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Contribution to the operation of smart rural distribution grid with energy resources for improvement of the quality of service

Francesc Girbau-Llistuella

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Doctoral Thesis

Contribution to the Operation of Smart Rural Distribution Grid with Energy Resources for Improvement of the Quality of Service

Tesi per compendi de publicacions

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Resum

Aquesta Tesi vol contribuir en el desplegament de les futures xarxes elèctriques intel.ligents, en entorns rurals que habitualment són oblidats. Cal mencionar que els principals avenços tecnològics i les inversions per part dels gestors de la xarxa s'han centrat en entorns urbans i industrials, ja que aquests solen demandar grans quantitats d'energia, fet que facilita la recuperació de la inversió. Per tant, en un entorn on la densitat de població i la demanda energètica és baixa i a més l'orografia és complexa resulta menys actractiu invertir-hi.

Per aquest motiu, la Tesi, en paral.lel al projecte Europeu Smart Rural Grid, s'ha centrat en el desenvolupament de les xarxes elèctriques en entorns rurals. El principal objectiu de la Tesi i alhora del projecte Smart Rural Grid és desenvolupar tecnologies per concebre les futures xarxes en entorns rurals. Aquestes han de permete incrementar la baixa eficiència, qualitat i resiliència de la xarxa. En aquest sentit, la Tesi ha contribuït en la concepció, disseny i justificació d'una innovadora arquitectura. Aquesta arquitectura, s'ha dut a terme en el final d'una línia de mitja tensió d'Estabanell Energia a Vallfogona del Ripollès. A més, aquesta arquitectura es caracteritza per integrar electrònica de potència, sistemes elèctrics d'emmagatzemament, un innovador sistema de gestió i de telecomunicacions, poden proporcionar a la xarxa una major robustesa, flexibilitat i capacitat per integrar a la nova generació distribuïda i renovable.

D'altre banda, la Tesi també s'ha centrat en la concepció i desenvolupament de nous modes d'operació, algoritmes i dispositius que permeten automatitzar i optimitzar la gestió dels recursos distribuïts; és a dir, la electrònica de potència, els sistemes d'emmagatzemament, la generació renovable i distribuïda i les càrregues controlables. Aquestes estrategies permeten solventar els problemes habituals en aquest tipus de xarxes, com per ejemple les variacions de tensió i les pèrdues. A més, també milloren i asseguren la qualitat i continuïtat del subministrament, ajuden a reduir els costos d'operació i retrassar la inversió en nova infraestructura.

Abstract

This Thesis aims for contributing in the deployment and operation of Smart Grid, in isolated rural areas. As it would be expected, technological developments and investments in the electrical field have mainly focused on urban and industrial areas where the energy demand is high, as well as, the possibility to recover easily the investment. Therefore, difficult accessing areas where population and electrical demand are low are less attractive to invest.

For this reason, this Thesis, in parallel to the European project known as Smart Rural Grid, has focused on the rural grid development. In this sense, the Thesis contributes directly in the design, conception and justification of an innovate architecture for rural systems. The architecture has been deployed and tested at the end of a medium voltage line of Estabanell Energia in Vallfogona del Ripollès. In addition, the presented architecture is characterised to integrate power electronics with embedded battery systems, an innovative management system and a proper telecommunication network in order to gain robustness, flexibility and hosting capacity for distributed and renewable generation.

To sum up, the Thesis has focused on the design and development of new operation modes, algorithms and equipment that allow to manage automatically and optimally the energy resources; like power electronics, energy storage systems, distributed and renewable generation, and controllable loads. These strategies are able to correct common issues in rural grids, such as voltage variations and electrical losses. In addition, they improve and ensure the power quality and supply continuity, contribute to reduce operational costs and infrastructure optimization and deferral.

Contents

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Nomenclature

Universities, groups, companies and enterprises

Initials	**Description**
CGA	Crompton Greaves Automation System Division
CITCEA	Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments
EyPESA	Estabanell y Pahisa Energia Sociedad Anónima
SMARTIO	Smart Innovation Østfold
SWRO	Stadtwerke Rosenheim
UPC	Universitat Politècnica de Catalunya
XOC	Xarxa Oberta de Catalunya

Thesis acronyms

Initials	**Description**
DG	Distributed Generation
DSO	Distributor System Operator
EMS	Energy Management System
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
SRG	Smart Rural Grid
ICT	Information and Communication Technology
TSO	Transmission System Operator
IDPR	Intelligent Distribution Power Router

Preface

Background

Rural distribution networks are more vulnerable than urban ones. The aged infrastructure of rural distribution networks combined with other habitual challenges such as low quality indices (number or time of interruptions), overloaded infrastructures, difficult access and scattered consumption, suggest to adopt updated solutions and cutting edge technologies. The increasing penetration of small distributed power plants and renewable energy resources can contribute to overcome these weaknesses defining a new electric paradigm. However, local renewable generation must be managed carefully because of its fluctuating nature.

The Distributor System Operators' (DSOs) mission is to provide a proper electricity supply and power quality in all environments. The particular conditions and operation boundaries of rural distribution grids need a re-thinking of how to keep the lights on while both making the best use of new energy resources and keeping infrastructure cost down. Traditionally, they adopted extremely costly and disruptive to local communities solutions such as extending and reinforcing physical infrastructure. Instead of adopting only these solutions, others can be assessed, such as those related to generation and demand management, as well as monitoring, sensing and automation equipment.

In this sense, both scientific community and industry are proposing and adopting different actuations to transform traditional distribution grids into active, Smart Grids (SGs). Numerous projects related to SGs and microgrids have been taking place in Europe. Their fundamental idea is transforming the conventional systems into an intelligent one that includes advanced meters, telecommunications and Distributed Energy Resources (DERs), but also to provide new functionalities as self-healing, high reliability and power quality, resistance to cyber-attacks, DER integration, asset optimization, minimization of operations and maintenances expenses, among others.

The Smart Rural Grid (SRG) project was one of these European projects and it is also the frame for the present Thesis. The SRG project has emerged to face the above mentioned challenges and helps to answer different technical and operational issues for the particular case of rural grids [1]. In this sense, the SRG project has explored and showed how to exploit the convergence between electricity and telecommunications networks for almost four years.

The undertaken work has aimed to point out how utilities can operate more efficiently their available electric resources than through business as usual practices and manifested how to interconnect energy prosumers to enable a multi-directional energy flow.

To clarify, a prosumer is an user that both consumes and produces electricity, and wants to become involved in the system operation, taking an active role instead of having a passive behaviour [2, 3]. The SRG project has also examined the best way to make the transition from present rural distribution networks to a new electric operational framework by using SG technologies without losing sight of the corresponding associated business concepts. The project concept was based on the integration of distributed energy renewable resources and energy storage systems to enable each rural region to become self-contained with energy and creating resilient systems.

The European Union has founded the SRG project for defining a novel system architecture for smart rural grids. It has been deployed as part of EyPESA's distribution network in Vallfogona, Catalonia, Spain. EyPESA was the project leader and combines both roles of a DSO and retailer. EyPESA has cooperated with CITCEA-UPC that is devoted to research, innovation and technological transfer to industry in mechatronics and enertronics fields; ZIV Communications who is a Spanish manufacturer with a complete variety of power line communications systems, digital protection and control equipment for low to high voltage electric power networks; XOC which provides fiber optical services in Catalonia; KISTERS which offers leading technology solutions and standard software for the energy market; SWRO Netze who is a German distributor of electricity, gas, water and heating that studies the viability to deploy the developed technology;CGA which is a leading supplier of control and automation solutions, services and products for monitoring and control of power transmission and distribution across various market sectors; and finally, SMARTIO which was a cluster of enterprises and academic institutions that realizes the SRG integration in control centre room and the dissemination of the project.

Thanks to the expertise of the SRG consortium, the SRG project has developed a set of devices, services and energy managers that assist the operation of the cited smart rural grid pilot.

Objective

The Thesis has been developed in parallel of the Smart Rural Grid project and its goals were conceived for fulfilling part of project requirements. Its main goal has focused on providing a contribution in terms of power quality, reliability and continuity of service to the rural distribution grid operation with renewable energy resources through advanced Information and Communication Technology (ICT) based solutions and power electronics with embedded energy storage.

Accordingly, the specific objectives of the Thesis are:

- The development of a novel architecture for rural distribution grids focusing on a real pilot network. In turn it leads to:
    + Analyse rural distribution grids, study their strengths and weakness, compare them to urban networks, evaluate the traditional actuations and solutions carried out in these grids for performing a proper operation and management.
    + Identify and determine sustainable actuations for evolving an aged rural network into a SG, considering future requirements like new operating modes, and a major degree of flexibility and observability.
    + Study how power electronics and energy storage systems can be integrated in these networks, the main functionalities which they have to perform for ensuring the power quality, reliability and continuity of service, and identify the main contributions of them to the system operation.
    + Introduce advanced operating modes for rural systems with renewable and distributed energy resources for increasing their power quality, reliability and continuity of service, with minimum costs and environmental impact.
    + Define a methodology for the sizing and location of new power electronic devices with embedded energy storage systems into the pilot network.
    + Design a proper management system hierarchy and its novel actors considering diverse technical and environmental constraints.
    + Plan a suitable telecommunications network for the power electronics and energy storage systems together with DERs that support the advanced operating modes. Also, plan actuations that offer major degree of flexibility and observability, taking into account important aspect like costs, reliability, cyber-security and environmental impact.
    + Finally, analyse the novel architecture for rural distribution grids focusing on its vulnerabilities like cyber-security and failure of one or more actors, planning an strategy to ensuring its operation and reliability.
- The development of an innovate Energy Management System (EMS) that manages renewable and DERs and, power electronics with embedded storage and optimizes the distribution network functioning in terms of economic and technical aspects with a global system vision. In turn it leads to:

  - Study of the extensive scientific literature about technical and economic EMs and relate the literature to previous novel architecture for rural distribution grids.
  - Define clearly a proposal system that combines technical and economic goals and present their mathematical formulation and their inputs and variables.
  - Identify and model real study cases and scenarios in order to test the innovative EMS in rural environments.
  - Propose mathematical metrics and indicators for evaluating the EMS contributions.
  - Simulate and evaluate the EMS behaviour in the prosed study cases and scenarios and check its contribution through the prosed metrics and indicators.

- To develop a second EMS that manages the available local assets with short time step and optimizes and ensures the regional functioning when the network operates connected or isolated from the rest of system. In turn it leads to:

  - Develop a local EMS implemented locally in an industrial computer, focusing on its communication protocols, functioning states, and actions performed.
  - Present the performed actions and calculations carried out by it in function of its functioning states.
  - Develop a mathematical algorithm answering the required needs for managing the local grid.
  - Identify and model representative study cases and scenarios in order to test the innovative EMS in rural environments.
  - Simulate and evaluate the EMS behaviour in the proposed study cases and scenarios.
  - Check and demonstrate in the pilot network the functioning of power electronics contributions through an ad-hoc monitoring software implemented in the local EMS.

Scope

Rural areas have important limitations, since they have been deployed under radial-based designs, following a tree-like shape, offering non-alternative paths (unlike urban grids) and disabling the possibility to execute other configurations. In addition, the eventual deployments in rural environments are conditioned by their non-negligible environmental impact, which strongly narrows possibilities of getting the required permissions from public authorities and even a minimum social acceptance. Therefore, rural distribution topologies are singular and very specific in terms of performance, quality of supply and potential to incorporate DER.

The telecommunications infrastructure is certainly no exception and is often sized according to the customers density. Indeed, because of low customers density, there is often only one or none telecommunications operator active in these regions, leading to an evident lack of competition for local businesses. In turn, this leads to lower investment and innovation, which yields communications with low data transfer speed and large latencies.

A key element for future SGs is the small or Distributed Generation (DG). It can minimise distribution losses and maximise the grid performance, support the island operation during contingencies, contribute maintaining the security of power supply, and it can even help for the security of supply to critical telecommunications infrastructure. However, the renewable generation have mostly an intermittent nature and output power fluctuations that may create integration issues that in turn may increases in these aged and rural networks.

Energy storage systems are able to mitigate problems associated to the variability of DG, and also provide other network services such as grid investment deferral, spinning reserve, voltage support and frequency regulation. Therefore, DG coupled to energy storage systems, along with controllable loads, offer the potential for enhanced grid flexibility and efficiency.

For the integration of such energy storage and DG though, key enabling technologies are Information and Communication Technologies (ITCs) and these, as previously introduced, are very scare in rural networks.

Further describing the above ecosystem, the regulation side should be also considered. Currently, there is a growing trend in Europe to request all generators fulfil the system requirements and support it increasing its security, reliability and resilience. Even, updated regulation may require them to be controlled via setpoints by the system operator as convenience. It pushes DSOs to continue moving to SG architectures, increasing its monitoring and observability capabilities, and its data and system advanced management, including new functionalities such as power flow control, automatic fault location, self-healing isolation and supply restoration, voltage control, power quality and indicator evaluation, among others. In addition, new market roles have being introduced progressively for democratizing the electricity market through the DG participation.

Despite above trends, current grids are still being operated via a control centre, deploying a vertical integrated architecture with limited possibilities to interoperate to other arrangements and realize the overall management. This, combined the present lack of infrastructure in rural environments slowdowns the future grid demands and the information exchange between market players and prosumers.

To sum up, the combination of intelligence, ITCs, power electronic devices and energy storage system deploying SG architectures can enable the increment of the DG integration, the supply security and power quality, thus facilitating the interoperability between distribution and transmission systems, and also enabling new actors to actively participate in electrical grids and markets.

Methodology

Addressing the objectives of the Thesis, related work has been structured as follows:

Chapter 1 introduces the Thesis state of the art. It provides a vision of the structure and operation of electrical power systems and presents the ongoing challenges and developments, as well as the regulatory framework. It defines also the Smart Grids focusing on their benefits and issues, especially in rural environments.

Chapter 2 is one of the journal papers composing the compendium. It presents a novel architecture for rural distribution grids designed to modernize traditional rural network into a new smart one. It presents the actuations carried out and their justification, also includes a study case sizing and showing the potentialities of developed technologies.

Chapter 3 is also a journal paper composing the compendium. It proposes an innovative EMS that optimizes the whole the grid operation based on economic and technical criteria. It defines diverse metrics and scenarios for evaluating the EMS performance.

From the above two journal papers, Chapter 4 presents the main conclusions of the work, relating them with the Thesis contributions and proposals for future work.

Chapter 5 summarizes the Thesis publications from journals, conferences, books and among others.

Appendix A presents a third paper that details and illustrates the operation of the so-called Local EMS during both grid-connected and disconnected operation modes.

Finally, Appendix B includes a fourth paper showing the experiences for integrating the power electronics through the Local EMS in field.

Chapter 1

State of the art

1.1 Introduction

Electricity supply is vital in modern societies. It is the most versatile, controllable, instant available and clean energy form [4]. The availability of electricity facilitates that a multitude of smaller, more reliable, safer and quieter electric tools are employed at workplace and at home [5]. These tools convert electricity into useful forms of energy or activity, like heat, light, data or movement, simplifying and improving people's life [5, 6].

Electricity has a direct impact on the social and economic development of areas, making the modern societies totally dependent on electricity supply [4].

The way to provide electricity to the society is through the electric power system. An electric power system is composed of wires and machines that carry the electricity from an origin –power plants– to consumption places –workplaces and homes – [5]. Power systems are generally similar in all countries, however, they vary in size, robustness, voltage levels and frequency [7].

Millions of consumers depend on the electrical power system, therefore, a proper design and operation is fundamental. Reliability, flexibility and competition are aspects that must also be taken into account [8].

The reliability is the probability that an electric power system is able to perform a required function under given conditions. In turn, it is typically divided into adequacy and security [8–10]. Adequacy is the ability of the power system to supply continuously the customers' needs in terms of power and energy through the generation, transmission and distribution facilities taking into account the scheduled and unscheduled malfunction or maintenance of system equipments. Security, also called safety and operating reliability, is the ability to respond and survive properly to the sudden disturbances like short-circuits or un-anticipated loss of components without an interruption of customer service.

A power system must be also flexible in order to give the opportunity to diversify the mix of generation, adapting the power system configuration to any demand and generation condition.

It must favour the competition less expensive generators can sell and deliver their power, forcing the expensive generators to become more efficient or to shut down.

An overview of electrical power systems focusing on their structure, operation and evolution is mainly described in Section 1.2.

It is essential that the whole system operates in a coordinated way in order to supply with an acceptable quality and continuity. For ensuring that, power plants have to modify and adapt their power output to meet demand necessities.

The electric regulation explain the manner to do that, however, the system and power plant park are evolving, new participants and devices such as power electronics and storage system are participating. Therefore, the present regulation have to change profoundly to integrate all.

An overview of present regulation focussing on this new power plant park is presented in Section 1.3.

Likewise the power plant park, the architecture and strategies to operate the system are evolving. Lots of experiences and demonstrations explore future grids and concepts such as Smart Grids, Smart Cities, micro-grids, among others. These aim to create an advanced power system for modern societies, but it is really necessary that the evolution will be viable and transversal covering all society layers, i.e. from cites to farmhouses.

An overview of future power system trends and rural environment risks is detailed in Section 1.4.

To sum up, Section 1.5 summarizes the chapter.

1.2 Electric power system overview

The vast majority of electrical power systems had evolved from a simpler arrangement, for instance a small system dedicated to supply a particular activity into a very sophisticated structure which involves many power plants and consumers. Initially, the electric power system had been designed as a natural monopoly where relatively small power plants supply all variety of consumers.

Since 1900s., the major part of electric power systems have been deregulated, and thus new challenges have appeared.

Power systems differ in terms of power capacity, types of clients and generation, geographical dimension, and electrical characteristics like frequency and voltage level. However, their structure and components (e.g. transformers, lines, disconnectors, breakers, etc.) are common.

Initially, the electrical power system structure was designed to be unidirectional. Similarly, as the mountain depicted in Figure 1.1, the power flows from the top –the generation– to the bottom –the consumption–.

The number of generators was always lower than consumers, and traditionally, the way to link them was unidirectional though the transmission and distribution systems.

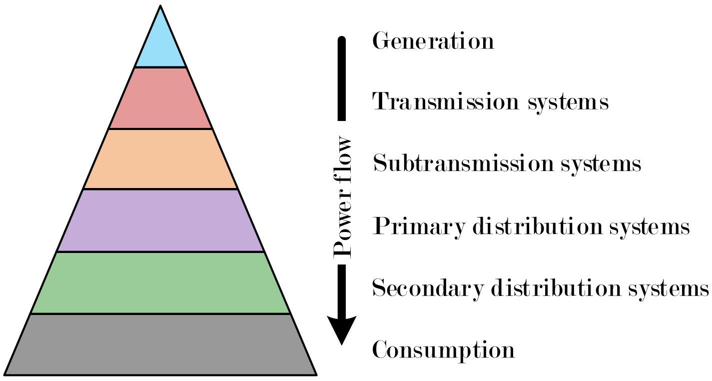

Figure 1.1: The electric power system structure [4, 7, 11–13].

On the mountain peak, large power plants can be found. They are essential in conventional power system, because they guarantee the stability and continuity of the whole arrangement [7, 12].

Frequently, a large power plant, which is also named as conventional generation, transforms large amounts of primary resources such as the potential and kinetic energy of water, the chemical energy stored in coal, fuel or oil, and the energy stored at the core of uranium atoms into electricity [11].

A plant is constituted by one or few rotating machines that transform a mechanical input power into electricity. These machines are commonly synchronous generators that generate electricity at several kilovolts (from 6 kV to 30 kV) and their power capacity varies from 50 MW to 1,500 MW [4, 7, 11–14].

Large power plants are spread across the territory. Often, they are located close to a primary form of energy to be more competitive and at the same time away from cities in order to avoid the pollution and noise.

Following, the next step is to carry out the generated power to final consumers and it is required an efficient infrastructure [14].

Note, that the generated voltage is not enough for the efficient energy transportation over long distances [11], since the alternating current line capacity increases in square times the voltage, whereas the cost per unit of power transmitted declines in the same proportion [7, 12].

For this reason, power plants are commonly connected to a high voltage system such as a transmission or subtransmission system, through a generation substation which increases the generated voltage with a step-up transformer [4, 13, 15].

The transmission system includes a collection of substations and switching stations connected by transmission lines that interconnects large generation plants with the subtransmission and distribution systems where loads are located. These substations and stations are constituted by redundant components in order to ensure the system reliability. Apart from increasing or decreasing the voltage, these substations also carry out other functions such as switching operations, reactive power compensation, voltage regulation, among others.

This arrangement is constituted by very long lines that carry huge amounts of power at hundred kilovolts (from 132 kV to 765 kV), large transformers, automated power breakers, switch-disconnectors, protection relays, and other auxiliary equipment placed along a great territorial extension [4, 7, 11–14].

The transmission system is fully automated, monitored, and well-protected against breakdown because huge amount of consumers depend on it, as can be seen in Figure 1.2. Note that the shaded red part area constitutes the transmission system which interconnects all large power generation plants within subtransimission and distribution systems.

Finally, the transmission system is designed in close-loop circuits in order to be reliable and redundant. Note, that the advantage of following this closed loop structure is basically the fact in case any part of the network is a breakdown, the load can be feed following a different way and thus, electrical supply is not interrupted [4, 13, 14].

One level below, there is the subtransmission system. It is similar to the previous arrangement and the difference between them is not always clear. In some occasions, it is constituted by a readapted part from an old transmission network [16].

The main function of a substransmission system is to supply the scattered distribution systems, but also in some cases it acts as link between a plant and a delivery point.

A subtransmission system transmits less amount of power, works at lower voltage level (from 32 kV to 110 kV), has a shorter length (from 80 km to 100 km) and is less coupled than a transmission [4, 11–13, 16].

