

Intelligent Distributed Generation and Storage Units for DC Microgrids - A New Concept on Cooperative Control without Communications Beyond Droop Control

Nelson L. Díaz, Tomislav Dragičević, Juan C. Vasquez,
and Josep M. Guerrero

Abstract

Low voltage dc microgrids have been widely used for supplying critical loads, such as data centers and remote communication stations. Consequently, it is important to ensure redundancy and enough energy capacity in order to support possible increments in load consumption. This is achieved by means of expansion of the energy storage system by adding extra distributed energy storage units. However, using distributed energy storage units adds more challenges in microgrids control, since stored energy should be balanced in order to avoid deep discharge or over-charge in one of the energy storage units. Typically, voltage droop loops are used for interconnecting several different units in parallel to a microgrid. This paper proposes a new decentralized strategy based on fuzzy logic that ensures stored energy balance, for a low voltage dc microgrid with distributed battery energy storage systems, by modifying the virtual resistances of the droop controllers in accordance with the state of charge of each energy storage unit. Additionally, the virtual resistance is adjusted in order to reduce the voltage deviation at the common dc bus. The units are self-controlled by using local variables only, hence, the microgrid can operate without relying on communication systems. Hardware in the loop results show the feasibility of the proposed method.

The paper has been published in the
IEEE Transactions on Smart Grid Vol. 5, No. 5, pp. 2476-2485, 2014.

Part III

Paper 2

Stability Analysis for Isolated AC Microgrids Based on PV-Active Generators

Nelson L. Díaz, Ernane Alves Coelho, Juan C. Vasquez,
and Josep M. Guerrero

Abstract

The current trend in isolated microgrids is oriented to distributed renewable energy generators, such as photovoltaic (PV) generators and their corresponding distributed energy storage systems (ESS) as an unit denoted as active generator (PV+ESS). In an isolated microgrid, every distributed generator (ESS or PV) may operate in two operation modes (grid-forming or grid-following) in accordance to specific operational conditions. Nevertheless, at least one distributed generator should assume the regulation of the common bus, and seamless transition between operation modes should be ensured for all the distributed generators. In particular, ESS's based on batteries require at least two different mode of charge. As consequence, the topological operation mode of the microgrid is affected by the changes of the operation mode of each distributed generator. Typically, droop control loops are used for interconnecting several different distributed generators in parallel to a common bus, whose parameters determine the stability and damping of the microgrid operation. In this paper, a small-signal stability analysis is applied to an isolated AC microgrid composed of (PV+ESS) active generators, regarding three different operation modes of the microgrid. The proposed analysis allows the designers an adequate selection of the droop coefficient in order to ensure the stability of the microgrid under different topological operation modes.

The paper has been published in the
Proceeding of 2015 IEEE First International Conference on DC Microgrids
(ECCE 2015), pp. 4214-4221, 2015.

Part IV

Paper 3

A Communication-less Distributed Control Architecture for Islanded Microgrids with Renewable Generation and Storage

Nelson L. Díaz, Juan C. Vasquez, and Josep M. Guerrero

Abstract

For reliable operation of an islanded microgrid, at least one of its distributed resources should assume the responsibility of forming the off-grid power system. This responsibility is usually assumed by energy storage systems based on their capability of compensating the unbalance between generation and consumption. However, the storage units may lose their capability of regulating the power grid when maximum and minimum limits of charge are reached. Under these conditions, the regulation of the power grid may be assumed by another unit with enough capability or the power balance should be adjusted coordinately. This paper proposes a coordination architecture for islanded ac microgrids, which considers the appropriate charge profiles for battery-based energy storage systems. The architecture is based on distributed decision-making mechanisms, which use only local measurements for determining the operation mode of each unit independently. The coordination relies on a bus-signalling method, which enables the distributed units to have a global perception about the operation of the microgrid, without any communication infrastructure. The proposed architecture includes cooperative operation between distributed energy storage systems for equalization of charge, which allows a uniform transition between appropriate charging stages. Experimental results validate the proposed strategy under different operational conditions in the microgrid.

The paper has been submitted to the
IEEE Transactions on Power Electronics 2016.