In comparison with transmission circuits, subtransmission lines are often arranged in open-loop and radial topologies. In some cases, there are exceptions when a higher reliability is required.

In Figure 1.2, the subtransmission system is represented in shaded orange area. Parts of it are designed in close-loop circuits and other parts are designed in open-loop or radial arrangements, which are cheaper and easier to operate.

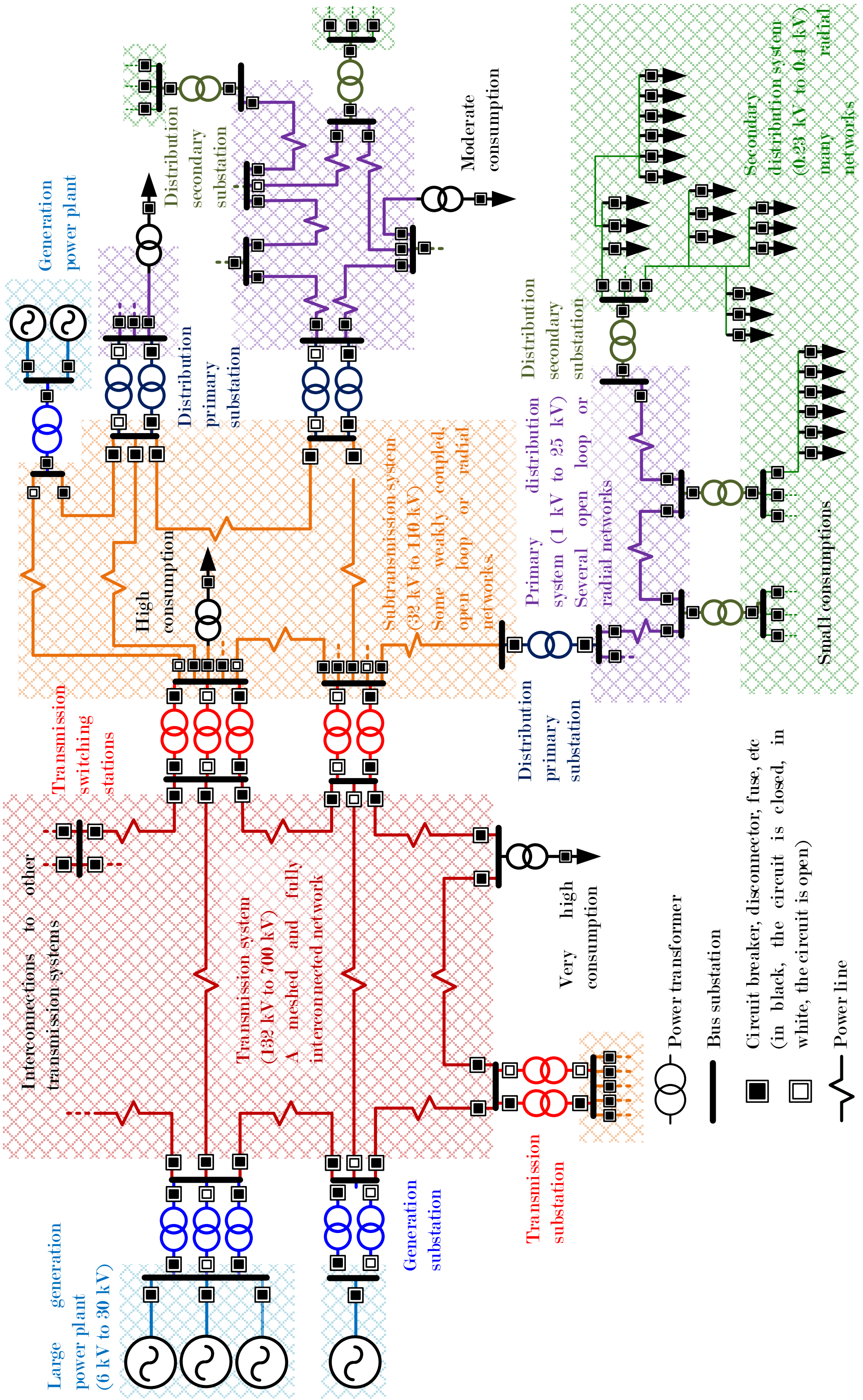

Figure 1.2: The traditional electric power system [4,7,11–14,16].

The subtransmission system finishes at distribution substations where transformers step down the voltage to the distribution level.

The distribution system represents the final stage in the delivery infrastructure. It takes the electricity from upper systems and delivers it to the consumptions.

Its main function is to supply continuously and high quality electricity to final consumers. Therefore, it is fully designed for them. As a consequence, it has to cross very diverse environments for example streets, rivers, mountains, etc. and in different ways such as through overhead or underground lines.

The distribution system is divided in two parts: primary and secondary in order to reach all consumers [4, 17].

The primary system works at medium voltage, i.e. at few kilovolts (from 1 kV to 25 kV) and is arranged in open-loop and radial topologies, depicted in shaded purple area in Figure 1.2. It delivers power to moderate consumers, and secondary systems [16].

The secondary distribution system starts on secondary substations which reduce the voltage from the primary level to secondary one which is at hundreds of volts (from 0.23 kV to 0.4 kV). The secondary system supplies the remain small consumers through radial circuits [12], depicted in shaded green area in Figure 1.2.

Finally, note that the secondary distribution system is the lest reliable, and here it is where the vast part of grid breakdowns occurs. Moreover, it is hardly automated and way to protect it via sacrificial or manual protections.

There are a wide variety of consumers, the major part are connected in the secondary distribution system, but also there are large consumers which are supplied directly by a upper system. Therefore, as it is depicted in Figure 1.1, the very high consumption could be connected directly to transmission systems, the high consumptions to subtransmission system and the moderate to primary distribution system.

Loads could be grouped in cites or industrial parks where consumers can be found every 15 meters or less; in suburbs every 15 and 100 meters; or every 100 meters or more in case of rural areas [17].

Industrial loads are few but they have a very high rate of power and energy consumption per area (kW/km^2 and kWh/km^2); commercial clients are several and have a high rate of power and energy consumption per area and a wide range of power; residential consumers are a lot but their consumption is small, and they have a moderate and high rate of power an energy consumption per area; finally the rural clients are few and scattered, and they have a small rate of power and energy consumption per area [14].

Finally, as it was mentioned above Figure 1.2 and summarized in, as going downstream the system is less automated, monitored and coupled, while as going upstream the system is more complex and reliable. Therefore, the system reliability is proportional to the load dependency and criticality.

By the end of the last century, small power systems have been pushed to a continuous growth and interconnecting in between each others to finally evolve to an advanced one. Despite the fact that the power system structure remains predominately the same, the current arrangement has incremented its capacity, robustness, and security. These points have facilitated the creation of a new common energy market where any generation can compete.

This new conception has been initiated in Europe by the Electricity Directive 96/92/EC [18,19]. Also, it has provided new opportunities for the new participants, companies and generation plants.

The liberalized energy market is crucial to ensure the electrical supply, increase the competitiveness and guarantee that all consumers can purchase energy at affordable prices [20].

Large power plants still have much importance in the energy market. They constitute the ordinary generation and are managed by private owners, who sell their production. Despite this fact, smaller generation plants have every day more presence and relevance in the power system [5, 11].

According to [21] these small power plants are known as Distributed Generation. They are electric generators which are directly connected to the distribution system or to the customer side of the network. They combine a large variety of new technologies, for instance, DG transforms the sun radiation, the wind and waves kinetic or the urban or agricultural residues into electricity [5, 11, 22]. The DG constitutes the non-conventional or special generation and may contribute to the reduction of line losses, environmental emissions and energy prices.

Figure 1.3 redepicts the ongoing power system which has evolved into a more horizontal and bidirectional arrangement, where the other system interconnections and the DG has a relevant importance in the power balance. Note that the DG is currently modifying the mix generation, the power flow in electrical power system, and the transaction activity in the wholesale market, and creating a big range of operational problems and challenges forcing to evolve the regulation and the passive role of operators [22].

Furthermore, the present regulation has split the power system activity into regulated and deregulated activities [19, 25]. Regulated activities focus on the network planning and operation. Their main objective is to ensure the proper functioning of the system. They are still quite traditional and are centralized entities. On the other hand, deregulated activities focus on the generation and commercialization. The generation, according to regulated activities guidelines, contributes directly to the system operation, supporting and ensuring the system stability.

The transmission and highest voltage parts of the subtransmission system are operated by a single operator, who is known as the Transmission System Operator (TSO). This operator must be coordinated with the rest of operators in order to ensure the whole power system [26]. Likewise, the rest of downstream systems are managed by one ore more Distribution System Operators (DSO) in function of the TSO's requirements.

Both activities have adopted such an important relevance in the wholesale market promoting the competition of generation. While, the transmission activity focuses on transporting large amounts of energy and ensuring the interconnected system viability, the distribution activity focuses on covering the customers requirements, in terms of power quality and service, as well as, the ongoing integration and efficiently energy redistribution of the DG.

The process of planning and operating the power system is significantly com-

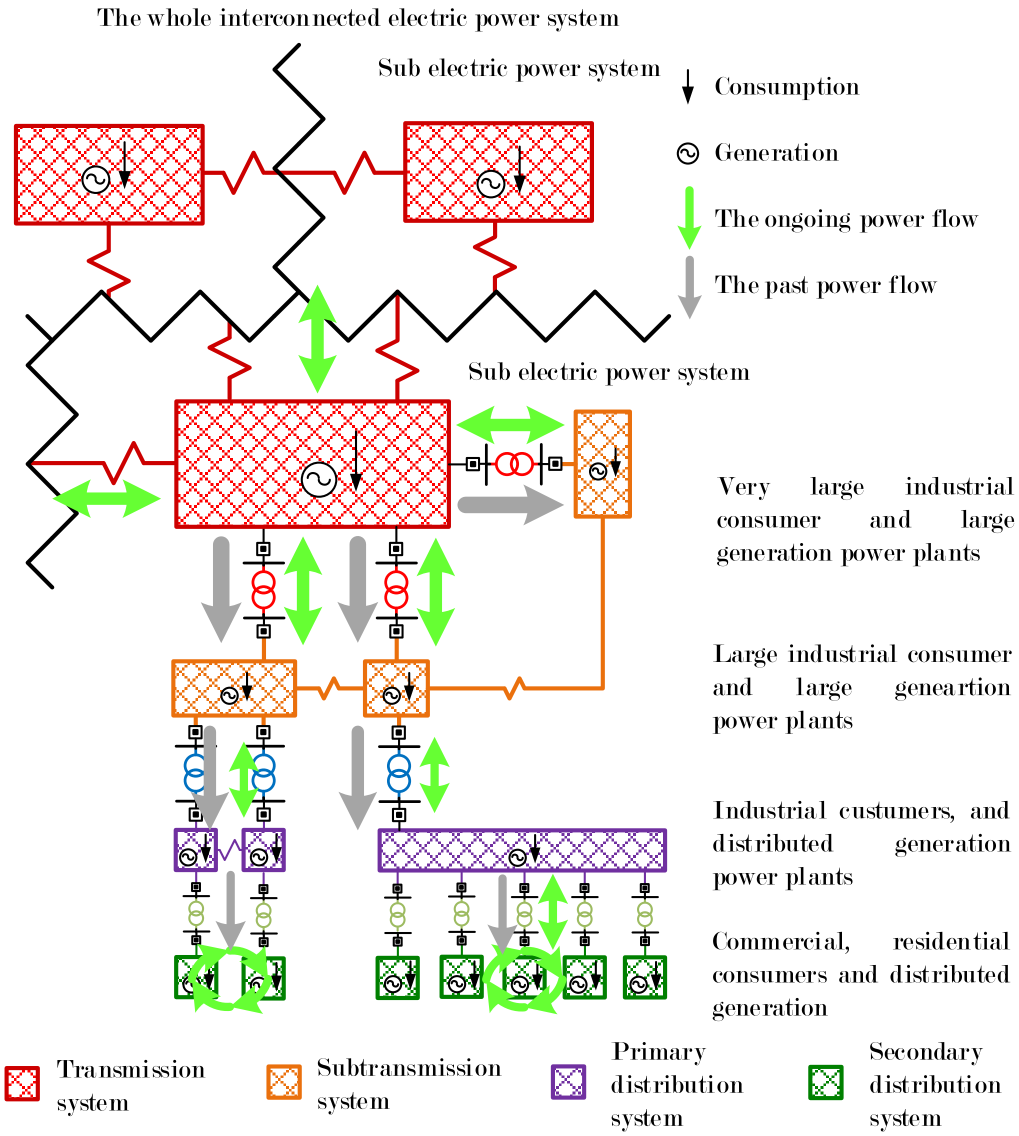

Figure 1.3: The ongoing electric power system structure [4, 7, 22–24].

plex because many issues are involved (e.g. technological, economic, social and environmental). They must be handled in function of the national regulation in order to select the best approach. A good way to chose the approach is dividing the whole problem into smaller and simpler issues arranged on time. Typically, they are enclosed in these two or four horizons, from the farthest to closest issues [4, 7, 10, 22, 27].

The farthest problems mainly related to the planing issues are split into two horizons, i.e. the long- and medium-term. The first term is projected since the past few months up to three years, and the second term since two up to thirty years. The closest problems mainly related to the operation issues are also divided into two horizons, short-term and real-time. The fist term is enclosed between few hours and a month, and the second term is applied at the moment or in the following minutes.

The long-term solutions are totally focused on the system expansion. They are purely based on strategic actions for the company that aim the system adequacy and increase of competitiveness. The planner has determined solutions from a total of possible scenarios for distant horizons taking into account different uncertainties like demand growth, technological innovations, fuel prices, and a set of technical, economic and political constraints. According to these possible scenarios, system operators plan the generation capacity, the transmission grid topology (also considering the previous planned generation), and the auxiliary equipment that ensures the power quality and continuity [27]. Naturally, these solutions are dynamic over time and hence they are periodically readjusted (every some years) taking into account the modified or clarified initial hypothesis and uncertainties.

The medium-term solutions are established in function of maintenance and operating procedures. As maintenance actions, cost-effective practices are programmed. Their main objective is to keep the equipment in good conditions, to maximize the system adequacy reliability, the proper functioning and operating life of the electrical components, and to minimize the system costs and failures. The operating procedures define the future energy necessities. They schedule the annual hydro-scheduling and establish the fuel contracts according to foretasted energy requirements, the estimated hydro-resources, the expected fuel costs, and the agreements with electricity retailers.

Just bellow, the short-term solutions seek to balance between the generation and consumption within in a closer time [28]. Their main objective is to coordinate effectively, optically and reliably the electrical power system resources in different horizon terms. They take into account the technical constraints and more accurate forecasts for daily horizons. They should also satisfy the technical constraints of the available generation resources and system capabilities at the minimum cost. Finally, they are the power economic dispatch, the daily hydro-scheduling and intra-day auxiliary services.

The shortest-term solutions, i.e. the real-time actions, are carried out in three levels depending on the processing time, scope and seed of response required. These levels are in the control centre, in the own generation plants and in the field. Control centre actions are carried out by the system operator who monitors, coordinates and controls in real time the fundamental elements of electrical power system through a

Supervisory Control and Data Acquisition (SCADA) system [4,7]. Generation plan actions regulate the average production according to the operator's instructions and at the same time ensures the rotor angle, frequency and voltage stability [7, 24, 27, 30]. Finally, the third level is implemented in the field, where a protection system is responsible to protect facilities and consumers. It must detect quickly and successfully any the electrical failure and isolate it in order to affect at least the rest of power system. Note that all of them are crucial for the system survival and their response must be fast, adequate and coordinate between all actors (TSO, DSOs, power generation plants, protections, consumers, among others).

Figure 1.4 depicts the previous planning and operation solutions over the time.

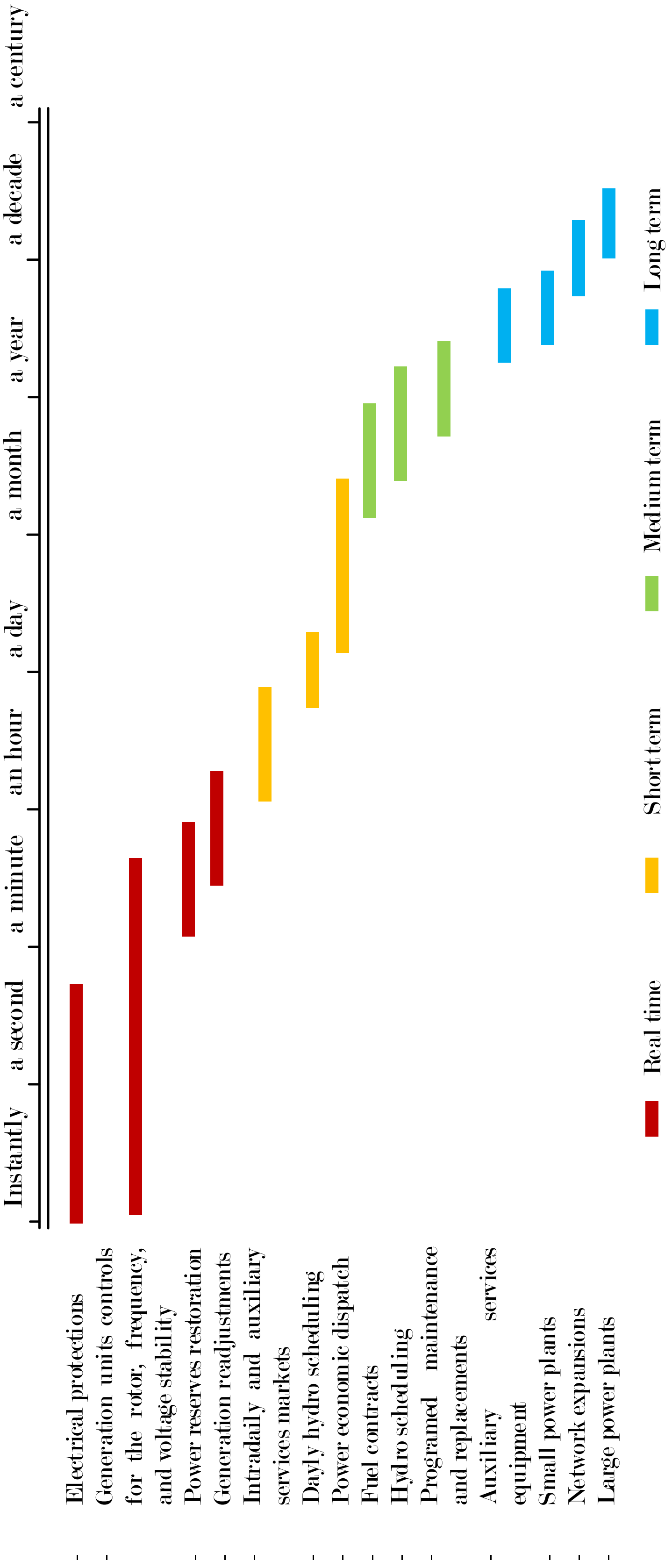

Figure 1.4: Examples of long-, medium- and short-term solutions and real-time actions [4, 7, 9, 10, 23, 24, 27].

1.3 Current guidance of power systems

The above mentioned traditional power system was exempt from the competition and the whole operation and planning was centralized by an unique operator. The operator was a transmission utility, in many cases a state-owned enterprise. It was the responsible for taking decisions. Also, it had to ensure the supply and fulfilment of the national regulation seeking the minimum investment and cost. To achieve that, the operator has controlled and monitored the whole system, corrected the generation dispatch, planed the grid expansion and drawn up lines and auxiliary facilities, and authorized the new generation power plants.

Traditionally, the operator has also requested some contributions from large plants which had represented almost the totality of generation capability for maintaining stable the power system. These requested contributions were collected in grid or network codes. The main requests are fault-ride-through capabilities, frequency and voltage controls.

The fault-ride-through capability is the ability of a power plant to bear a severe disturbance occurs in the electrical system. This capability is a fundamental requirement to maintain the security and prevent wider frequency collapse. In addition, it is typically expressed via voltage-against-time-profile, as is presented in Figure 1.5. This profile is composed by two or three areas: the shadowed blue area is where the power plant must stay connected to the grid and maintain its normal generation; the shadowed yellow area is where the plant must stay connected, maintain the generation, and sometimes provide support by delivering a specific reactive current; finally the shadowed red area is where the disconnection of a power plant is allowed.

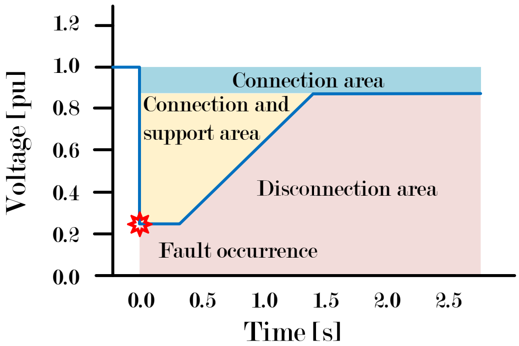

Figure 1.5: Voltage-against-time profile example.

In a second plane, there is the grid frequency which is a fundamental aspect in the power system. It is not constant due to load changes and electrical faults.

Therefore, power plants have to manage continuously the active power output according to these frequency variances in function of certain predefined droops [7, 24, 27, 29, 30]. These droop are typically defined by the national regulation, or the TSO network code. Figure 1.6 presents a frequency control, shadowed in yellow, together with a response example, shadowed in red.

On the one hand, the frequency control purpose is to stabilize the system frequency through the management of the output active power [30]. It can be achieved through three provisions: the first provision dispatches a constant reserve of power which was expressly reduced for supporting the frequency when it is below than a threshold. In second and third provisions, regulate the power contribution according to a droop, i.e. increasing or decreasing output power in function of the frequency is above or below a specific threshold. At times, it is usual to include a short dead band around the nominal frequency, i.e. the output power should not modified. On the other hand, the frequency response goal is to avoid its collapse by an automatic downward regulation of active power which when it excesses a threshold.