Part V

Paper 4

A Robot-Soccer-Coordination Inspired Control Architecture Applied to Islanded Microgrids

Nelson L. Díaz, Jose G. Guarnizo, Martin Mellado, Juan C. Vasquez,
and Josep M. Guerrero

Abstract

Nowadays islanded microgrids present a high interest due to the increasing penetration of renewable energy resources, especially in remote areas, or for improving the local energy reliability. A microgrid can operate in grid-connected or islanded mode, being necessary the use of energy storage systems under islanded operation, in order to ensure the generation/consumption power balance and smooth uncertainties in the dynamics of the renewable energy sources. Particularly, in islanded operation at least one of the distributed energy resources should assume the regulation of the common bus. In a microgrid, every distributed energy resource may be able to cooperate with the grid regulation in accordance to its particular operational conditions. In this sense, a centralized unit with a global perception of the load demand, the power provided by the renewable energy sources, and the storage capacity of the energy storage systems, may ensure proper and reliable operation of the microgrid. This paper proposes a structured architecture based on tactics, roles and behaviors for a coordinated operation of islanded microgrids. The architecture is inspired on a robot soccer strategy with global perception and centralized control, which determines the changes among operation modes for the distributed energy resources in an islanded ac microgrid.

The paper has been accepted for publication in the
IEEE Transactions on Power Electronics, Early Access,
DOI. 10.1109/TPEL.2016.2606653, 2016.

Part VI

Paper 5

Energy Management System with Equalization Algorithm for Distributed Energy Storage Systems in PV-Active Generator Based Low Voltage DC Microgrids

Nelson L. Díaz, Adriana C. Luna, Juan C. Vasquez, and Josep M. Guerrero

Abstract

This paper presents a centralized strategy for equalizing the state of charge of distributed energy storage systems in an islanded DC microgrid. The proposed strategy is based on a simple algorithm called equalization algorithm, which modifies the charge or discharge rate by weighting the virtual resistor of local droop control loops at each distributed energy storage system. The proposed strategy, can be used as an additional function of the microgrid energy management system where the state of charge of distributed ESS is equalized within a determined window of time. Finally, real-time simulation results of a low voltage DC microgrid are presented in order to verify the performance of the proposed approach.

The paper has been published in the
Proceeding of 2015 IEEE First International Conference on DC Microgrids
(ICDCM 2015), pp. 293-298, 2015.

Part VII

Paper 6

Centralized Control Architecture for Coordination of Distributed Renewable Generation and Energy Storage in Islanded AC Microgrids

Nelson L. Díaz, Adriana C. Luna, Juan C. Vasquez, and Josep M. Guerrero

Abstract

The coordinated operation of distributed energy resources such as storage and generation units and also loads is required for the reliable operation of an islanded microgrid. Since in islanded microgrids the storage units are commonly responsible for regulating the voltage amplitude and frequency in the local power system, the coordination should consider safe operating limits for the stored energy, which prevents fast degradation or damage to the storage units. This paper proposes a centralized control architecture, applicable for local area power systems such as a small-scale microgrid. The centralized architecture is based on three supervisory control tasks which consider: active power curtailment of generation for avoiding overcharge of the storage units, load shedding actions for preventing deep discharge of the storage units, and equalization of the state of charge among distributed storage systems for avoiding uneven degradation. The proposed equalization method has proved to be effective for equalizing the state of charge of distributed energy storage systems and for ensuring uniform charge/discharge ratios regardless of differences in the capacity of the storage units. Additionally, the strategy is complemented with an optimal scheduling of load connection, which minimizes the connection and disconnection cycles of the loads within a time horizon of 24 hours. The proposed architecture is verified experimentally in a lab-scale prototype of a microgrid, which has real communication between the microgrid and the central controller.

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Part VIII

Concluding remarks

Conclusion

1 Summary

This thesis proposes different coordination architectures for small-scale islanded microgrids based variable renewable energy sources and energy storage systems based on batteries. These kinds of microgrids are highly used for the electrification of non-interconnected and remote villages or communication stations. Due to the variability and unpredictable behaviour of the primary energy resources, the islanded power system relies on energy storage systems for ensuring a reliable operation. The Energy storage systems can provide the required energy backup and energy buffer for supporting the variations on the primary energy resources and provides enough autonomy to the islanded power system. Particularly, battery-based energy storage systems continue dominating the applications in islanded systems, thanks they offer the best compromise between lifetime, energy density, power density, availability, and cost.

The proposed coordination architectures enable an appropriate interaction of the energy storage systems based on batteries with other distributed generators within an islanded power system, by considering the limitations, particular requirements, and appropriate charging stages of the storage units. As a matter of fact, the coordination strategies are based on charging profiles, which ensures a proper charging process of the energy storage system.