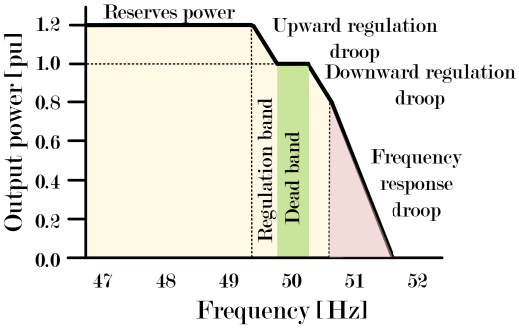

Figure 1.6: Frequency control and response examples [20, 31].

Finally, the voltage is such an important aspect in the power system. It can move out of the normal operation range as a result of an disturbance, high power exchanges, or a failure demanding big amounts of reactive power. Typically, large power plants and sometimes auxiliary services were responsible for maintaining the voltage between a range.

On the one hand, the power plants keep the voltage in a range adjusting the alternative current generator excitation from synchronous generators [4, 27], since the voltage level is closely related to the balance of reactive power (in high voltage level). On the other hand, the auxiliary services and power plants without synchronous machines can support applying strategies based on predefined reactive power droops, as Figure 1.7 presents. The idea is close to the frequency control, the power unit should exchange reactive power according to the voltage increment or decrement.

As of today, the majority of power systems have been operated by private companies. The present operators have similar responsibilities just like traditional ones in terms of system operability. However, they attempt to maximize their business earnings, and minimize the economic and financial risks, and anticipate their returns on investment criteria instead of the system cost minimization. Furthermore, the current power system, as previously mentioned, is fully interconnected, so the operator must cooperate to the rest at all levels in order to ensure the well functioning [26].

Despite the fact that a significant proportion of generation is still connected to the transmission system, the number of smaller power plants in lower systems is continuously growing. Therefore, it is changing the way how the power system is managed. Nowadays, DSOs have to be more proactive and collaborate actively

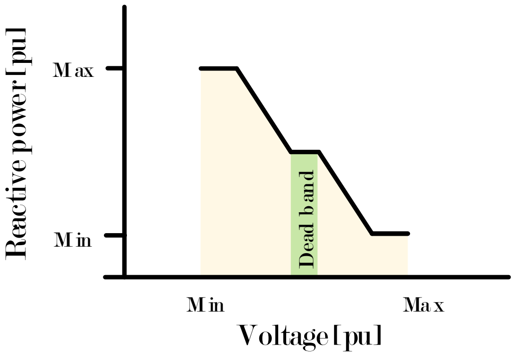

Figure 1.7: Voltage control via a droop control example.

with the TSO. They have to cooperate in order to maintain the energy balance, the security of supply, the voltage, the frequency and the power quality.

The present regulation is also requesting a contribution from DG. Likewise large plants, they should contribute to the grid supporting and the sustainable growing and the reliable operation. The national regulation of European members establish some basic grid codes for power plants. As previously mentioned, they request a response to any frequency and voltage deviation.

For instance, the Danish network code is one of the most recent codes. It has been published after the European Directive (subsequently treated) [20]. It takes into account the ongoing DG (i.e. the solar and wind power plants), and also battery plants [31]. It categorizes and specifies a wide range of strategies for power plants during normal and abnormal operating conditions. It is very similar to the European Directive [20].

To illustrate some strategies for normal operating conditions, the Danish regulation proposes active power, constraint and reactive power control functions. They are equipped in function of plant type (i.e. conventional, solar, wind, batteries, etc.), the rated power and the voltage level of the point of common coupling [31]. Active functions are basically automatic frequency controls and responses performed by plants. Constraint functions imposes that the output power of a plant must be controllable, being able to used by operators to avoid instabilities or overloading of the grid. Reactive power functions allow the reactive power output management and the voltage control by operators [31]. Finally, to illustrate an strategy for abnormal operating conditions, the grid code establishes the fault-ride-through capability of power plants and their required support during an electrical fault.

The German regulation is older and previous than the European Directive. It has started to impose technical requirements to medium and low voltage plants. These plants can be synchronous and asynchronous generators, and also power converters [32, 33]. This fact is because Germany is one of the European countries with more low voltage photovoltaic penetration which is integrated by power converters [32, 34].

The German code sets also that a power plant has also to be connected during a fault and provide reactive power support during an electrical fault (i.e defines the fault-ride-through capability). It imposes that the DG should reduce its output power above a frequency threshold (i.e. sets the frequency response), and a reactive power setpoint can be fixed or adjusted by a signal from operator (i.e. defines the reactive power control).

In countries like Spain and France, their network codes are older and simpler [33, 35]. They specify only the requirements for grid connection and operation for large generation power plants connected to the transmission system.

Furthermore, the European Commission has joined the previous grid codes and published the European Directive 2016/631 [20] a common guideline for all European power plants. The guideline is valid for power plants constituted by synchronous and asynchronous machines (i.e. traditional ones) and non-synchronous ones (i.e the ongoing distributed generation).

First of all, the Directive sets a simply and clear classification for all the European power plants. This classification goes from the small generation (type A) to large power plants (type D). They are classified in function of their rated power, their point of common coupling voltage and their synchronized area. The Directive sets the following European synchronized areas: the Continental Europe, the Great Britain, the Nordic, the Ireland and Northern Ireland, and the Baltic systems, as Figure 1.8 presents.

Types A, B, and C are exclusively for power plants located in a subtransmission or distribution system, i.e. the voltage level of their point of common coupling is less than 110 kV, while, power plants type D corresponds to any plant connected to a transmission system, i.e. the voltage of their point of common coupling is equal or greater than 110 kV. In addition, plants types A, B, and C are classified according their rated power. Table 1.1 presents the maximum rated power for each type. It needs to be stressed that generation units below than 0.8 kW are out of the Directive scope and if the rated power of a plant is greater than rated power limit summarized in Table 1.1 its type is D.

Table 1.1: Rated power limits for power plants in function of the synchronized area [20].

Synchronous areas	Type A	Type B	Type C
Continental Europe	1 MW	50 MW	75 MW
Great Britain	1 MW	50 MW	75 MW
Nordic	1.5 MW	10 MW	30 MW
Ireland and Northern Ireland	0.5 MW	5 MW	10 MW
Baltic	0.1 MW	10 MW	15 MW

The Directive sets also that power plants have to remain connected to the system during certain time periods despite the fact that frequency moves out of the normal operation. Table 1.2 defines the time period in function of their synchronized area.

Furthermore, the Directive sets fault-ride-through profiles. They depend on the power plant type and nature, i.e. if they are synchronous or park modules plants (i.e. non-synchronous generators). In general, types B and C must be capable of remaining connected to the system and continuing to operate stably

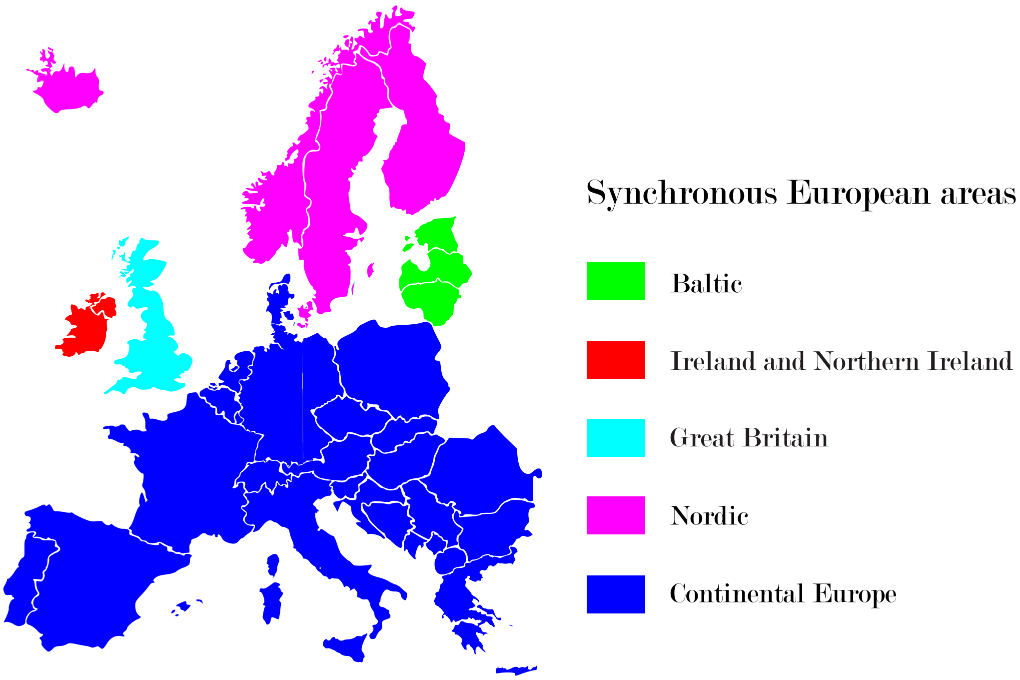

Figure 1.8: European synchronous areas [20, 37].

Table 1.2: Time periods for power plants in function of the synchronized area [20].

Synchronous areas	47.5-48.5 Hz	48.5-49.0 Hz	51.0-51.5 Hz
Continental Europe	$\geq 30min$[1]	$\geq Xmin$[2]	$30min$
Great Britain[3]	$90min$	$\geq 90min$[1]	$90min$
Nordic	$30min$	$\geq 30min$[1]	$30min$
Ireland and Northern Ireland	$90min$	$\geq 90min$[1]	$90min$
Baltic	$\geq 30min$[1]	$\geq Xmin$[2]	$\geq 30min$[1]

[1] to be define by each TSO

[2] to be define by each TSO, but not less than the period for 47.5-48.5Hz

[3] additional frequency ranges, 47.0-47.5 Hz during 20 seconds and 51.5-52.0 Hz during 15 min

after the disturbance. Their voltage-against-time-profile peak can be the 5% up to 0.25 seconds, at most, while type D plants must also be capable of supporting null voltage up to 0.25 seconds, at most.

Furthermore, a collection of strategies are proposed to involve all generation park in the frequency stability for over-, under- or normal conditions. In over-frequency situations all power plants have to reduce their output power delivered (i.e. frequency response strategy). The possible threshold defined by the TSO should be between 50.2 Hz and 50.5 Hz and the droop between 2% and 12%. In under-frequency situations, power plants have also to ensure a minimum output power (i.e. maximum power capability reduction with falling frequency). The admissible reduction is delimited by the TSO, it can start between 49.0-49.5 Hz and the reduction rate must be between 2% and 10%. In addition, the largest plants (types C and D) should be able to activate the provision of active power frequency response at a threshold between 49.8 Hz and 49.5 Hz and with a droop specified from 2% to 12% by the operator.

Despite of previous contributions in over- and under-frequency conditions, the frequency system can also being regulated in a shorter range by power plants types C and D. They should keep constant it through the frequency control strategy with more accuracy (at least 0.03 Hz). In other words, the power plant should be capable of regulating their output power according to the operator's settings between 1.5% to 10% for both sides (i.e. incrementing and decrementing it) with a droop between 2% and 12%. Note that, a small dead-band (0.5 Hz or less) can be added by the operator

In addition, power plants should be equipped with a logic interface or input power, for switching down them (type A), reducing their output power (type B), or adjusting the active power according to a setpoint (types C and D). So, from type B power plants will be coordinated by system operators for contributing in emergency situations.

Then, on the one hand, synchronous power plants type B and above should contribute to the voltage stability, procuring reactive power through excitation control system to keep constant the voltage. Type C plants should additionally procure reactive power for compensating other reactive power demands like lines, cables, transformers. Finally, the type D should also perform an automatic voltage regulator with regard to steady-state and also transient voltage control. On the other hand, non-synchronous plants type B and above should contribute to the voltage stability, procuring the fault current. Power plants type C, likewise the synchronous ones, should additionally procure reactive power for compensating other reactive power demands. In addition, these plants should provide reactive power automatically via voltage, reactive or power factor control modes (likewise Danish codes [31]).

Furthermore, other requirements are suggested such as, the system restoration, i.e. the conditions under which power plant is capable of connecting automatically to the network. Plants type C and D are able to take part in island operation if required by the operator, plants type B and above shall be capable of activating the supply of fault current.

To sum up, an harmonized guideline is published in order to provide a legal framework for all European power plants, facilitating their integration, ensuring the system security, increasing the competition in the energy market, facilitating the renewable generation integration. Thanks to this guideline, the European power system will perform an efficient use resources for the benefit of society, requesting a contribution from all power plants in function of their type.

Type A requirements are quite basic and the control level by the system operation is minimum. However, they have to ensure no loss of generation in the operation ranges and minimize the possible affectation during system-critical events.

Type B requirements provide a higher level of control by the system operator and information. They have to give an automated response to mitigate the impact of, and maximize dynamic generation response to, system events.

Type C requirements provide a refined, stable and highly controllable dynamic response like auxiliary services. The plants have to cover all system states and ensure the real-time response.

Type D requirements are designed for higher voltage generation with an impact on control and operation of the whole system. They should ensure stable operation of the interconnected power system.

1.4 Smart grids and future challenges in rural environments

In spite of the fact that electricity consumption has undergone sustained growth and the system has been able to adapt to it since the beginning, the energy sector is exposed to the winds of change. The current generation mix is changing and becoming very diverse and scattered with the rapid technological and regulation advances.

The new distributed and renewable generation must be integrated performing a reliable, competitive and sustainable system. In addition, since the society is evolving towards a new paradigm in which citizens want to be empowered and participate in domains which were reserved for the political arena or for large corporations, the current consumers are becoming more exigent with the product quality. They want to become prosumers so that they can make their own choices in terms of costs and energy mix. Moreover, other technical and social challenges such as demand response strategies, the energy conservation and carbon footprint policies; are reducing and displacing the electricity usage. They achieve that changing the price of electricity, paying incentives, updating equipment, and/or performing a better and sustainable use of energy. For all the aforementioned points, power systems are being forced to evolve profoundly.

The evolved power system is also called Smart Grid [36]. It is an advanced energy delivery system that supplies a high quality electricity and pursues the society satisfaction. The SG aims at a sustainable development and a future based on low carbon technologies. It economies also along with active and informed consumers. They could choose how to consume or produce its energy, as well as how to share it with its neighbours, while paying attention to the prices and environmental impact. The evolved system becomes a really complex system that has to respond efficiently and quickly to wide ranging technical constraints, situations and events.

To achieve an SG, a collection of Information and Communication Technologies, an advanced metering infrastructure, automated and controllable equipments, distributed energy resources such as small generation power plants and storage systems, all being supported by an proper telecommunications network are mainly needed [38–40]. Therefore, an important investment is required for transforming an aged power system into a smart one. However, the return on investment also increases in parallel with costs, thanks to the possibility of offering new services to consumers and to the reduction of operational costs. The main SG contributions may be summarised as follows [36, 39–41]:

(i) It can supply more continuously the electricity thanks to its self-healing capacity and advanced operation (e.g. island operation, automatic network reconfiguration), so the system reliability and power quality increase.

(ii) It is able to accommodate easily the distribution generation, facilitating expanded deployment of renewable energy sources, and reducing the peak demand and electrical losses, so the system performance and capacity increase.

(iii) It has a wide and diverse generation mix that can reduce the greenhouse gases and the external resources consumption, providing environmental and conservation benefits.

(iv) It accommodates the electric vehicles and energy storage options that allow an efficient management of energy resources, profiting the surplus of renewable sources, so it increases the savings and reserves.

(v) It increases consumer flexibility and participation, enabling new products, services and markets, allowing them to efficiently manage their electrical consumption and generation, so it provides financial benefits.

(vi) It will create new opportunities, services and business, favouring the cooperation between participants, so it will democratize the system.

In addition, once the SG is generously deployed and has been socially accepted, consumers can expect to see their level of comfort improve more quickly than the related costs will rise, all without having to invest any of their time. Despite the benefits, a SG will produce a huge volume of data which must be managed, stored, and transformed into useful information. For that reason, advanced strategies and systems that ensure the data privacy and grid safety are necessary.

The need for reaching the 20-20-20 targets [42] has driven lots of SGs experiences around Europe. The most of them have focused on smart cities and micro-grids and the distribution system has had a relevant role [41, 43]. The distribution systems, unlike the transmission ones, are very diverse. They are completely conditioned to the environment and consumer density.

The SGs, likewise the distribution systems, are limited by geographical and economic constraints, since the regions with low population density and difficult orography such as rural ones are usually rejected due to the high deployment costs and low returns. If the SGs leave out the rural citizens, they are forced to continue to use the energy just as they did in previous decades. It can be translated into less businesses opportunities, less system participation and engagement, lower quality of service, higher costs and less flexibility. All these, added to the fact that the performance and quality of service is typically lower than urban system, because the rural systems are usually in remote locations where some other technical and logistical issues arise during processes of restoring voltage or repairing damage.

The no evolution to SGs in rural areas can emphasise the Digital Divide phenomena. It describes the gap between, those who have ready access to information and communication technologies, as well as the skills for making use of those technologies, and those who have neither the access nor skills for using those same technologies within a geographic area, society or community.

Almost 32% of the European citizens are currently living in what are considered rural areas [44]. For this reason, the SG development must be wider than the “smart city”, one that limits the intelligence of grids and their benefits to cities and their inhabitants. Therefore, there is a need for deploying ICTs, distributed energy resources, telecommunications and developing a smart rural grid that can decrease existing and future regional unbalances and respects the technical, economical and socials rural constraints. Otherwise, this will limit even more the possibilities of citizens living and/or working outside the city boundaries.

1.5 Summary

To conclude, this section presents a brief summary of the state of the art. In this chapter, the electrical power System is introduced.

First of all, a general overview of the electrical power System is presented together with its current ongoing tendencies, which assist them trough change. After this, the power system planning and operation is described. As it was previously introduced, new operational challenges have recently risen up. They are closely related to the DG, but also with new power electronics and electrical storage systems. In this sense, the power system operation is evolving and also reverting to DG.

This chapter introduces some European grid codes in order to illustrate its main functionality, even tough, they are currently up to date. In this respect, an European directive which provides a legal framework for all European power plants is also presented.

Finally, this section introduces the future electrical system trend, such as SGs. To end this section, the important risk of extending SG development in rural areas is empathized. In these areas, the population density is low and current SG technologies are not deployed. The most relevant causes why these technologies are not applied are the impossibility of recovering the investment and the technology incompatibility.

Chapter 2

Smart Grid Architecture for Rural Distribution Networks: Application to a Spanish Pilot Network

2.1 Introduction

This chapter focuses on the first Thesis objective and corresponds to a journal paper [45]. A novel architecture for modernizing traditional rural networks into SGs is presented. This architecture tackles innovation actions on both the power plane and the management plane of the system. In the power plane, it exploits the synergy between telecommunications and innovative technologies based on power electronics managing low scale electrical storage. In the management plane, a decentralized management system is proposed based on the addition of two new agents assisting the typical SCADA system of DSOs.

Altogether, the proposed architecture enables operators to use more effectively–in an automated and decentralized way–weak rural distribution systems, increasing the capability to integrate new distributed energy resources. This architecture is being implemented in a real network located in Spain, in the frame of the European Smart Rural Grid project. It also includes a study case showing one of the potentialities of one of the principal technologies developed in the project and underpinning the realization of the new architecture: the so-called Intelligent Distribution Power Router.

2.2 Publication

energies

MDPI

Article

Smart Grid Architecture for Rural Distribution Networks: Application to a Spanish Pilot Network

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Abstract: This paper presents a novel architecture for rural distribution grids. This architecture is designed to modernize traditional rural networks into new Smart Grid ones. The architecture tackles innovation actions on both the power plane and the management plane of the system. In the power plane, the architecture focuses on exploiting the synergies between telecommunications and innovative technologies based on power electronics managing low scale electrical storage. In the management plane, a decentralized management system is proposed based on the addition of two new agents assisting the typical Supervisory Control And Data Acquisition (SCADA) system of distribution system operators. Altogether, the proposed architecture enables operators to use more effectively—in an automated and decentralized way—weak rural distribution systems, increasing the capability to integrate new distributed energy resources. This architecture is being implemented in a real Pilot Network located in Spain, in the frame of the European Smart Rural Grid project. The paper also includes a study case showing one of the potentialities of one of the principal technologies developed in the project and underpinning the realization of the new architecture: the so-called Intelligent Distribution Power Router.

Keywords: intelligent distribution power router; rural distribution networks; smart grid technologies

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1. Introduction

A stable energy supply is a prerequisite for the social, industrial and commercial development of societies, and therefore any technology that will enhance it will cause a tremendous positive impact [1,2]. Distribution networks, since coping with 95% of network infrastructure in Europe—and experiencing nearly 90% of all power outages and disturbances of the whole system [3–5]— have a key role for the achievement of the above-mentioned goals [6].

The conventional distribution (and transmission) networks were designed so that the electricity generation is often centralized in large scale power plants, away from populated areas [5,7,8]. From these generating facilities, the electric power is distributed to consumers thus mostly yielding predictable unidirectional power flows [3,5]. The above paradigm is rapidly changing by the massive inclusion of renewable and distributed generation, the adoption of an active role by consumers and the emergence of new actors in the fields of the stationary energy storage and electro mobility [3,9–12]. Such technological revolution demands a development of new mechanisms for ensuring the flexible, stable and efficient operation of electrical networks and markets (so making the grid smart), and also for their planning and reinforcement in their modernization [9]. For instance, the German Energy

Agency (in German, Deutsche Energie-Agentur) shows in a recent study that the required amount of network reinforcements for the German power grid for the "Energiewende" until 2030 entails investments between 27.5 billion € and 42.5 billion € [13]. Accordingly, the planning of innovative grid update strategies could be translated into massive economic savings in the required network reinforcement costs [10].

Both the scientific community and industry are proposing and adopting different actuations to transform traditional distribution grids into active, Smart Grid ones [3,7,9,10,14–27]. In this sense, actuations mainly tackle the exploitation of new communication capabilities and distributed energy resources. All proposals are aligned with the idea of transforming a radial and dumb distribution system into a meshed intelligent one. This transformation focuses mostly on the inclusion of advanced meters, and deploying telecommunications and distributed energy resources that provide new functionalities such as self-healing, high reliability and power quality enhancements. Additionally, other issues such as the cybersecurity, the distributed energy resources integration, the asset utilization optimization, and the minimization of operations and maintenances expenses are also treated.

Contributing to such proposals, this paper proposes an innovative grid architecture to transform a real and traditional rural distribution grid into an active and smart one. This architecture relies on exploiting the convergence between electrical and telecommunication networks and this is one of the main contributions of the paper and project [28]. In the management plane of the architecture, the work undertaken aims to show how utilities can operate more efficiently and to interconnect energy between a variety of actors including prosumers, consumers, distributed generation and energy storages, to enable multi-directional power flows [29]. Such power flows are managed by an innovative hierarchical management tool, enabling the optimal operation of the rural grid while both isolated and connected to the main distribution grid.

In the power plane of the architecture, power flows are controlled by exploiting the flexibility provided by a variety of wired and wireless communication technologies that helps to cope with geographical restrictions of the rural environment, along with an innovative so called Intelligent Distribution Power Router (IDPR) device. This device, which is based on power electronics and secondary batteries, permits actually routing power between each of the phases of the three-phase distribution system, thus ensuring the required network power balance and quality.

The whole formulation of the innovative algorithms in the management plane can be found in [30–32]. Thus, this paper mainly focuses on the transformations evolving the power plane: such actuations evolving the network into a smart new one. The management plane is secondarily addressed by quantifying the algorithms performance managing the network under different operational scenarios. It should be noted that the aim is to assess the potentiality of including a set of new Smart Grid technologies and power electronics in different parts of the network but not to specifically quantify the impact such technologies into the global grid performance. Therefore, the present work, instead of deeply discussing the mathematics presenting the management algorithms, opts for describing in a holistic way all actuations to evolve the distribution network into a smart new one. These actuations cover the management but also other updates on the power plane, i.e., telecommunication network and innovative power electronics with embedded storage. In addition, as a difference with reference [31], the present paper depicts a study case evaluating the impact of the above-mentioned actuations around the inclusion of power electronics to evolve the rural grid, while study cases in [31] focus on the management of the whole smart grid.

The work presented in this paper is framed into the European research project Smart Rural Grid (SRG). The project key impacts are directly related with the delivery of significant cost and investment savings in rural electricity distribution (by overall reducing the percentage of electricity lost during electricity distribution and the gap between electricity generated and electricity consumed). They also refer to allowing for an increased potential to inherently accommodate the integration and distribution of renewable energy sources. Moreover, it enables new operation modes that guarantee the continuity of supply and reliability even in the case of the external failure conditions [18,26,28,30–32].

The contents of this paper have been structured into five main sections. First, Section 2 presents the typical characteristics of rural distribution networks, also focusing on that for the adopted network. Second, Section 3 introduces the proposed architecture (both addressing management and power planes) evolving the rural network. Third, Section 4 describes the new operation modes for the network enabled by the new architecture. Fourth, Section 5 develops a study case that shows the performance of the new architecture (focusing on the power electronics included to provide advanced services). Finally, the main conclusions of the work are presented in Section 6.

2. Typical Rural Distribution Networks

This section presents the main features of rural grids, stressing in the usual characteristics for electrical infrastructure, e.g., the topology of network, the typical protection devices and so on; and for the telecommunications network, e.g., the communication technologies (in Section 2.1). Then, this section also presents the Pilot Network (PN) adopted for the purposes of the SRG project, which will serve to define the proposed architecture and the study case in subsequent sections of this paper (in Section 2.2).

2.1. General Features of Rural Distribution Networks

Focusing on the rural systems, the majority of rural distribution networks comprise long overhead Medium Voltage (MV) lines, which are operated between 1 kV and 36 kV [5,23] with bare cables [4]. From these MV lines, overhead Low Voltage (LV) lines feed customers up to few hundred meters away by crossing valleys, mountains and forests. Furthermore, due to the orography, these networks are difficult to access, which is aggravated by adverse meteorological conditions. Both line types can basically be considered resistive. Historically, overhead lines with bare cables were erected because they are the most cost effective way to provide power supply to rural and remote areas [4]. This type of electrical line is critical because the majority of failures suffered in rural distribution systems occur precisely in overhead bare lines during severe weather conditions. In particular, according to [4], about 62% of all middle voltage network faults are caused by nature; with adverse weather conditions, this figure increases up to 92%.

The rural distribution circuits are sized according to their mechanical factors rather than according to voltage drops or maintaining the continuity of supply to a number of large consumers [5,23]. Accordingly, Distributed System Operators (DSOs) have been replacing the LV overhead bare lines with overhead or underground three- or four-wire cables, which are more reliable but more expensive. However, the majority of MV lines are still overhead bare conductors.

The typical topology of rural systems is radial [5,8,23] and usually connects dispersed consumers across a wide territory. This yields important variations in voltage levels between the feeder and different consumption points [4]. In contrast to the urban distribution networks, the capacity of rural lines is limited by the important voltage drops and mechanical requirements, not by the thermal rating of the conductor [5,33,34]. In addition, the rural distribution networks lack strong interconnections with transmission systems, thus converting rural networks into weak systems [33].

The configuration of rural systems cannot be easily changed because there are few switches and disconnectors, in addition to being manual and in remote locations [4,35]. The electrical protections are also weak because they are sacrificial protections like fuses [4,35]. In contrast to urban, industrial and commercial mesh networks, the rural ones usually have only an upstream protection device that disconnects the whole system in case of any fault. This greatly reduces the network resilience and increases the number of hours without supply to the consumers. Therefore, it is recommended to improve the resilience and performance of the system by sectionalising the network with recloser or automatic recloser circuit breakers, including back-up distribution substations, and by deploying Distributed Generation (DG) and fault indicators [4].

Rural distribution grids are more vulnerable than other grids. The aged infrastructure of a rural network combines with the other usual challenges in this kind of location, where we can find lower quality indices (number or time of interruptions), difficulty of access after electrical contingencies, voltage variations, grid congestion, tree pruning and scattered consumption. All of this requires updated solutions and cutting edge technologies for facing them.

Traditionally, electrical utilities have solved these issues by building new secondary substations, lines, and other electrical infrastructures. Even in specific cases, capacitors are deployed in order to compensate reactive power flows and reduce voltage drops. In addition, the new DGs have exacerbated the issues mentioned above, demanding more static and non-flexible reinforcement of the network.

In addition, rural grids, unlike urban ones, usually have no communication infrastructures. Therefore, DSO ignores what is happening there and is not able to take actions to face network eventualities, thus increasing the time without supply for consumers. However, the DSOs are progressively deploying telecommunications in their networks for managing Smart Grid technologies, e.g., smart meters and new protection devices. They have been typically used in their networks the following communication technologies [22,36]: (i) Power Line Communications (PLC), which use the distribution lines and cables as a transmission channel; (ii) Wireless or Radio Communications (WLC), which use the radio technologies for transferring between two or more points the information; and (iii) Fiber Optical Communications (FOC), which use pulses of light through an optical fiber for transmitting information. The FOC has the best transmission properties, reaching hundreds of Gbps; unfortunately, the civil works associated with the infrastructure deployment are very expensive, thus restricting their applicability to urban environments and high voltage transmission networks. The WLC has good transmission properties and may reach transmission rates on the order of tens or even hundreds of Mbps. Moreover, the WLC is featured to be reachable, which means that it could provide data access at rural and remote areas where wired connectivity is next to impossible; simply, in order words, its development is easier in comparison to a wired network and it has facile maintenance. Nevertheless, the hard orography and adverse meteorological conditions may accentuate the service degradation and undergo problems. In general, the WLC is a good option for non-critical networks like rural ones, either by subcontracting the service to a telecommunications operator or using private infrastructure. Finally, the PLC for long distances (up to 3 km) can reach few tens or even hundreds of kbps, with the additional advantage that uses distributor transmission channels and so no special license is required for its exploitation. However, the conduced electromagnetic interference and abrupt line impedances variations may also degrade the service and present issues [22,24,36]. To sum up, the PLC together with WLC are viable options for non-critical rural environments.

When combined with advanced communication and control technologies, this increasing penetration of small distributed power plants, electrical storage systems and electric vehicles can contribute to overcoming rural grid weaknesses while defining a new electric paradigm. In this new electric paradigm, new local electric generation and distributed electrical storage is optimized for its optimum purpose. Therefore, now is the time for defining a new proper rural network with a high quality power supply that has neither electrical interruptions nor sudden voltage drops. With the addition of a reliable and robust telecommunications infrastructure, all of this will provide incentives to rural producers and small enterprises for investing there.

2.2. A Particular Pilot Network in a Rural Area

The SRG network is focused on a real rural distribution grid with a substantial potential for improving efficiency, in particular in terms of continuity of supply [34]. The distribution network where the project is carried out is the last part of a 5 kV network in a rural zone operated by EyPESA (Distribution System Operator, Granollers, Spain) [37]. EyPESA is a DSO that operates a distribution system in Catalonia (Spain). EyPESA provides service to around 56,000 customers along its 1,500 km of lines [37]. The principal particularity of the EyPESA system is that about 50% of its network is deployed in a rural environment where over two-thirds of the customers are from the domestic and service sectors. The EyPESA network is connected to the transmission system at 220 kV through two fully automated primary substations. Internally, the DSO distributes the electricity at 40 kV and then to networks at 20 kV, 5 kV and 3 kV, through automated primary substations. Finally, the DSO distributes to its clients using LV networks through Secondary Substations (SSs) that are mostly not automated.

The network chosen here concerns an area with a low population density, barely 25 customers distributed across four low-level secondary substations (see Figure 1) and who are residential and agrarian. This network is characterized as a non-manageable radial grid, where operational safety is guaranteed—as in traditional networks—through manual switch-disconnectors and fuses. Furthermore, failure detection and access is complicated by the fact that the MV lines of the grid cross valleys and mountains, exposing them to adverse weather conditions.

As seen in the right-upper part of Figure 1, the electrical scheme of the PN is depicted. An overhead bare line comes from a substation which interconnects to a 40 kV subtransmission system located several thousand meters from the PN. In the PN, the overhead bare line covers from several hundred to a few thousand meters, constituting the MV network at 5 kV. In that network, three manual switch-disconnectors can be tripped during maintenance tasks (see Figure 1). The MV lines end at the three-phase circuit breakers of each SS. The three-phase circuit breakers are directly connected to the SS transformer. Following the SS transformer are the LV lines, which are four-wire braided cables that are protected by single-phase fuses, providing passive protection in case of overcurrent. Finally, the SS LV networks supply customers dispersed around the rural area. Each of them is equipped with a smart meter and a power switch that limits maximum power consumption and provides protection against grid eventualities (though it does not actively manage the load). Most of the clients in the PN demand a single-phase power supply, and this is translated into an unbalanced load through the three-phase distribution network.

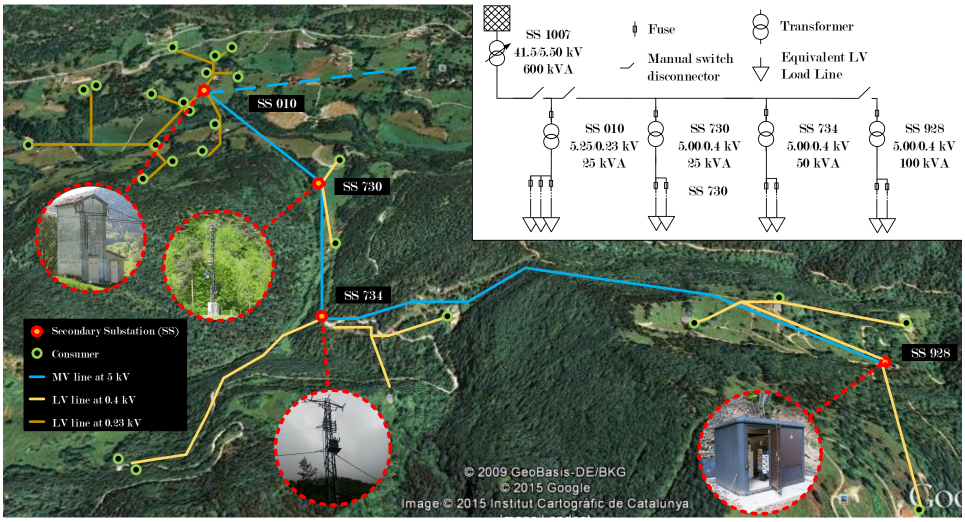


Figure 1. Area from Pilot Network (PN) and its electrical scheme.

3. Electrical Actuations to Evolve the Rural Grid

As presented in Section 2, traditional rural networks present several weaknesses that difficult their management and planning. Among the aspects mostly affecting the planning, we highlight: the orography and the presence of aged and long resistive distribution lines to access to remote areas with spread and few consumers. In turn, among those affecting the operation, we identify: meteorological conditions that provoke frequent grid faults; sensible over and under voltages that affect power quality for consumers; and the stringent flexibility due to the inclusion of few and manually operated switches and disconnectors.

Traditionally, electrical utilities solved these issues reinforcing the infrastructure (e.g., commissioning new lines, secondary substations, etc.) This strategy is neither the most economical one, nor possible from regulations for all cases.

An example addressing economic aspects could be the commitment for distribution operators to feed a consumer in a remote location. In this case, the operator could opt for tracing a new line (and even a dedicated transformer) to the consumer, this being an expensive alternative. As a figure of merit, current prices for low voltage distribution four-wire cables (wire section between 50 mm^2 and 100 mm^2) are between 10,000 € /km and 20,000 € /km [38]. Thus, depending on the distance to reach the isolated consumer, the commissioning of the whole new infrastructure could easily reach hundreds of thousands of euros. Instead of doing this, an alternative could be to install smart power electronics with embedded storage at the consumer's place and this may be an economical option, according to the experience of the authors of the present paper.

Furthermore, as an example of addressing regulatory issues, to increase reliability of a radial network, it may be an option to close it, thus performing a ring with two feeders. However, and because of the orography and limited access to protected natural areas (regulatory issues), it may not be possible. Thus, an alternative is to reinforce such radial network with smart grid technologies (e.g., distributed storage and telecommunications).

The above examples suggest the development of actuations to update rural grids in a different manner than traditional options, and these are proposed in the present paper. After deploying the innovative grid architecture and addressing the adoption of both new management tools and technologies, the PN will become deeply transformed, resulting in the scheme depicted in Figure 2. Next, the above actions for upgrading the rural grid are listed [18,26,32,39], and the following subsections go deeper into describing the above updates for developing the rural grid: promoting the distributed generation (detailed in Section 3.1); including new protection devices (detailed in Section 3.2); installing back-up resources (detailed in Section 3.3); deploying a proper telecommunications network (detailed in Section 3.4); developing new control and management agents (detailed in Section 3.5); and (detailed in Section 3.6).

3.1. Promotion of Distributed Generation

The presence of renewable generation in power networks is progressively gaining more and more importance [33]. The growth of DGs in the PN will improve the grid reliability and the continuity of supply to customers, increasing the global efficiency of the grid. For the adopted network, the maximum generation capability of DGs for end-use customers is high because the legal ceiling is about 64 kW, according to Spanish Regulations [40], while the consumption peak is below 30 kVA. The latter, along with the availability of space that rural consumers have to install DGs, yields a tremendous potential for decarbonising the rural grid. Photovoltaic is the most usual DG technology, offering the lowest levelised cost of energy amongst the eligible options [41]. However, there are other technologies such as wind, gasification and biomass, which are also attractive to rural areas, thanks to the availability of farm and forestry residues [33]. In addition, the DSO has carried out strategies in order to apply a curtailment to these DGs when necessary.

3.2. Inclusion of New Protection and Monitoring Devices

As previously indicated, the protection elements of the PN are not equipped with automatic reclosing, thus they are able to isolate only part of the electrical grid in case of a malfunction. Modern rural grids require a certain degree of flexibility in order to offer new electrical configurations and new modes of operation [35]. For instance, they should allow isolated operation and reconnection of some or any parts of the grid when various grid eventualities occur [30]. To do so, the overload LV lines should be independently managed in order to energize the islands through back-up energy resources. Therefore, it is proposed that the LV fuses of feeders be replaced with automated and remotely controlled Electrical Power Switches (EPSs), who say breakers. This in turn impacts the selectivity of LV lines during grid eventualities.

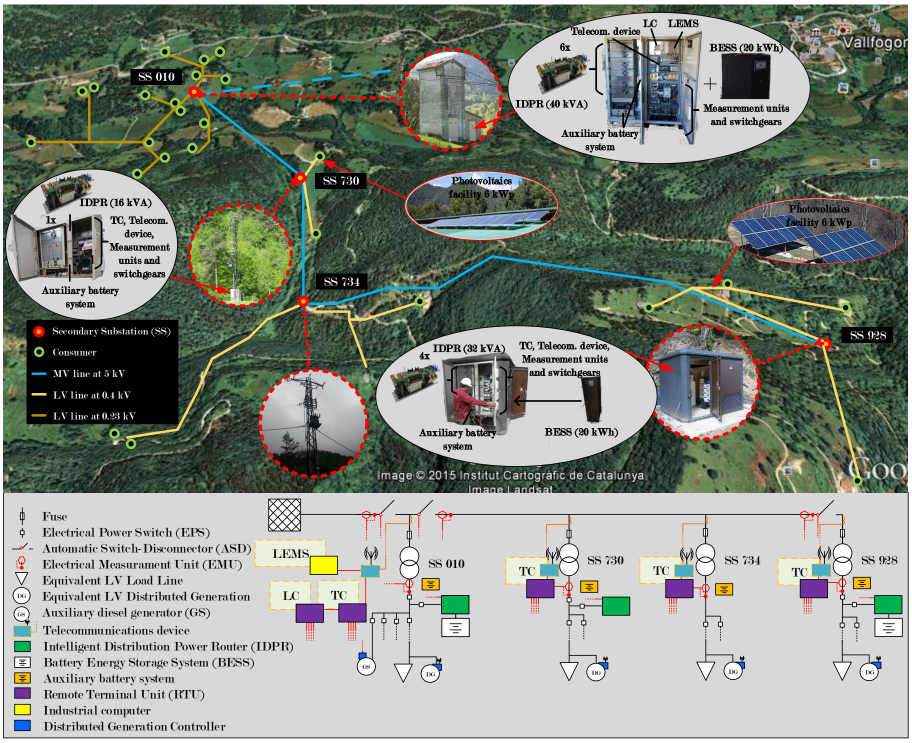


Figure 2. Electrical scheme of Pilot Network with new element after actuations. For the sake of completeness, acronyms not specified in the figure are: Local Energy Management System (LEMS), Local Controller (LC), and Transformer Controller (TC). The whole list of acronyms can be found in abbreviations section.

Moreover, it is indispensable to have selectivity at the MV level in order to disconnect the PN from the rest of system and also to have the possibility of creating different electrical configurations. Consequently, some manual switch-disconnectors are automated and remotely controlled (hereinafter Automated Switch-Disconnectors (ASDs)).

Furthermore, to overcome the lack of observability in rural grids, the PN is also updated with distributed monitoring devices (so-called Electrical Monitoring Units, EMUs). Such enhanced monitoring provides flexibility for grid operation.

To integrate and remotely manage the new protection and monitoring devices, an element is included: the so-called Remote Terminal Unit (RTU). The RTU is a solution for substation or power stations automation to interface with all substation equipment that provides protection and control. The RTU delivers information to the Supervisory Control And Data Acquisition (SCADA) of the DSO grid and offers full capability for integrating and controlling devices through different communications protocols.

In the particular case of the PN, five RTUs are installed, four of them are in charge of each SS where they are placed and one is in charge of the whole PN. They are used to integrate mainly all new smart technologies, and controlling, monitoring and protection devices with the telecommunications network, and command of the PN according to the control algorithms. Thus, they act as a multi-protocol bridge between the SCADA and controllable equipment [42].

3.3. Back-Up Resources

Diverse types of back-up resources can be adopted so as to improve the network reliability. One option is the inclusion of diesel generators. Such systems enable the isolated operation of the network, even in the absence of DGs and storage.

Alternatively, one could opt for power electronic-based solutions. In this regard, the SRG project developed the IDPR [31,39,43,44]. An IDPR, like diesel generators, enables isolated operation of the system in case of faults [45]. Thus, the IDPR is a device located at strategic nodes of the distribution network and its main goal is to control power flows. As can be seen in Figure 2, the PN is comprised of three IDPRs. There are only two IDPRs equipped with a Battery Energy Storage System (BESS) because of space limitations in secondary substations. In addition, an auxiliary diesel generator (GS) is set up in SS 010, thus enabling isolated operation in the absence of DGs and storage. Note also in Figure 2 that, in the case of protection devices, the back-up resources are also integrated into the PN through RTUs.

The biggest challenge of the SRG project has been the development of an IDPR. This device is comprised of an innovative electronic-based power conversion system. The IDPR is a modular power converter connected in parallel with the low voltage grid and it can be connected with an energy storage device. Moreover, the control system of the IDPR is easily managed by the system operator setpoints as well as a permanent monitoring of the power flow upstream and downstream of its coupling point via Modbus RTU protocol In terms of performance, the power stage implements an extremely compact transformer-less topology based on the new highly efficient silicon carbide power semiconductor devices [26,39,45]. Figure 3 presents the IDPR architecture.