The proposed coordination architectures can be easily deployed and adapted for either ac or dc microgrids, since are based on expert systems which manage the complexity derived from the interaction of different kinds of distributed units from a higher level of abstraction. The distributed units in the microgrid are able to operate independently and without any coordination by means of a proper definition of inner and primary controllers. Therefore, the coordination strategies are properly dimensioned and integrated to the hierarchical control structure defined for microgrids. In this sense, by acting over the first level (inner control loops, in the hierarchical control structure), it is possible to modify the role (control mode) of the distributed units in order to achieve different stages for charging the energy storage system and assigning the responsibility of forming the local power grid to a distributed unit with enough capability. Meanwhile, adjustments in the primary controllers (second level) allow the definition of cooperative behaviours between distributed units.

Conventional droop control loops have been considered for the primary controllers. Therefore, the adjustment derived from cooperative functions defined within the coordination strategy are properly scaled by considering the stability issues and constraints. To do that, small-signal models of the islanded microgrid have been obtained and studied, which consider different configurations and interactions between grid-forming units operating in voltage control mode, and grid-following units operating as constant power sources or loads.

One of the cooperative operations explored within this project is the equalization of the state of charge of distributed energy storage systems. The SoC equalization allows the operation of distributed energy storage systems as an aggregated one by unifying the SoC profiles. This fact allows simultaneous transitions between charging stages by facilitating the definition of coordination actions. Additionally, the Soc equalization avoids uneven degradation of the distributed storage units, by exposing them to similar levels of stress, or proportional to their capacity, during their operation.

Both. distributed and centralized strategies have been explored. The distributed approaches take advantages of their inherent modularity and expandability making them more suitable for applications which require a progressive expansion or where the use of dedicated communications channels are not possible. Meanwhile, centralized approaches take advantages of the global vision provided by the central controller in order to perform more accurate and multi-objective tasks. Therefore, centralized strategies add more flexibility to the operation of the distributed units, since it makes possible the definition of additional collaborative behaviours.

The coordination problem of multi-units systems has been widely explored in different fields. For instance, the coordination of multi-robot in automation systems. In this sense, similar principles and approaches can be adopted for the coordination of islanded microgrids as was proposed in this work by defining a structured architecture based on tactics, roles behaviours previously used for teams of robot soccer.

2 Contributions

This sections summarizes the main contributions from the point of view of the Author:

- The definition knowledge-based fuzzy functions for enabling an adaptive operation of droop control loops, which allows the equalization of the state of charge of distributed energy storage systems. The fuzzy systems rely only on qualitative knowledge, because of that, the can be easily adapted for ac and dc microgrids. Apart from that, the fuzzy system can perform multi-objective functions such as the reduction of voltage deviation in dc microgrids.

- The definition of complete coordination architectures which ensure appropriate stages and profiles for charging battery-based energy storage systems. The proposed strategies consider the batteries as voltage limiting devices, then the control modes in the energy storage units and in the whole microgrid are adjusted for ensuring proper stages of charge.
- The development of distributed coordination strategies based on bus signalling methods without the use of additional communication infrastructure. The proposed strategies are completely modular and scalable and allow an easy integration of additional distributed generators and storage units.
- The development of small signal models, which considers different topological circuit model for an islanded microgrid. The proposed small-signal models allow the stability analysis of a microgrid composed by parallel connected units in voltage control mode with droop control loops and their interaction with constant power sources and constant power loads.
- The design of a novel SoC equalization method based on a centralized function, which has proved to be effective for equalizing the state of charge of distributed energy storage systems and for ensuring uniform charge/discharge ratios regardless of differences in the capacity of the storage units.
- The adaptation of structured coordination architectures, which have been previously used in other fields, in the coordination of distributed energy resources in islanded microgrid.

3 Future Work

The strategies and contributions developed in this thesis show the following promising aspects to be investigated in the future:

- This work has considered the coordination of microgrids with battery-based energy storage systems. However, the interaction with energy storage systems with high power density, such as Supercapacitors, should be addressed in order to enhance the transient behaviour under sudden variation in generation and consumption and also providing support for enhancing the dynamic response and smoothing the operation of the microgrid under the transitions in operation modes.

- The earliest form of artificial intelligence, such as the knowledge-based system based on logical assertions has been considered within this thesis for defining the coordination architecture for islanded microgrids. In this sense more sophisticated reasoning tools such as optimization methods based on probability and economics goals, neural networks, probabilistic methods for uncertain reasoning, etc. which should be considered in order to have more learning, planning, self problem-solving and reasoning capability, within the coordination architecture.