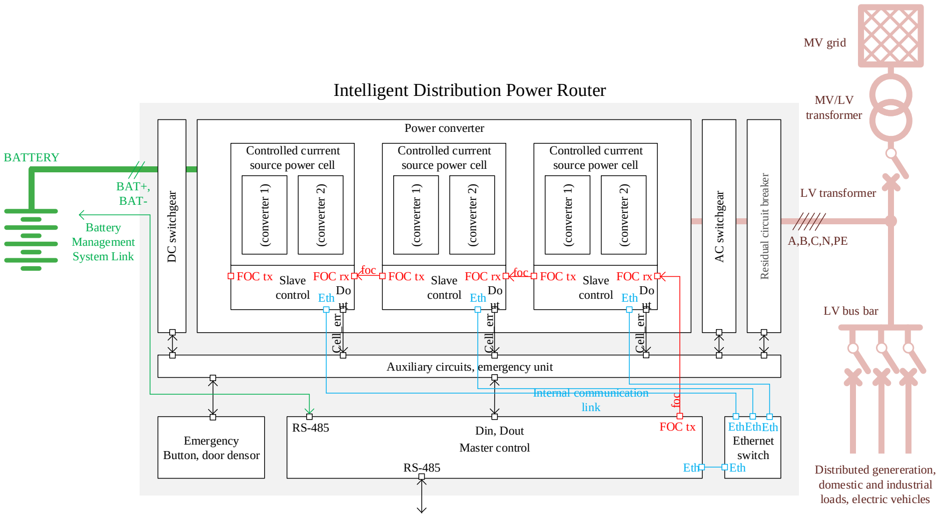


Figure 3. Architecture of an Intelligent Distribution Power Router (IDPR) with a battery [39].

The power converter is based on a determined number of controlled current source power cells, each of them based on two converters. Each power cell has its own control board (slave control), which is responsible for controlling the cell output current. The current setpoints are received on each cell from the master control through an Ethernet communication link, centralized in an Ethernet switch. In order to make the system safe in the event of a communication failure of the Ethernet link, a hardware wired output is included, allowing notification of any error in a cell to all other cells and to the outside of the power converter. The switching frequency of the converters is fixed to 30 kHz and the switching signals are synchronized by fibre optic triggers. The number of power converters depends on the number of stages of the converter (i.e., if it integrates a BESS) and the rated current in each IDPR (i.e., the rated power of the IDPR). There are DC and AC switchgears consisting of a main relay and a precharge circuit. The function of these parts is to allow the precharge of the converter DC bus from both sides and to connect or isolate the power electronics to the outside (grid or battery) in order to respectively operate or turn off the converter. A thermal magnetic and residual circuit breaker protects the IDPR from an overcurrent, a shortcircuit or a ground fault in AC side. In addition, there are auxiliary circuits for ensuring that all the signals from the master control to/from the switchgears, emergency button, door sensors, and power cells are correctly adapted. Finally, the master control board is the responsible for managing the different power cells, and communicating with the battery management system and system operator [39].

The IDPR enables the integration of distributed generation, renewable sources, domestic and industrial loads and electric vehicles into the distribution systems. Moreover, it favours the integration of energy storage devices and, finally, it improves the power quality and grid support [46,47].

The IDPR functionalities include power quality improvement as a result of the active compensation for current harmonic, reactive power and unbalance on the current demand side. At the same time, active and reactive power can be dispatched because of its 4-quadrant operation. A normal operation mode is conceived for converting the entire system downstream to an aggregated bidirectional load that can be regulated in order to match the upstream requirements of the system operator in terms of stability and energy management. This is how the IDPR is aimed at being a powerful element for integrating DG or renewable sources, domestic or industrial loads, and electric vehicles. Therefore, in this operation mode (so-called slave), the voltage and frequency in the coupling point of the IDPR is provided by the main grid, by an auxiliary generator or by another IDPR. The IDPR, while operating in slave mode, is controlled as a current source for delivering or consuming power, according to exogenous setpoints. It is required that the grid has to be under normal operating conditions in regard to voltage and frequency levels while the IDPR is balancing the circulating currents. Therefore, the local consumption is seen by the grid upstream as aggregated consumption, and this compensates the reactive power while cancelling harmonic content, which in fact minimizes losses in the distribution system.

In case of grid failure or a scheduled disconnection, the IDPR is able to restore the LV grid and MV grid through an SS transformer in isolated mode. This grid-disconnected operation provides a voltage reference to the system in order to supply loads, DGs and/or storage systems. Therefore, the developed IDPR is able to work while fixing the voltage and frequency of the local area. At the moment this mode is put into operation (so-called master mode), the main grid has to be decoupled from this area and no other IDPRs can be connected in master mode. The master mode starts from a zero voltage situation with a progressive local grid energization consisting of a voltage ramp. After that, when the grid is stabilized up to its nominal values, consumers, DGs and slave IDPRs allocated inside the same area can be progressively connected and configured in order to assure that the master IDPR is able to guarantee system stability. This mode is disabled if no storage device is installed in the IDPR.

3.4. New Telecommunications Network

The SRG project explores the convergence between electricity and Telecommunications Networks (TN). A new infrastructure is proposed with the aim of guaranteeing the efficient integration and management of DGs, new back-up resources, and new protection and control devices through RTUs. TN is an essential infrastructure to support the new SRG, transmitting commands and setpoints for remote management and control, data obtained from measurements and smart meters, even speech signals. The TN is presented in Figure 4. As mentioned previously, the TN is comprised of two different environments: an inner TN and an outer TN for the network. At the lower layer of the open system interconnection, the solution adopted for inner TN implements a wireless area at the SS level, thus enabling DGs to connect directly to control devices. In the second step, a main channel that employs the PLC technology will be set up, allowing communications between SSs. Then, the wireless network can also be used as an alternative link channel if the main one is incapacitated [24]. On the one hand, the Worldwide Interoperability for Microwave Access (WiMAX) is the wireless standard chosen for creating the SS wireless area and the alternative point-to-point channel between SSs.

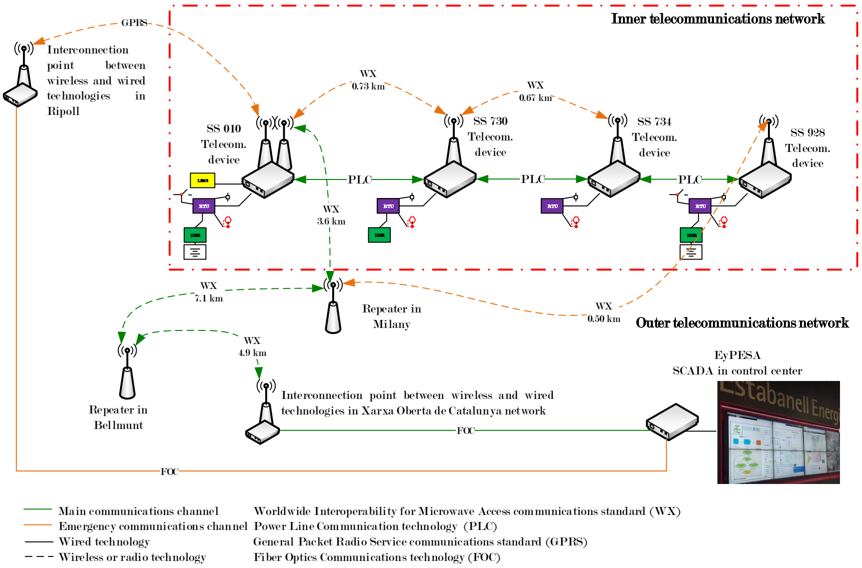


Figure 4. The telecommunications network.

The wireless technologies (e.g., WiMAX) do not require a core infrastructure to operate, which simplifies operations and reduces initial deployment costs [48,49]. WiMAX communication standard is similar to the Wi-Fi, but the former has better capability to operate at higher speeds for users connected over a large area like rural environments, in particular, it can stretch up to a maximum range of 50 km. The WiMAX is the name of the wireless broadband standard IEEE 802.16, which is a wireless local area network technology for fixed and portable devices [49]. It is able to provide access at a maximum bit rate between 1 Mbps to 75 Mbps. It could be potentially deployed in a variety of spectrum bands such as 2.3 GHz, 2.5 GHz, 3.5 GHz and 5.8 GHz [39,48,49]. The adopted WiMAX service uses a dish antenna to connect straight to the nearest wireless tower, providing a strong and stable connection.

On the other hand, the PLC technology deployed combines a spread spectrum for those parts of the TN where robustness is fundamental, and a modulation multicarrier for those parts of the TN where distances are shorter but higher capacity is required [24,50]. The transmission rate reaches 3 Mbps to 30 Mbps at short and medium distances even in the presence of strong interfering signals (e.g., photovoltaic inverter) and 320 kbps at distance of 8 km. Nominal bandwidth is between 2 MHz and 30 MHz and the internal latency is between 4 ms to 6 ms.

The solution adopted for the outer TN, which connects the PN with the SCADA and other exogenous agents, is based on two communications channels. The main channel connects the PN with the SCADA through new point-to-point links in order to cross the mountains using WiMAX communication standard to the private fiber optics network from Xarxa Oberta de Catalunya (XOC). The emergency channel uses a public wireless link based on General Packet Radio System (GRPS) to connect the PN to another fiber optics public telecommunications network. Radio technologies, like WiMAX and GPRS, deliver data access services at low cost [24]. GPRS, unlike WiMAX, provides a data rate significantly smaller between 56 kbps to 114 kbps [51]. GPRS is a wireless technology that distributes packets of data across multiple channels, making efficient use of the bandwidth and providing the minimum information a secure channel for the link [24].

The coexistence of such a heterogeneous group of technologies is justified by two main reasons: the existence of certain communications infrastructures, like XOC and public telecommunications network, at the time of modernizing the project; and geographical constraints that make it difficult to deploy wired communications in some parts of the PN.

The whole set of communication links forms a meshed network, so networking technologies and services were deployed for successful operation of the PN. The TN according specific metric chooses the best path route from PN to control room, taking into account the existence and availability of previous communication infrastructures. Note that there are mainly two valid solutions to deploy these communications: the 2-layer solutions, which are based on Ethernet addresses; and the 3-layer solutions, which are based on Internet Protocol (IP) addresses. The SRG project focuses on the 3-layer solutions because of their advantages, which are an easier scalability, more cybersecurity, an easy integration with public telecommunications operator's networks, as well as with the International Electrotechnical Commission (IEC) protocol number 60870-5-104. This IEC protocol is an IP utilised for supervision, control and data acquisition in the power system applications [13,52,53].

An alternative to IEC-60870 is the IEC-61850 [53]. The IEC-61850 standard is a good solution that takes into account all aspects that are common in an electrical substation. It deals with general requirements, engineering, data models, communication solutions and compliance tests. A significant advantage of the IEC-61850 standard is its extensibility characteristic obtained by making the communication independent of the application by specifying a set of services and objects. This has allowed us to design different applications without depending on specific protocols. As a consequence, the data objects defined in the IEC-61850 standard allow us to apply them in multiple communication solutions without having to modify the models. However, despite the advantages of IEC-61850 over other standards in the project, we have opted for applying the IEC-60870, which focuses on the interaction between SCADA and RTUs. The reasons are diverse: (i) the previous experience at the time of executing the project; (ii) the complexity of deploying the IEC-61850 within the frame of the project; and (iii) the stringent requirements of this standard in terms of communications and related infrastructure.

In more detail, the main logical transmission requirements are aspects related to: addressing, quality of service, topology discovery and routing, cybersecurity, network management and time synchronism. Addressing aspects are essential to clearly and uniquely identifying the origin and destination points. This is carried out through IP version 4 addresses that permit user identification. This solution, in comparison to a 2-layer one, is more scalable but also more complex.

The requirements for applications in terms of bandwidth, latency and bit error rate are included within quality of service aspects. In particular, when different applications co-exist in the same network, or when certain users have more important information to transmit, it is very common to create different traffic flows and assign to each application a priority. In addition, 3-layer approaches segment the traffic through Virtual Private Networks (VPNs), and likewise 2-layer solutions with Virtual Local Area Networks.

Topology discovery and routing aspects choose the best route to transmit the information. The solution adopted is based on one of the most common routing protocols, which is the Routing Information Protocol (RIP). RIP is a standardised distance vector protocol that uses the inherent capability of creating new routes when the original one is interrupted.

The cybersecurity is a critical feature in the Smart Grid environments and is a broad subject that must be dealt with to form a number of different points of view. The messages to be transmitted must be ciphered to make sure that unauthorised recipients do not have access to the information, and the terminals themselves must have proper access passwords to make sure that their configuration is not changed and company policy must be enforced for personnel training. At 3-layer architectures, VPNs with an inherent security (that is IP security) are created, and they encrypt the IP packets to be transmitted using protocols to exchange the password. In addition, network access is reinforced with network authentication through the multiprotocol label switching as principal access and the Remote Authentication Dial-In User Service (RADIUS) protocol as a second path.

The Network Management is a tool that ensures the successful network operation and helps to diagnose problems. The most common protocol is the Simple Network Management Protocol (SNMP), whose messages are encapsulated in user datagram protocol and IP. The whole network is managed with the commercial solution SolarWinds platform via SNMP. It primarily applies to time stamped data or information from battery-powered devices at remote locations where the device time may deviate (causing issues with the time-stamped data). To prevent this problem from occurring, users can specify that the server synchronize the device time using the Network Time Protocol.

Finally, time synchronism aspects are essential for the IEC-60870-5-104 protocol and cybersecurity implementations in terms of specifying the time zone and time synchronization properties of devices [52]. The IEC-60870-5-104 protocol allows the master to specify zone and time. Table 1 sums up the previous points.

Table 1. Summary of solutions for the logical transmission requirements.

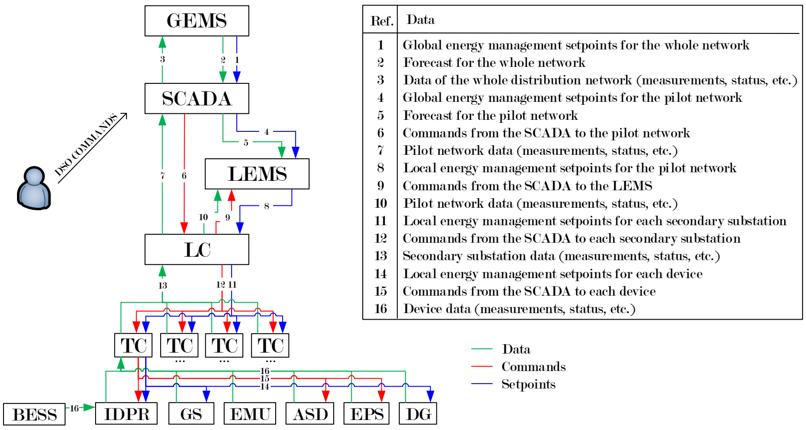
Network Architecture Requirements	Solution Adopted
Addressing	Via IP version 4 with private addresses
Quality of service	Traffic segmentation via VPNs
Topology discovery and routing	Route creation via RIP
Cybersecurity	Though VPNs with IP security and RADIUS protocol authentication
Network management	With SolarWinds platform via SNMP
Time synchronism	Through IEC-60870-5-104 master

3.5. New Control and Management Agents

The previous subsections have presented diverse new Smart Grid technologies (e.g., IDPRs, EPSs, ASDs, DGs, etc.) for modernising the grid [31,39]. They need to be managed externally and coordinated for grid operation optimization. In order to efficiently manage the grid, diverse management agents are defined. These agents interact with one another by exchanging data and commands. From a bottom-up approach, the management hierarchy is configured by the so-called Transformer Controller (TC), the Local Controller (LC), the Local Energy Management System (LEMS), the SCADA and, finally, at the top of the management structure is the Global Energy Management System (GEMS) [31,39]. The hierarchy and relationships are depicted in Figure 5.

In detail, the TC is a software that is executed in the RTU. In the particular case of the PN, there are four units and each one is in charge of each SS (see Figure 2). They directly exchange information and setpoints with the back-up resources and distributed generation, as well as with control and protection equipment, and Electrical Measurement Units (EMU). Thus, the RTU that executes the LC has to be able to process analogue and digital inputs and outputs, as well as to collect the above-mentioned network components data and alarms through wired (e.g., serial RS485 and Ethernet) or wireless communications. They also have to support standard protocols like Modbus (for integrating IDPRs, EMUs, etc.), IEC-60870-5-104 (for being integrated by the LC and SCADA), etc. [42,52,53].

In turn, the LC is a software that configures the second level of the management architecture. The LC, like the TCs, is implemented in a RTU. In contrast to the TCs, the LC is responsible for managing all the TCs of the PN. The RTU that executes the LC has to support the IEC-60870-5-104 protocol over Transmission Control Protocol (TCP) and IP for reading all the TC collected data, and transferring to TCs the commands and setpoints provided by, respectively, the SCADA and LEMS. It should be noted that the commands refer to network configuration orders, like those for the process of turning on/off switchable elements or devices and for incrementing or decrementing the transformer's tap changer, while the setpoints refer to active and reactive power control signals for network operation. Therefore, the LC acts as a bridge between upper management agents, i.e., SCADA and LEMS, and TCs.



Ref.	Data
1	Global energy management setpoints for the whole network
2	Forecast for the whole network
3	Data of the whole distribution network (measurements, status, etc.)
4	Global energy management setpoints for the pilot network
5	Forecast for the pilot network
6	Commands from the SCADA to the pilot network
7	Pilot network data (measurements, status, etc.)
8	Local energy management setpoints for the pilot network
9	Commands from the SCADA to the LEMS
10	Pilot network data (measurements, status, etc.)
11	Local energy management setpoints for each secondary substation
12	Commands from the SCADA to each secondary substation
13	Secondary substation data (measurements, status, etc.)
14	Local energy management setpoints for each device
15	Commands from the SCADA to each device
16	Device data (measurements, status, etc.)

Figure 5. The hierarchy of agents.

While the TCs and LC ensure proper supervision and protection, the LEMS enables the operational optimization of the network. The LEMS calculates on a minute-by-minute basis the setpoints in order to back up resources and distributed generation, doing so by using data collected by the LC, the SCADA constraints and commands, and the GEMS setpoints and forecasts. The network data comes from the LC via Modbus TCP/IP each minute, while SCADA constraints and commands are updated asynchronously through the LC. Conversely, GEMS setpoints and forecasts come through the SCADA via Secure File Transfer Protocol (SFTP). Furthermore, the LEMS records the most relevant information of the network so that it can be checked when there is a failure. The LEMS is the last level of the management architecture included in the network environment. Due to the complexity of the calculations carried out by LEMS, it is implemented in an industrial computer (see Figure 2). This has been selected because it has high computing power and also an extended temperature range, which means it needs no fans and is thus compact in design, protecting it from dirt, dust and humidity while enduring the harshest conditions.

The SCADA is just above the network and there is only one. Thus, it monitors the status not only of the network but also of the system the network is connected to. Eventually, the SCADA will allow remote operation of some network elements like switches, transformers, capacitor banks, etc. for maintenance and the eventual maneuvering of the network. Therefore, the SCADA is the element that delivers commands to the LC via the IEC-60870-5-104 protocol over TCP/IP. These commands are conventionally determined by the network operator at its convenience. The SCADA is not a new element to the management architecture of networks, but, for the innovative approach proposed for the network operation, it offers new functionalities beyond the state of the art. Specifically, these new functionalities are transferring to the GEMS all the system data via SFTP each 15 min and transferring to the LEMS the GEMS setpoints and forecasts via SFTP. Thus, in general terms, the SCADA acts as a secure bridge and filter between inner and outer management agents of the network.

In the same way as the SCADA, the GEMS is in an outer environment of the network. The GEMS calculates a series of active and reactive power setpoints for managing the whole network. This means that GEMS provides control setpoints for each IDPR and distributed generation within the network. It is divided into two modules. The first module forecasts the consumer's consumption and distribution network generation, according to the network data that is provided by SCADA, as well as data from other inputs such as meteorological and calendar data. The second module generates the distribution network and IDPR setpoints in order to increase the performance of the network. Data is exchanged between GEMS and SCADA every 15 min via SFTP.

The management agents presented above comprise a novel management architecture, which allows for controlling the newly installed Smart Grid technologies, e.g., distribution generation, back-up resources and new protection devices. One remarkable advantage of the architecture is that it decentralizes the operation of the system according to its electrical configuration (e.g., whether the grid is connected or isolated). Another advantage is that it enhances the potential scalability of the system, making it possible to replicate the same architecture throughout the whole network. Furthermore, this decentralization increases the reliability of the system, since not everything depends on the decision of the SCADA. Instead, intelligence is allocated also to other agents that can act even autonomously in case of any malfunction. Such advantages go beyond the typical working practices of grid operators in weak rural systems.

3.6. Overview of the Applications of the New Technologies

The software and hardware technologies described throughout this section can provide numerous services for diverse agents in the electrical sector, which are deeply analysed in [54–57]. To provide a general overview, Table 2 summarizes such services, linking them with potential stakeholders.

Table 2. Applications of the new technologies evolving the distribution grid [54–57].

Application	Involved Technologies	Stakeholders	Description
Power quality improvement	IDPR (back-up resource)	DSO	Fulfilment of standards related to power quality in LV grids through power electronics.
Integration of DG (e.g., self consumption)	IDPR with BESS; GEMS and LEMS (new management agents); telecommunication network	DSO; final grid users	New technologies ensure the proper operation of the network under both grid connected and isolated modes.
Optimal power distribution	IDPR with BESS; GEMS and LEMS; telecommunication network	DSO	Optimal power dispatch of controllable resources permits the DSO to minimize distribution power losses.
Promotion of electrical vehicles	IDPR with BESS	DSO; final grid users	Power electronics and distributed storage facilitate the integration of electrical vehicle charging facilities into LV grids.
Grid ancillary services (e.g., voltage control)	IDPR	DSO	Power electronics can manage reactive power for voltage control.
Grid ancillary services (e.g., frequency control)	IDPR with BESS; LEMS; telecommunication network	Transmission System Operator and DSO interaction	Power electronics can manage active power for frequency control.
Continuity of supply	IDPR with BESS; protection and monitoring devices; LEMS; telecommunication network	DSO	Islanded operation reduces the time final users may be affected by planned eventual (either planned or unplanned) mains failures. In addition, protection and monitoring devices permit the detection and isolation of grid faults.
Grid congestion alleviation	IDPR with BESS; GEMS and LEMS; telecommunication network; monitoring devices	DSO	New technologies ensure permit to maintain peak power flows through distribution infrastructure within admissible levels.
Grid update deferral	IDPR with BESS; GEMS and LEMS; telecommunication network; monitoring devices	DSO	New technologies extend the lifespan of aged infrastructure respecting electrical standards.

4. New Electrical Configurations and Operation Modes

On completion of the reinforcements carried out to develop the PN, this results in a highly flexible system that offers various operational capabilities and new possible vulnerabilities, which are described in this section. To this aim, this section first identifies the different operational circumstances for the PN (in Section 4.1). Second, the section defines duties for each of the agents composing the novel management architecture proposed in this study (in Section 4.2). Finally, new vulnerabilities are discussed and analysed through a vulnerability analysis and a management plan is presented to avoid any risk situation (in Section 4.3).

4.1. Operational Circumstances for the Pilot Network

It is known that the PN falls within one of the three following different circumstances: Circumstance 1 (C1) is the most usual, and this occurs when the PN, or at least part of it, is supplied by the External Grid (EG) without experiencing grid eventualities; Circumstance 2 (C2) is when the PN, or at least part of it, operates isolated from the external grid without experiencing grid eventualities (this means that back-up resources, like an IDPR or a diesel generator, ensure the security of supply for consumers and the power balance of the PN, or part of it.); finally, Circumstance 3 (C3) is when the PN, or part of it, experiences grid failures, e.g., a blackout or a short-circuit (including also situations when the PN, or part of it, is not supplied because it is undergoing scheduled maintenance tasks).

According to the presented operational circumstances and the disposition of switches and back-up resources in the PN (see Figure 2), the grid can be divided into three sectors, as depicted in Figure 6. Sector 1 (S1) and Sector 3 (S3) can be operated in isolated mode since they are equipped with IDPRs (including a BESS) and/or a diesel generator. For instance, by being able to operate isolated, they can fall under the operational circumstances C1 and C2. Conversely, Sector 2 (S2) can only operate while connected to the external grid or with the support of other sectors, since this sector is not equipped with IDPRs or a BESS. Table 3 collects all possible scenarios for the PN, according to the operability of sectors and the state of links between them [30–32,39].

Table 3. Pilot Network scenarios depending on state of links and operability of sectors [30–32,39].

Links between Sectors			**Operationality**			**Circumstances**
EG-S1	**S1-S2**	**S2-S3**	**S1**	**S2**	**S3**	
C	C	C	O	O	O	C1
C	C	D	O	O	N	C1 + C3
C	D	D	O	N	N	C1 + C3
D	C	C	O	O	O	C2
D	C	D	O	O	O	C2
D	D	C	O	O	O	C2
D	C	D	O	O	N	C2 + C3
D	D	C	N	O	O	C2 + C3
D	D	D	O	N	O	C2 + C3
D	D	D	O	N	N	C2 + C3
D	D	D	N	N	O	C2 + C3
C	C	D	O	O	O	C1 + C2
C	D	C	O	O	O	C1 + C2
C	D	D	O	N	O	C1 + C2 + C3

C: Connected; D: Disconnected; O: Operating; N: Non operating.

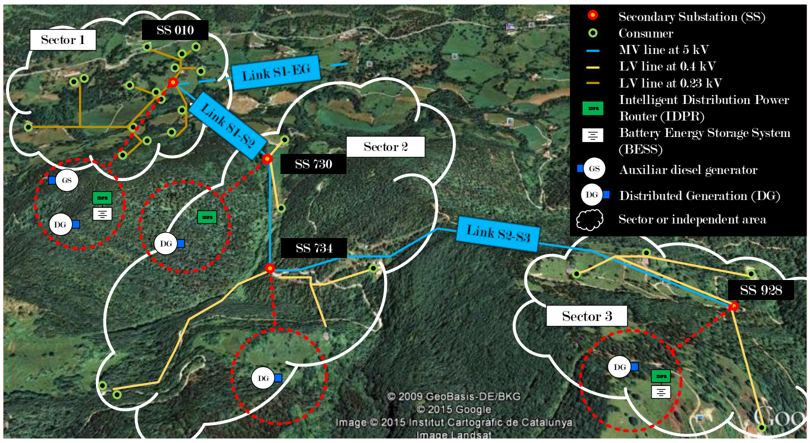


Figure 6. The Pilot Network divided into three sectors [30–32,39].

4.2. Particular Goals for Each of the Agents of the Pilot Network Architecture

The operational scenarios were defined in the previous subsection and they mainly comprise operational circumstances for sectors that consider them to be isolated (C2) or connected to the EG (C1). Depending on whether a sector is connected or not to the EG, there can be different optimization goals for its operation. This subsection precisely describes the role of the two Energy Management Systems (EMS) that handle the PN, the Global and Local EMS while taking into consideration the above-mentioned operational circumstances [30–32,39].

As has been previously mentioned, these two EMS determine the series of active and reactive power setpoints for managing the whole network, and they calculate on a minute-by-minute basis the setpoints in order to back-up resources and DGs using data collected by the LC, SCADA constraints and commands, and forecasts. Both EMSs optimize, insofar as possible, the operation of the PN. Such optimization is solved in two steps. The first optimization, called economic optimization hereinafter, solves an optimal economic dispatch and thus addresses the market aspects such as the availability and cost of the DGs as well as back-up resources. The second optimization relies on the inputs of the first to adjust active and reactive dispatches for the DGs and back-up resources while considering technical aspects such as power losses, thus allowing it to perform an Optimal Power Flow (OPF). Depending on the operational circumstance, i.e., grid connected (C1) or isolated (C2), the above-mentioned optimizations are global or local.

The global optimizations comprise the whole network. The horizon for the economic optimization is 24 h, while the horizon for the Optimal Power Flow is a few hours. For both global optimizations, the time step is 15 min. It is worth noting that, to successfully solve the economic optimal dispatch, the applied algorithm requires forecasts that exceed the 24 h horizon [31].

Conversely, the local optimizations comprise just the PN, since it is not connected to the external grid. The horizon and the time step for both the economic and OPF optimizations are 1 min. The required forecast data for economic optimization is one day ahead.

Table 4 summarizes the roles that GEMS and LEMS adopt—depending on the operational circumstances for the PN—while executing the above described optimizations. Moreover, these optimizations are presented and detailed in [30–32,39].

Table 4. Roles of Global Energy Management System (GEMS) and Local Energy Management System (LEMS) depending on the operational circumstances.

	GEMS	LEMS
C1	• Generates the consumption and generation forecasts for the whole system. • Executes the global economic optimization, function of the global market aspects, availability and cost of DGs and back-up resources. • Executes the global OPF, function of the global economic optimization setpoints and network features. • Provides the global setpoints file for the following 24 h, in time steps of 15 min.	• Adjusts the global setpoints on a one-minute basis while considering other technical eventualities • Provides the adjusted global setpoints to the DGs and back-up resources.
C2	• Generates the consumption and generation forecasts for the PN. • Provides the forecast file for the following 24 h, in time steps of 15 min.	• Executes the local economic optimization, function of the local market, availability and cost of DGs and back-up resources. • Executes the local economic optimization, function of the local market, availability and cost of DGs and back-up resources. • Provides the local setpoints to DGs and back-up resources.

4.3. Analysis in Vulnerabilities on Communications and Related Management Plan

The PN operation depends highly on a wide sensory and monitoring system, and a collection of automated switch-disconnectors and electrical power switches. All of these are remotely managed through the telecommunications system. Initially, the telecommunication systems of electric power systems were limited, small and carefully isolated from the other telecommunication systems in order to guarantee their own security. However, the continued growth of the network, the increment of data volume, and the obsolescence of their infrastructure force the use of new wireless or wired channels that pass the data through the public telecommunication network. In addition, the lack of cybersecurity, the lack of safety, and the unencrypted protocols are provoking that the cyberattacks are becoming increasingly common, representing a vulnerability. In addition, in terms of cybersecurity, like the telecommunications systems, the SCADA system is also critical and crucial. This is because it provides three vital functions, which are data acquisition, supervisory control and alarm display, centralising the communications and network management. The SCADA polls periodically the RTUs to gather the real-time measurement data from all the substations and sends out control signals to the specific remote devices. Therefore, a proper cybersecurity protection system should be provided, in order to avoid a route for hackers from that creates a disruption, takes control, or causes damage.

The SRG potential vulnerabilities are inherited from the traditional telecommunications and management systems. These are outdated private telecommunication networks; the embedded and default passwords that were not changed; and the use of unsafely protocols like hypertext transfer, Telnet and trivial file transfer protocols. Different ways have been selected to reinforce the cybersecurity in the SRG project. The first way is creating a secure channel over an unsecured network (e.g., the public telecommunication network). For instance, the wireless networks are experiencing a great reception in control environments due to the important advantages they provide, and they can pose a significant risk due to the continuous technological change to which they are subjected. To create a secure channel over these unsecure networks, the Secure Shell (SSH) protocol is deployed. The SSH is a cryptographic network protocol for operating services securely over an unsecured telecommunication network. The SSH protocol supports secure remote logins, commands, file transfers, access control, etc. [58]. Furthermore, the Asymmetric Encryption Standard algorithm is the selected technique for encrypting the data exchanged. The second way is establishing VPNs. A VPN creates a safe and encrypted connection over less secure networks, which is employed to securely connect geographically separated facilities forming one unified telecommunication network. The access to such VPNs is restricted. To do so, two techniques are adopted: the first one is using an adequate and unique password, and the second one is controlling the physical port access. In terms of passwords and keys, they periodically expire and they are subjected to dedicated policies (e.g., default passwords are forbidden, a minimum level of complexity is required). In addition, the internet access for these VPNs is absolutely restricted. The physical port access protection measures have been implemented mainly installing the technology inside cabinets protected under key and restricting the use of Universal Series Bus technology. Furthermore, the network architecture is minimised, so the number of connections with the system is the minimum required.The third way of reinforcing the cybersecurity is identifying and removing all unnecessary services in order to get an extra level of security to be simpler, reliable and secure. Disused ports and services are disabled in order to prevent unauthorized use. There is full knowledge about the ports that are open and what services and protocols they use. Additionally, attention has also been paid to computer security aspects like possible failures in memory (e.g., memory leaks, unhandled memory allocation, badly handled memory, memory fragmentation), stack buffer-overrun bugs, and in random addressing of internal libraries' failures. Computers are equipped with firewalls and antiviruses, which restrict access rules to protect connections between control systems and others.

To sum up, the hardware and software dedicated to measuring, detecting, acting and modifying the state and set of all associated services are fully integrated and encrypted. In other words, the operation and information technology are combined in real time in order to ensure the proper supervision and control, and be more flexible and fast. In addition, the firmware code has been hidden and the embedded passwords have been removed to avoid their reading. Finally, just note that security audits are conducted regularly to identify, list and subsequently describe the various vulnerabilities that may arise. Metadata, a vulnerability management system, ensures that these are minimized.

Finally, communication failure scenarios are presented. Note that all the possible communication channels are identified, and the information flow through those channels is depicted in Figure 7. Based on this diagram, twelve possible communication failure scenarios have been listed and described in Tables 5–7. Note that the behaviour also depends on the circumstance in which the PN is operating. Note further that the failure happens when the data does not arrive, is corrupted or is not acceptable.

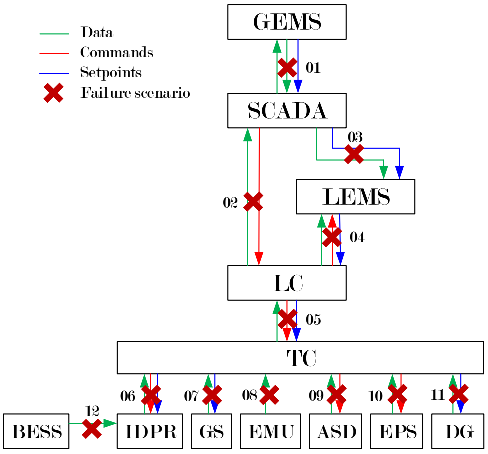


Figure 7. Failure communications scenarios.

Table 5. Actions in function of the operational circumstances 1, 2, and 3. Part A.

Scenario: Interaction	**Actions**	**Result**	**Detection Time**
01: GEMS to SCADA	● GEMS: It is responsible for detecting the communication failure, but it continues calculating the global setpoints (only in C1) and doing forecasts without the SCADA updated data. It tries to exchange the information with the SCADA via SFTP again. ● SCADA: It is responsible for detecting the communication failure and notifying all downstream devices (LC, TCs and LEMS). It updates the corresponding error register and displays a warning message on the operator console. It tries to exchange the information with the GEMS via SFTP again. It continues communicating with the LC but stops the information transfer to the LEMS. ● LEMS: It continues adjusting and sending setpoints to IDPRs/DGs until it finishes the last global setpoints provided by the GEMS via SCADA and after that, it will send null setpoints to IDPRs and no setpoints to DGs in C1. Conversely, it continues calculating and sending the setpoints to IDPRs/DGs until it finishes the last forecast provided by the GEMS, and after that, it applies the rule based disconnected operation in order to guarantee the supply in C2. ● LC/TCs/IDPRs: They continue operating as usual.	The PN operates with the non-updated or without setpoints in C1, or with the calculated setpoints based on a local optimization (if there is an available forecast) or by predefined rules, in C2. Therefore the PN performance may not be optimal. Note that there is no problem in C3.	15 min
02: SCADA to LC	● SCADA: It is responsible for detecting the communication failure and notifying the upstream device (GEMS). It updates the corresponding error register and displays a warning message on the operator console. It continues exchanging information with the GEMS and LEMS, and tries to communicate with the LC via IEC-60870-5-104 protocol again. ● LC: It is responsible for detecting the communication failure and notifying all downstream devices (TCs and LEMS), and updates the corresponding error register. LC refuses any change in the grid configuration and operation. ● GEMS/LEMS/TCs/IDPRs: They continue operating as usual.	There is an external loss of control and information over PN. The PN performance may not be optimal because of the GEMS does not have the LC updated data. Note that in this case it is not possible to start up or reconfigure the network in C3.	3 min
03: SCADA to LEMS	● SCADA: It is responsible for detecting the communication failure and notifying the upstream device (GEMS), updates the corresponding error register and displays a warning message on the operator console. It continues exchanging information with the GEMS and the LC, and tries to transfer the information to the LEMS via SFTP again. ● LEMS: It is responsible for detecting the communication failure. In C1, it continues adjusting the last global setpoints provided by the GEMS and sending them to IDPRs/DGs until there are global setpoints, and, after that, it will send null setpoints to IDPRs and no setpoints to DGs. Conversely, in C2, it continues calculating until it finishes the last forecast provided by the GEMS, and sending then to IDPRs/DGs, and after that, the LEMS will apply the rule based disconnected operation in order to guarantee the continuity of the supply. ● GEMS/LC/TCs/IDPRs: They continue operating as usual.	The PN operates with the non-updated or without setpoints in C1, or with the calculated setpoints based on a local optimization (if there is an available forecast) or by predefined rules, in C2. Therefore, the PN performance may not be optimal. Note that there is no problem in C3.	15 min

Table 6. Actions in functions of the operational circumstances 1, 2, and 3. Part B.

Scenario: Interaction	Actions	Result	Detection Time
04: LC to LEMS	● LC: It is responsible for detecting the communication failure and notifying all upstream and downstream devices (GEMS, SCADA and TCs) and updates the corresponding error register. In such circumstances, it imposes null power and the last voltage and frequency setpoints to IDPRs, and no setpoints to DGs. It also send null setpoints to the auxiliary diesel generator. ● SCADA: It continues operating without any change expect that it displays a warning message on its operator console. ● GEMS: It continues operating as usual and assumes that the LC has performed control actions for IDPRs, DGs and GS. ● LEMS: It is responsible for identifying the communication failure and updates the corresponding error register. It assumes that the LC has performed control actions for IDPRs, DGs and GS. It tries to transfer the setpoints to IDPRs/DGs and to read the information from the LC via Modbus again. ● TCs/IDPRs: They continue operating as usual.	The PN operates with the predefined setpoints. Therefore, the PN performance may not be optimal. Note that there is no problem in C3.	1 min
05: LC to TC	● LC: It is responsible for detecting the communication failure and notifying all upstream devices (GEMS, SCADA and LEMS), and updates the corresponding error register. The LC refuses any change in the grid configuration and operation from the SCADA that has a direct impact on this TC. The LC tries also to communicate with this TC via IEC-60870-5-104 protocol again. ● GEMS/LEMS: They continue operating as usual and assume that the TC has performed control actions for IDPRs, DGs and GS. ● SCADA: It continues operating as usual and it displays a warning message on its operator console. ● TC: It is responsible for detecting the communication failure and updating the corresponding error register. In such circumstances, it imposes null power and the last voltage and frequency setpoints to IDPRs, and no setpoints to DGs. It also sends null setpoints to the auxiliary diesel generator. ● IDPRs: They continue operating as usual.	The PN operates with the predefined setpoints. Therefore, the PN performance may not be optimal because the TC updated uncompleted data. Note that in this case it is not possible to start up or reconfigure the affected part of the network in C3.	3 min
06: TC to IDPR	● TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. The TC tries also to communicate with IDPRs via Modbus RTU again. ● GEMS/LEMS: They continue operating as usual and assume that the IDPRs are not available for the network operation and that they operate with null power and the last voltage and frequency setpoints. ● SCADA: It continues operating as usual and displays a warning message on its operator console. ● IDPR: It is responsible for detecting the communication failure, it self-imposes null power and the last voltage and frequency setpoints. ● LC: It continues operating as usual.	The PN operates without the IDPR power management capabilities. Therefore, the network performance may not be optimal.	1 min
07: TC to GS	● TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. The TC blocks any setpoint to GS and tries also to communicate with this GS via Modbus RTU again. ● GEMS/LEMS: They continue operating as usual and assume this GS is not available for the network operation. ● SCADA: It continues operating as usual and displays a warning message on its operator console. ● LC: It continues operating as usual.	There is only a loss of control and information over the auxiliary diesel generator. Note that the auxiliary diesel generator must detect that no setpoints arrives and turns off itself automatically.	3 min

Table 7. Actions in function of the operational circumstances 1, 2, and 3. Part C.

Scenario: Interaction	Actions	Result	Detection Time
08: TC to EMU	• TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. TC refuses any change in the grid configuration and operation. • GEMS/LEMS: They continue operating as usual assuming that there is a loss of information. • SCADA: It continues operating as usual and displays a warning message on its operator console. • LC/IDPRs: They continue operating as usual.	There is a loss of information. Therefore, the network performance may not be optimal. Note that in this case it is not possible to start up or reconfigure the affected part of the network in C3.	3 min
09: TC to ASD	• TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. TC refuses any change in the grid configuration and operation. • GEMS/LEMS: They continue operating as usual and they consider the state of the automatic switch-disconnector is the same as before. • SCADA: It continues operating as usual and displays a warning message on its operator console. • LC/IDPRs: They continue operating as usual.	There is a loss of control and information over automated switch-disconnectors. Note that in this case it is not possible to start up or reconfigure the affected part of the network in C3.	3 min
10: TC and EPS	• TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. TC refuses any change in the grid configuration and operation. • GEMS/LEMS: They continue operating as usual and consider that the state of the electrical power switch is the same as before. • SCADA: It continues operating as usual and it displays a warning message on its operator console. • LC/IDPRs: They continue operating as usual.	There is a loss of control and information over electrical power switches. Note that in this case it is not possible to start up or reconfigure the affected part of the network in C3.	3 min
11: TC and DG	• TC: It is responsible for detecting the communication failure and notifying all upstream devices (LC, LEMS, SCADA and GEMS), and updates the corresponding error register. • GEMS/LEMS: They continue operating as usual assuming that there is a loss of control and information over this DG. • SCADA: It continues operating as usual and displays a warning message on its operator console. • LC/IDPRs: They continue operating as usual.	There is a loss of control and information over distributed generation. Therefore, the network performance may not be optimal. Note that there is no problem in C3.	15 min
12: IDPR and BESS	• IDPR: It is responsible for identifying the communication failure and notifying all upstream devices, opens the DC main switch thus isolating the battery. It also ignores the active power setpoints and reenergising commands. • GEMS/LEMS: They continue operating as usual assuming that IDPR is not able to provide active power capabilities or energise the grid. • SCADA: It continues operating as usual and displays a warning message on its operator console. • LC/TCs: They continue operating as usual.	The PN operates without IDPR active power capabilities. In C2, the PN may be switch off as a consequence of loss of the IDPR which is energising the island. Therefore, the network performance may not be optimal. Note that in C3 it is not possible to start up the affected part of the network with the IDPR.	100 ms

5. Study Case

The study case section assesses the applicability of one of the main actuations underpinning the modernization of the PN: the inclusion of IDPRs. As previously described in Section 3.3, the IDPR functionalities include power quality improvement in connected mode and grid restoration in isolated mode. Therefore, this section has been split into three subsections. The aim of Section 5.1 is to demonstrate the IDPR functionalities, as a fundamental part for the modernization of the PN and the realization of the proposed innovative architecture. Complementing simulation results presented in Section 5.1, Section 5.2 briefly depicts the performance of IDPR in field. Finally, Section 5.3 reports the methodology to size IDPRs in the function of the PN topology and energy flows for operational defined modes.