- A centralized program has been proposed, which has proved to be effective for enabling uniform charging/discharging profiles for distributed ESSs. Therefore, this program should be approached from a distributed perspective in order to reduce the dependence of a central controller. In this sense, multi-agent approaches should be considered. In this way, the advantages of distributed and centralized approaches can be put together.

- Additional cooperative approaches can be included within the coordination strategy which take into account the reactive power sharing, the harmonic sharing and compensation, unbalance compensation, and other power quality issues.

- Coordination architectures for distributed energy storage systems in grid-connected microgrids should be also considered by taking into account the uniform operation of distributed units.

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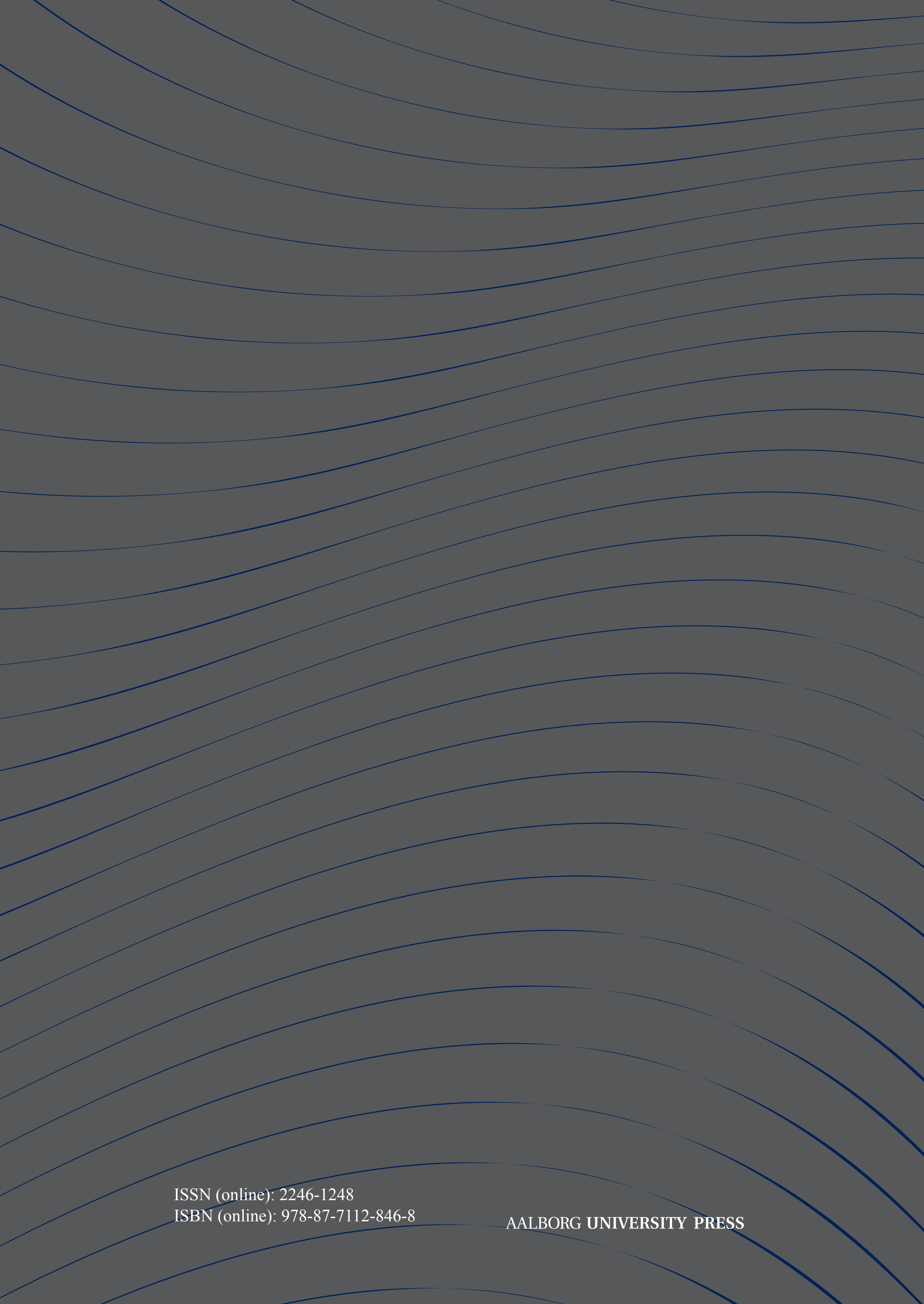

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