5.1. IDPRs Contributions in the Electrical Network

The connected functionalities are the balancing of three-phase currents, the compensation of reactive power in the PN and cancellation of harmonic currents. Thus, as to fulfil this goal, the PN is modelled and simulated (time horizon for simulation, one day) in four different scenarios:

- Scenario (1) serves as the base case; this scenario is representative of the initial state of the PN, which does not comprise IPDRs neither DGs. This scenario comprises the existing unbalance power flows among the three-phase distribution system.
- Scenario (2) represents a transitory situation in which SSs are equipped with IDPRs, but there are no DGs. This scenario considers the initial state of the PN in a short term. The objective here is to evaluate the performance of the IDPRs while solving unbalanced power flows (and reactive components) among the three-phase distribution system due to the existing single phase loads.
- Scenario (3) represents a fictitious situation in which the PN is not equipped with IDPRs, but it does comprise DGs. This situation can be representative of an unplanned evolution of DGs in a rural area. Such DGs are considered to be single phase facilities and their integration into the network is not pursuing balanced power flows.
- Scenario (4) represents a final situation in which the PN is equipped with IDPRs and comprises DGs. The objective here is to evaluate the performance of the IDPRs while solving unbalanced power flows (and reactive components) among the three-phase distribution system due to single phase DGs and loads.

The three-phase system of the PN is modelled in DigSilent PowerFactory software (PF v15.2, DIgSILENT Gmbh, Gomaringen, Germany), addressing the characteristics previously presented in Section 2.2. The IDPRs, which are working on connected mode, are modelled as current sources. The loads are also modelled as current sources, aggregating the demand at each SS level.

Figures 8 and 9 depict the active and reactive power demand profiles at each SS. These profiles derive from real data (see Figure 10) and are directly applied for the base case scenario (1), and also for scenario (2). Active power demand profiles at each SS for scenarios (3) and (4) are derived from the above profiles adding the effect of DGs (see Figure 11). The DG curves were extracted from the repository [59] and were added on the real consumption profiles. Conversely, reactive power demand profiles for scenarios (3) and (4) are the same as for scenarios (1) and (2), since it is assumed that DGs do not inject reactive power and the LV lines of the PN are basically resistive.

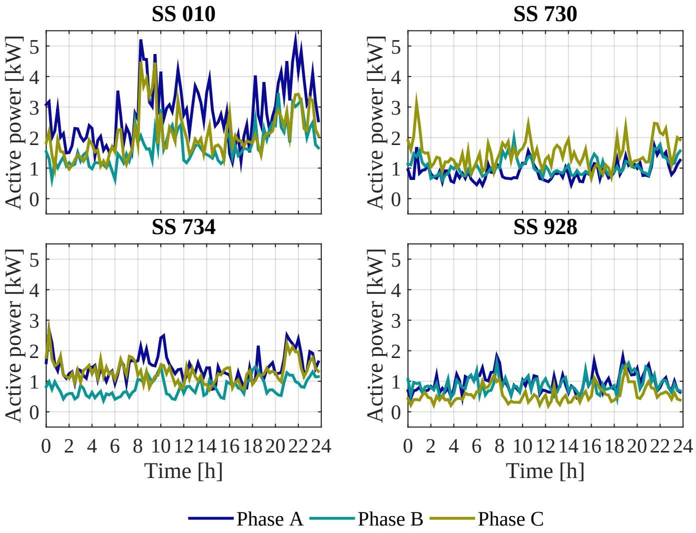


Figure 8. Active power demand profile for phases A, B and C at each Secondary Substation (SS) for scenarios (1) and (2). Note that both scenarios share the same active power demand profile, so results can be applied to both scenarios.

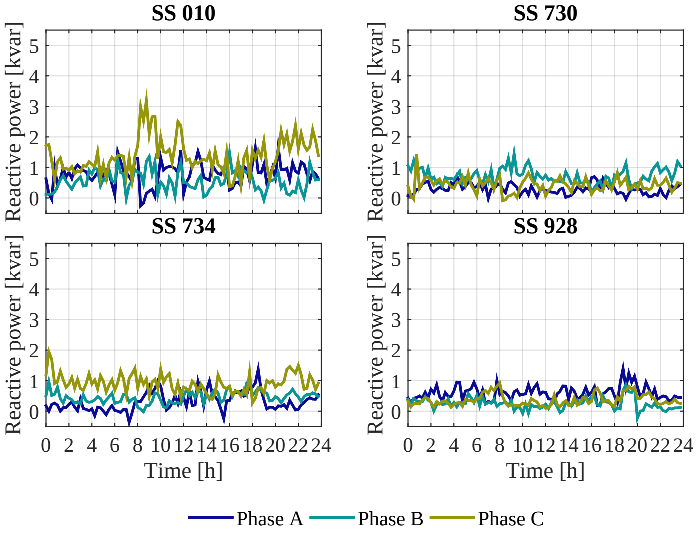


Figure 9. Reactive power demand profile for phases A, B and C at each SS for all scenarios.

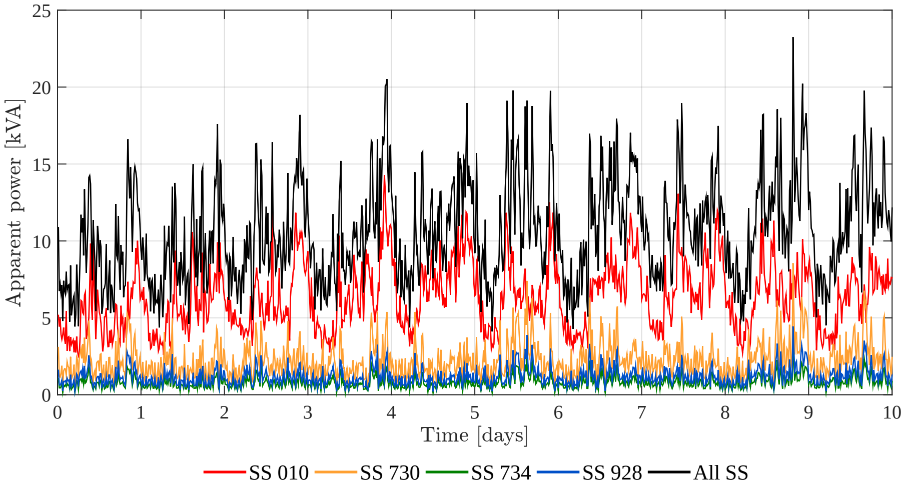


Figure 10. Total apparent power feed by each SS and the Pilot Network (PN) during 10 days.

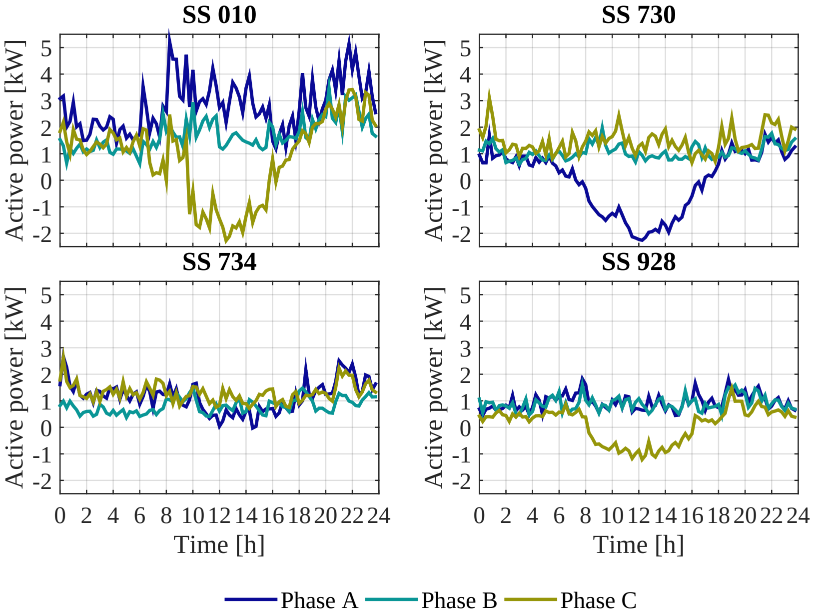


Figure 11. Net active power profile for phases A, B and C at each SS for scenarios (3) and (4). Note that both scenarios share the same net active power profile, so results can be applied to both scenarios.

Figure 12 presents the performance of the IDPR while balancing the three-phase currents at each SS. Presented results refer to the point of connection of the PN with the external grid. As can be seen, in the case there are no IDPRs installed (scenarios (1) and (3)), the currents in the three-phase distribution system could be unbalanced.

The provision of supply to consumers is planned by the distributor system pursuing balanced loading through the three phases of its network. This means that each consumer in the PN could be supplied by different phases. If such demand sharing is properly done, the system is translated into similar loading for each of the three-phases of the system (see scenario (1)). The eventual inclusion of DGs by consumers a posteriori might affect the currents flows in the PN (see scenario (3)). For instance, note that, during the central hours of the day, while distributed photovoltaics are generating, the currents through the three phases of the system can result in being greatly unbalanced.

The deployment of IDPRs guarantees the balancing of currents (see scenario (2)), even in the case of having DG (see scenario (4)). Therefore, IDPRs solve possible inaccurate planning for the provision of supply to consumers and the effect of unplanned DG deployment by the distributor, or other unexpected changes in the habits of consumers.

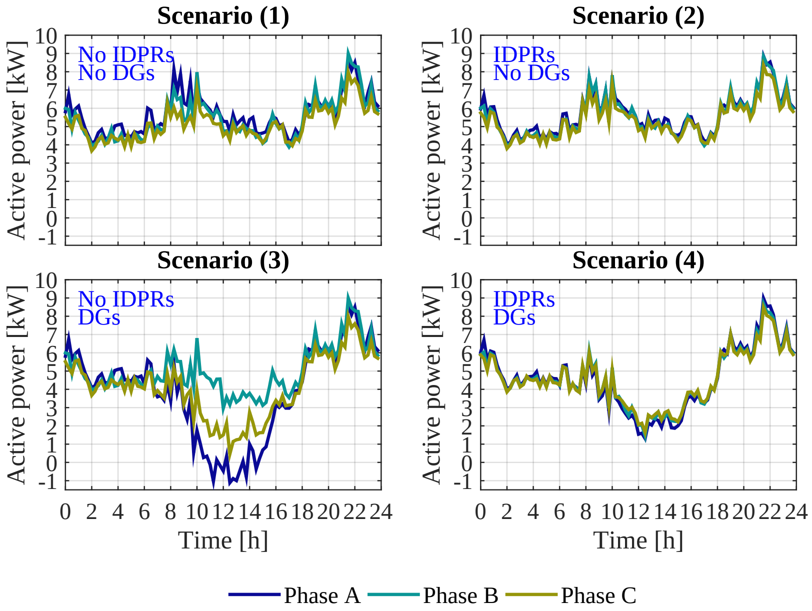


Figure 12. Net active power exchanged per phase with the external grid by the PN with and without including Intelligent Distribution Power Router (IDPRs).

Analogous to the management of active power, IDPRs can help to minimize reactive power flows in the PN. This can be observed in Figure 13, comparing reactive power flows per each of the three phases of the system and for all computational scenarios. As can be noted, since reactive power compensation is done at the SS level—where the IDPRs are installed—, the net reactive power exchanged at the point of connection of the PN with the external grid is not cancelled, due to reactive power consumption in MV lines and transformers. Such cancellation is not pursued in this case, since reactive power consumption guarantees that currents are delayed from voltage waveforms, favouring the proper operation of electrical protections.

The above described application of the IDPRs helps to reduce the loading of the transformers at SSs. As can be noted in Figure 14, in scenario (1), the transformer of the most important secondary substation (the first SS) is quite loaded, reaching almost 65% in loading. Thanks to the IDPR (see scenario (4)), the loading decreases down to 50% at most.

A similar effect can be experimented with while comparing scenarios (3) and (4), thus considering DG. In this case though, it is important to note that, without the inclusion of IDPRs, the deployment of DGs (scenario (3)) could be translated into higher loadings for transformers (see the loading for transformer in the third secondary substation) while compared to the base case, in which there is no DG (scenario (1)). For instance, the transformer in the third secondary substation in scenario (1) is loaded up to 20% during the central hours of the day, and its loading reaches up to 40% (so increases by a factor of 2) in scenario (3). With the inclusion of an IDPR in this SS, the loading of the transformer during the central hours of the day decreases down to 5% approximately (so decreases by a factor of 4 compared to the base case).

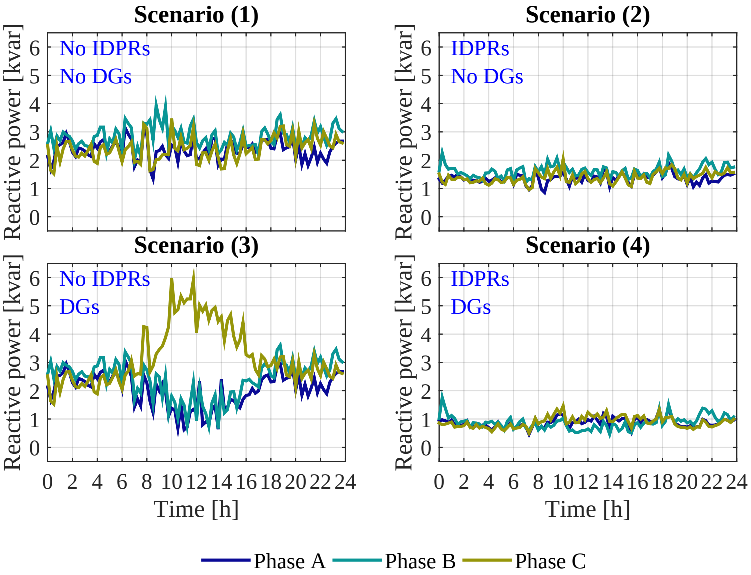


Figure 13. Net reactive power exchanged per phase with the external grid by the PN with and without including IDPRs.

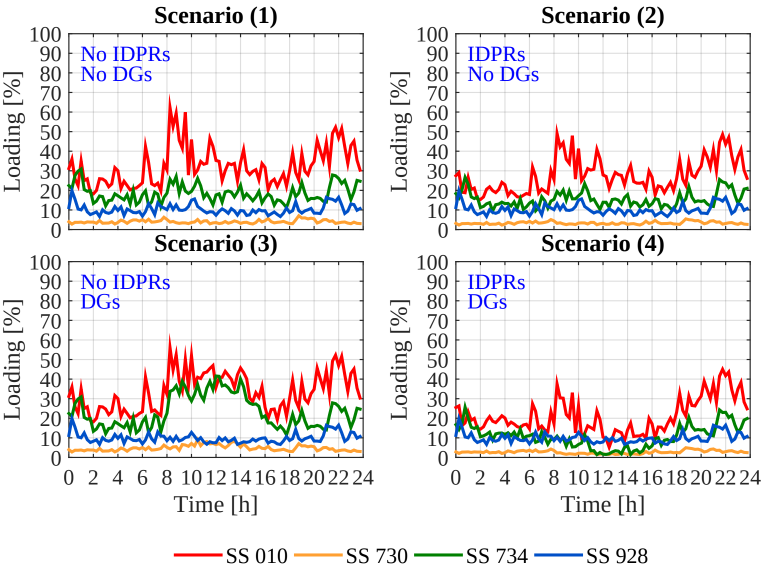


Figure 14. Transformer loading for each scenarios.

Thus, IDPRs, while providing the above described services, can greatly contribute to the integration of renewables, expand the useful life of infrastructures and make the most of their utilization.

It is important to note that other functionalities of IDPRs, such as those related to the exploitation of the embedded BESS, can serve to expand the applicability of these devices for the provision of other services, such as time shifting of active power flows for techno-economic optimization of the PN and improvement of security of supply to consumers.

5.2. IDPR Field Performance

This subsection presents the performance of the IDPR in the LV grid [26]. The waveform recording is carried out with an oscilloscope, and then the data is processed and treated with the mathematical software Matlab (R2014b, MathWorks, Natick, MA, USA).Four different scenarios are proposed in order to test the IDPR contributions to improve the power quality of the grid:

- The scenario (1) depicts an IDPR balancing the three-phase currents.
- The scenario (2) depicts an IDPR balancing the three-phase currents and compensating the reactive power.
- The scenario (3) depicts an IDPR mitigating the harmonic currents.
- The scenario (4) depicts an IDPR balancing the three-phase currents, compensating the reactive power and posteriorly dispatching 12 kvar.

The recorded three-phase voltage and current waveforms for each scenario are shown in Figures 15–18. Note that the voltage waveforms correspond to the phase-to-neutral voltage.

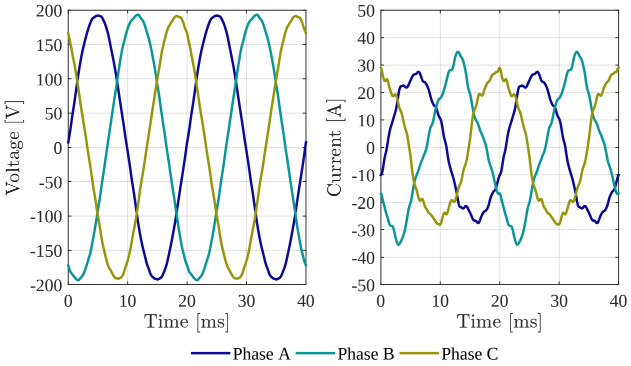


Figure 15. Voltage and current waveforms for scenario (1): balancing three-phase current from the consumptions.

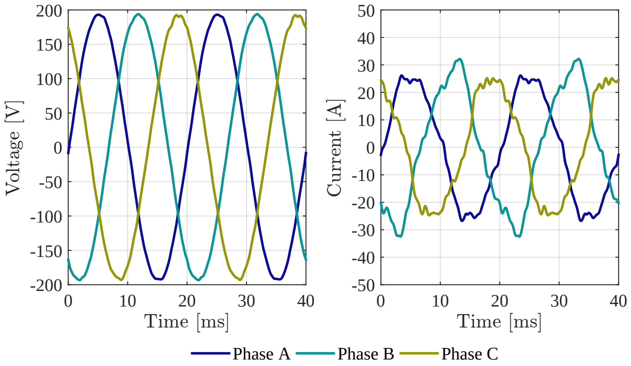


Figure 16. Voltage and current waveforms for scenario (2): balancing three-phase current and compensating the reactive power from the consumptions.

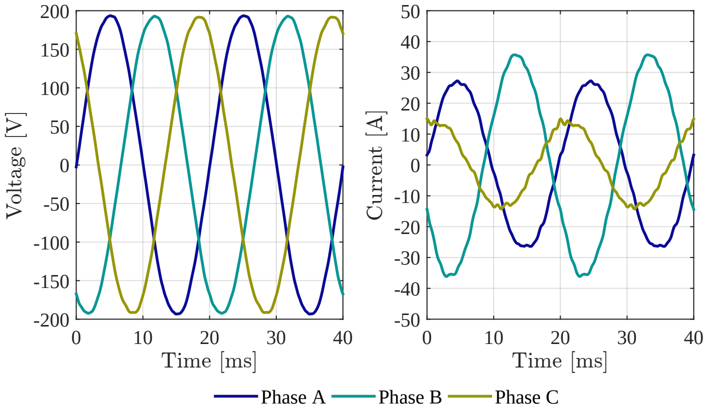


Figure 17. Voltage and current waveforms for scenario (3): mitigating the harmonics from the consumptions.

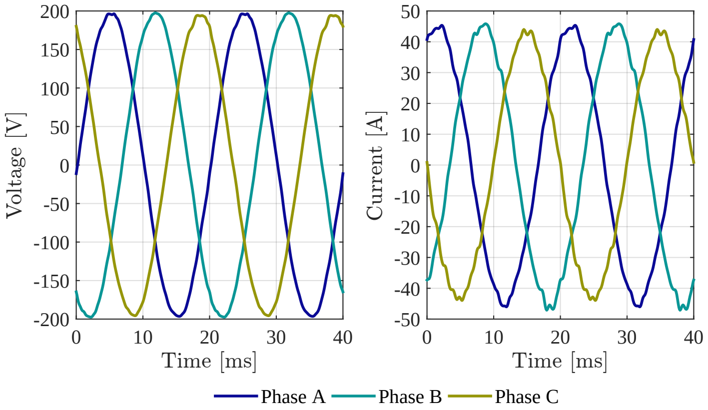


Figure 18. Voltage and current waveforms for scenario (4): mitigating the harmonic, balancing the three-phase currents, compensating the reactive power and posteriorly dispatching 12 kvar.

The voltage waveforms are sinusoidal and their Root Mean Square (RMS) value remain about 137 V in all scenarios and phase (which corresponds to 230 V phase to phase voltage RMS). Table 8 picks up for all scenarios their voltage and current RMS for each phase. It is possible to appreciate that the RMS voltage value lightly increases in scenario (4) because of the reactive power dispatching. In addition, note that the unbalanced current scenario is the third one.

On the other hand, the currents' waveforms are not completely sinusoidal, and also not equal in all scenarios, and their RMS value is also different. The main differences between them are described below. When scenario (1) is compared to scenario (2), the reactive power compensating capability is demonstrated. This particularity is observable in phase A, the phase difference between voltage and current waveforms is null in scenario (2) (see phase A from the right plot of Figure 16), while the phase difference is not null in scenario (1) (see phase A from the right plot of Figure 15). When scenario (1) is compared to scenario (3), the harmonic mitigating and current balancing capabilities are proven. The harmonic mitigating capability is easily observable in scenario (3) (see the right plot of Figure 17) where the current waveforms are much more sinusoidal than the previous scenarios (1) and (2). In scenario (3), it is also observable that the current balancing is disabled because the phase difference between phases A, B, and C is not constant (see phase B from the right plot of Figure 17) , while, in the rest of scenarios, this difference is constant and equal to $2\pi/3$ rad. Finally, when the previous scenarios are compared to scenario (4), the capability of dispatching reactive power is demonstrated (see the right plot of Figure 18. In this last scenario, the RMSs of current waveforms are equal and bigger than previous cases because of this dispatching.

Table 8. Voltage and current Root Mean Square (RMS) values.

Parameter	Scenario	Phase A	Phase B	Phase C
Voltage	(1)	137.38 V	137.60 V	135.75 V
	(2)	137.54 V	137.96 V	135.97 V
	(3)	138.10 V	137.14 V	136.48 V
	(4)	140.05 V	140.54 V	138.32 V
Current	(1)	19.25 A	21.31 A	19.87 A
	(2)	18.51 A	20.55 A	18.07 A
	(3)	19.32 A	25.25 A	9.95 A
	(4)	31.78 A	32.20 A	30.64 A

The IDPR contributes to reducing the asymmetrical losses and diminishing the operational stress of the distribution transformer. In order to validate this contribution, the Total Harmonic Distortion (THD) from the voltage and current, the power factor and the degree of unbalance are calculated. The degree of unbalance is defined as the part of the total current that corresponds to each phase [26]. Table 9 presents the results with and without the IDPR contribution. In case of the voltage THDs, this fulfills the power quality requirements, which are defined as EN 50160 [60]. In addition, the THD is reduced around 1.5% after the harmonic mitigation. In the case of the current THDs, this is moderate and experiences a significant improvement thanks to the IDPR, reducing the initial situation to 6.5%. This contribution is what provokes a reduction of the voltage THDs. In the case of the power factors, the IDPR contribution is easily detectable, increasing any power factor to the unit. Finally, in case of the degree of unbalance, it is also noteworthy that the IDPR balances the three-phase currents.

Table 9. Real measurements for proving the IDPR contributions.

Parameter	IDPR Contribution	Phase A	Phase B	Phase C
THD of voltage	No contributing	1.66%	2.52%	2.09%
	Contributing	1.46%	1.50%	1.50%
THD of current	No contributing	12.42%	17.09%	15.83%
	Contributing	6.44%	6.54%	6.77%
Power factor	No contributing	0.9949	0.8380	0.6005
	Contributing	0.9999	0.9982	0.9910
Degree of unbalance	No contributing	35.5%	46.3%	18.2%
	Contributing	33.6%	34.0%	32.4%

5.3. The Dimensioning of IDPRs

This subsection presents the methodology to size the IDPRs, according to the magnitude of the existing power flows in the network and addressing the new operation modes for the grid, as previously defined in Section 4. The PN currently feeds 25 consumers, who have an overall contracted power of 150 kW [39]. Figure 10 presents the total apparent power fed by each secondary substation and the network. However, the total consumption peak of the whole PN does not exceed 30 kVA, as can be seen in Figures 10 and 19. Furthermore, as introduced in Section 2.2, the MV grid of the PN distributes at 5 kV and the step down transformers in each SS permits interfacing to the final users at 230 V or 400 V. Such characteristics will be translated into the modelling of the PN in the following section.

While assessing the introduction of IDPRs into the PN, one should consider that these back-up resources could be eventually operated in master mode. Such operation mode greatly influences the required power and energy storage capacities for IDPRs, as in such circumstances an IDPR could even ensure the supply for the whole PN. Accordingly, even the proposed computational scenarios consider the operation of the IDPRs in slave mode, and their sizing should be a function of the requirements while in master mode.

The minimum power capacity for an IDPR in isolated mode is defined from the analysis of the demand patterns presented in Figure 10. A probabilistic analysis of the above-mentioned profiles shows that the PN value does not exceed 18.7 kVA (see the maximum value of the last box-plot representation in Figure 19). Therefore, 18.7 kVA is determined as a threshold level for the minimum power capacity for an IDPR, which is required for isolating the whole system. Note that, from this minimum sizing, a 50% security factor has been applied, in order to ensure the right operation of the power electronics under electrical transients, e.g., transformer and load inrush currents. As a result, the rated power should be set at 30 kVA. Thus, a 30 kVA IDPR is able to energise and maintain balanced the whole PN. Despite a 30 kVA IDPR could energise the whole PN at the same time, a good strategy for reducing the electrical transients during the energisation process is to energise step by step the network, starting with the biggest SS. According to Figure 19, it is also possible to size IDPRs for different autonomous sectors. For example, the required power should be about 20 kVA for S1, 30 kVA for S1 and S2, 5 kVA for S3, and 15 kVA for S2 and S3.

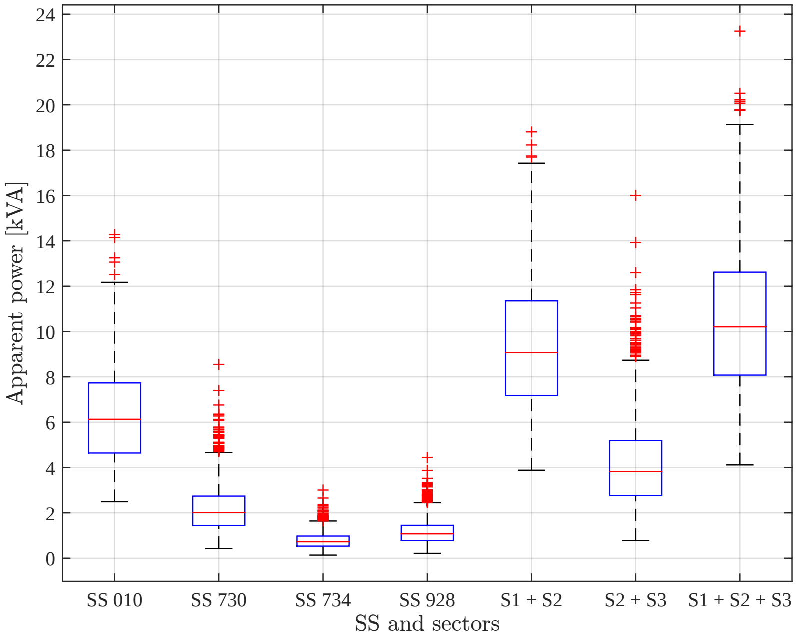


Figure 19. Statistic analysis of power demand profiles in the PN through box plots. For the sake of clarity, the red central mark indicates the median, and the bottom and top edges of the blue box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the red "+" symbol.

In addition, the energy capacity for an IDPR in master mode should be enough to supply the loads of the PN during different horizons. In particular, four cases are considered, taking into account that the rural distribution grid non supplied times are greater than urban ones. In particular, the four different frames are analysed at one, two, three and four hours. Figure 20 shows a probabilistic analysis of the consumed energy during these defined frames in the PN, from the power profiles in Figure 10. In addition, Table 10 picks up the maximum energy demands for the 95% of the cases.

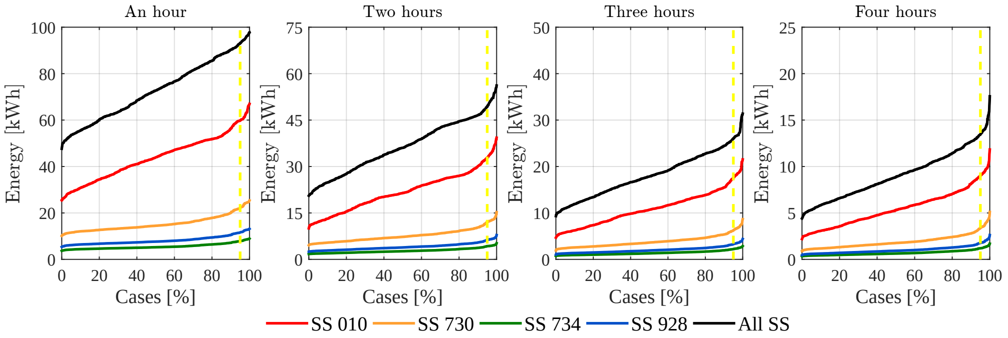


Figure 20. Probabilistic analysis of energy demand profiles in the PN.

Table 10. Energy consumption (in 95% of cases) for each SS and according to the sector configurations.

SS	An Hour	Two Hours	Three Hours	Four Hours
SS 010 (S1)	9.91 kWh	19.39 kWh	36.21 kWh	65.81 kWh
SS 730	3.35 kWh	6.26 kWh	12.05 kWh	22.19 kWh
SS 734	1.19 kWh	2.21 kWh	4.37 kWh	7.85 kWh
SS 928 (S3)	1.77 kWh	3.26 kWh	6.28 kWh	11.61 kWh
S1 + S2	11.99 kWh	23.10 kWh	43.47 kWh	79.30 kWh
S2 + S3	4.74 kWh	8.73 kWh	16.84 kWh	31.08 kWh
S1 + S2 + S3 (all SS)	13.75 kWh	26.36 kWh	49.76 kWh	90.91 kWh

6. Conclusions

The presented architecture tackles the modernization of traditional rural networks into new Smart Grid ones, addressing innovation actions on both the power plane and the management plane of the system. In the management plane, one principal feature of the architecture is that it permits decentralizing the operation of the network either while grid connected or isolated. In addition, the proposed architecture can be easily replicated along large areas since it is integrated through communications. As long as the capabilities of such telecom networks are powerful enough, the management system can integrate large controllable equipment in the network, such as distributed storage and power electronics, making the system greatly scalable. Furthermore, this decentralization increases the reliability and self-healing aspects of the system since the intelligence is allocated into diverse agents through the network that can act even autonomously in case of any fault. Such advantages are beyond typical working practices for grid operators in weak rural systems.

In the power plane, the innovative IDPRs result as a key technology for the realization of the proposed architecture. IDPRs are modular by design, and this facilitates their scalability to large networks as required. IDPRs can provide different services such as harmonic and reactive currents' compensation (see the low level of current harmonic distortion, 6.5%, achieved in field tests with IDPR), current balancing, energy back-up and network restoration, among others. These services greatly contribute to ensuring a power quality and security of supply to customers; to enhance the integration of renewables; and to expand the useful life of grid infrastructures. For instance, as derived from the results of the study case, by balancing currents and compensating reactive power flows through the three-phase distribution system of the PN, the IDPR can reduce inaccurate planning for the provision of supply to consumers. In addition, it can alleviate the inconveniences for the DSO due to unplanned DG deployment and the uncertainty in the consumers' habits.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASD	Automated Switch-Disconnector
BESS	Battery Energy Storage System
C1	Circumstance 1 (operating connected to the EG)
C2	Circumstance 2 (operating disconnected from the EG)
C3	Circumstance 3 (in blackout conditionts)
DG	Distributed Generation
DSO	Distribution System Operator
EG	External Grid
EMS	Energy Management System
EMU	Electrical Measurement Unit
EPS	Electrical Power Switch
FOC	Fiber Optics Communication
GEMS	Global Energy Management System
GPRS	General Packet Radio System
GS	Auxiliary diesel generator
IDPR	Intelligent Distribution Power Router
IEC	International Electrotechnical Commission
IP	Internet Protocol
LC	Local Controller
LV	Low Voltage
LEMS	Local Energy Management System
MV	Medium Voltage
OPF	Optimal Power Flow
PLC	Power Line Communications
PN	Pilot Network
RADIUS	Remote Authentication Dial-In User Service
RIP	Routing Information Protocol
RTU	Remote Terminal Unit
RMS	Root Mean Square
S1	Sector 1 (comprises only the SS 010)
S2	Sector 2 (comprises SSs 730 and 734)
S3	Sector 3 (comprises only the SS 928)
SCADA	Supervisory Control and Data Acquisition
SFTP	Secure File Transfer Protocol
SNMP	Simple Network Management Protocol
SS	Secondary Substation
SSH	Secure Shell

SRG	Smart Rural Grid
TC	Transformer Controller
THD	Total Harmonic Distortion
TN	Telecommunications Networks
VPN	Virtual Private Network
WLC	Wireless Communications
WiMAX	Worldwide Interoperability for Microwave Access
XOC	Xarxa Oberta de Catalunya

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2.3 Summary

One principal feature of the presented architecture is that it permits decentralizing the network operation either while grid-connected or grid-discon-nected. In addition, it can be easily replicated and greatly scalable along large areas as long as the capabilities of such telecommunication networks are powerful enough. The management system can also easily integrate controllable equipment in the network, such as distributed storage and power electronics. This decentralized architecture has increased the reliability and self-healing aspects of the system since the intelligence is allocated into diverse agents through the network that can act even autonomously in case of any fault. Such advantages are beyond typical working practices for grid operators in weak rural systems.

Chapter 3

Optimization of the operation of Smart Rural Grids through a Novel Energy Management System

3.1 Introduction

This chapter is based on the second Thesis goal and also corresponds to a journal paper [46]. It proposes an innovative Energy Management System (EMS) that optimizes the grid operation based on economic and technical criteria. The presented methodology takes into account demand and renewable generation forecasts, electricity prices and the status of distributed storages. The EMS performance has been evaluated from both a technical point of view and an economic perspective through some scenarios and diverse proposed metrics. They are based on a real rural grid from the Smart Rural Grid project, varying the penetration of distributed generation.

3.2 Publication

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Article

Optimization of the Operation of Smart Rural Grids through a Novel Energy Management System

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Abstract: The paper proposes an innovative Energy Management System (EMS) that optimizes the grid operation based on economic and technical criteria. The EMS inputs the demand and renewable generation forecasts, electricity prices and the status of the distributed storages through the network, and solves with an optimal quarter-hourly dispatch for controllable resources. The performance of the EMS is quantified through diverse proposed metrics. The analyses were based on a real rural grid from the European FP7 project Smart Rural Grid. The performance of the EMS has been evaluated through some scenarios varying the penetration of distributed generation. The obtained results demonstrate that the inclusion of the EMS from both a technical point of view and an economic perspective for the adopted grid is justified. At the technical level, the inclusion of the EMS permits us to significantly increase the power quality in weak and radial networks. At the economic level and from a certain threshold value in renewables' penetration, the EMS reduces the energy costs for the grid participants, minimizing imports from the external grid and compensating the toll to be paid in the form of the losses incurred by including additional equipment in the network (i.e., distributed storage).

Keywords: rural electrical grids; energy management system; energy storage; distributed generation

1. Introduction

In the 1990s, the stiff and vertical monopolistic electrical system in Europe experienced a transformation, evolving into a new, more flexible and competitive system based on market aspects [1]. In this new reality the electricity producer decided (and still decides) when and how much to produce, and how to plan and implement their plant maintenance programs [1]. From then on, the traditional unidirectional grid, generally used to carry power from few and far power plants to many clients, is moving to a new modern grid, that integrates scatter and smaller generators throughout the territory. Consequently, modern electric grids combine scatter and smaller generators (even at consumers' location) with the conventional architecture of the power system [2]. As a result, electrical networks are experiencing bidirectional power flows through distribution grids that impose new challenges for network operation.

To properly manage modern grids, new management strategies for network operators are needed [3–5] and the implementation of these management tools are transforming grids into Smart Grids (SGs) [6]. The term energy management was firstly related to those tools managing the demand in grids [7–9]. In 1980s the term Demand-Side Management (DSM) was presented by Clark W. Gellings in [7]. The DSM focuses on the idea of influencing customers, through a set of interconnected and flexible programs based on energy efficiency, energy conservation and sustainable development.

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These programs incentive customers to shift their electricity demand to low energy price periods, and to reduce their overall consumption [8]. From this first conception, the field of energy management evolved to include also the supply-side management, thus yielding the general concept of the Energy Management System (EMS), also known as grid energy management or smart energy management system [3,4,8–13]. The EMS turned out to optimize the energy usage at different levels: generation, transmission, distribution and consumption, to ensure an efficient, thrifty and sustainable system [8]. Literature around the development of EMSs is very extensive. In general terms, and despite the diversity of EMSs, it can be concluded that from the formulation point of view the main optimization objective for EMSs is to find a compromise between generation and demand bids, matching the offer with the demand, while minimizing costs or maximizing profits for the agents involved [12]. EMSs are integrated in different architectures, which can be classified mainly as centralized or decentralized (also called distributed) [12,14]. The proposed architectures are in turn constituted by different players (or agents) [15]. An agent is a software (or hardware) that pursue its objectives, being able to react rapidly to the changes, and negotiate, cooperate and compete with others [12,14,15].

The most common architectures are centralized. They are featured to be completely supervised and managed by a central agent (or agents, thus resulting into a Multi-Agents System (MAS) [14,16–18]), in a master-slave relationship. This requires a high computing capacity and a stable and fast communication system [3,19]. The goals for these central agents focus on diverse aspects such as optimizing the generation power scheduling, the DSM and the operation of storage units, all reducing the emissions and improving the power quality. These may be implemented in residential systems [20,21], grid-connected microgrids [16,22–25] and isolated systems [22–26]. Centralized MAS architectures can manage large microgrids or distribution grids [17,22,27,28], and even power the system as a whole [29,30].

In contrast, decentralized architectures are a collection of management agents who are usually deployed at local controllers of Distributed Energy Resources (DERs) [14]. Typically, distributed architectures are characterized to be faster, more flexible, reliable and independent than centralized ones, resulting into lower risk of system failure (i.e., improved reliability), enhance scalability and with less information between agents [3,14]. On the other hand though, coordination between agents is more complex than in centralized architectures, adding complexity to the overall design of the solution. Decentralized architectures may be good options, for instance, in microgrids with a wide range of DER [14,31,32].

In EMSs for distribution grids, management optimizations are primarily expressed addressing economic terms, leaving technical aspects, such as frequency and voltage stability, to other and/or secondary management procedures [27,33–36]. This is because of the existence of dedicated capacities and markets in networks to answer these needs. In particular, frequency and voltage support in networks are included within the so called ancillary services, and these are provided by contracted generators and large consumers for these purposes [1]. The coordination of such services is conventionally managed by the Transmission System Operator (TSO) of the network. However, the inclusion of large amounts of distributed generation in medium and low voltage distribution grids is forcing also Distribution System Operators (DSOs) to develop new tools so as to maintain the required stability and quality in their networks, as the transmission system operator does.

This is particularly important in weak or rural distribution networks. Indeed, distributed generation in rural grids can provoke overvoltages in radial lines and this is something to be solved by the DSO, among other technical issues [32,37–39]. In fact, the absence of management tools in such networks and the weak infrastructures installed for the few and dispersed consumers make these grids as perfect candidates to experience overvoltages, load unbalances among the three phase distribution system, undesired reactive power flows, harmonics, and unavailabilities due to short-circuits and other types of eventualities, all affecting the power quality and security of supply for customers. Accordingly, the management tools for DSOs, especially in rural grids, should not be only based on economic criteria so as to optimize the grid operation. Instead, they should also perform a power dispatch among the loads and generators in the grid considering other aspects that ensure a proper system stability, quality and reliability.

Addressing the need of developing new tools for the proper management of modern rural distribution grids, this paper proposes a new EMS to be executed by the DSO and that optimizes the grid operation based, simultaneously, on an economic criterion (i.e., the minimization of the global operating costs) and a technical criterion (i.e., the maintenance of the required quality in the service level). The combination of the two optimization criterion resulting in a novel EMS is one of the two contributions of the paper. The proposed EMS adopts a centralized architecture where a central MAS system manages the optimization of the system addressing economic criterion. In addition, technical aspects related to power quality are addressed by distributed management agents through the network at DERs. Such architecture permits us to exploit the main advantages of centralized ones (e.g., easy coordination of the different DERs) with the advantages of distributing some management duties through DERs (e.g., fast reaction against eventualities, enhanced flexibility and scalability of the solution). Altogether, this permits us to effectively address the needs of rural distribution networks. The second contribution is the formulation of diverse quantitative metrics so as to evaluate the performance of the proposed management tools for improving the grid operation. The proposed EMS is to be tested using real data from a rural distribution grid. This grid is actually being used as a demonstration site for the concepts presented in this paper, in the frame of the FP7 European research project Smart Rural Grid.

2. The Proposed Energy Management System for Rural Grids

The energy management system is composed by diverse agents, which from a top-down approach are: (i) the Global Energy Management System (GEMS); (ii) the Supervisory Control and Data Acquisition (SCADA); (iii) the Local Energy Management Systems (LEMSs); (iv) the Local Controller (LC); (v) Transformer Controllers (TCs) and finally, at the bottom of the structure there are all manageable and controllable equipment.

All of them configure a system in the form of that presented in Figure 1. As can be observed the different agents of the system are distributed into three management levels. At the top level there are the SCADA and the GEMS. Both agents are the responsible of the proper operation of the whole Distribution Network (DN). At the intermediary layer there are LEMSs and LCs. These two types of agents are in charge of the operation of limited parts of the DN. Finally, at the bottom level there are the TCs that manage and control Secondary Substations' (SS) equipment. Depending on the relevance of each SS, an area can collect one or more SSs.

The management agents in Figure 1 are also classified in terms of their programmability (see the color code). In this regard, the SCADA is the agent with the highest level of programmability. It is a rule-based system supervised and managed by the DSO.

Just below the SCADA there are the GEMS and the LEMS. In terms of programmability, these agents determine the series of active and reactive power setpoints for optimizing the whole or part of the rural DN. Also, they calculate, on a one minute basis, the setpoints to manageable and controllable equipment, such as some Distributed Generators (DG), Controllable Distributed Loads (CDL), Diesel Generators (GS) and back-up resources (or, as named, Intelligent Distributed Power Routers (IDPRs), with Battery Energy Storage Systems (BESS)).

The IDPR is a power converter that improves the power quality and if it allocates a BESS, then it also manages energy packages. The main challenge of the IDPR in terms of power quality is to compensate for unbalanced currents (of the three-phases), compensating reactive power and cancelling the harmonic content of currents at coupling point, in a slave mode. Also the IDPR can storages energy from distributed generation and provides it during pick hours or during a supply disruption, since the IDPR is the responsible to restore the supply in the network providing a voltage and frequency of the local set, in a master mode [40,41].

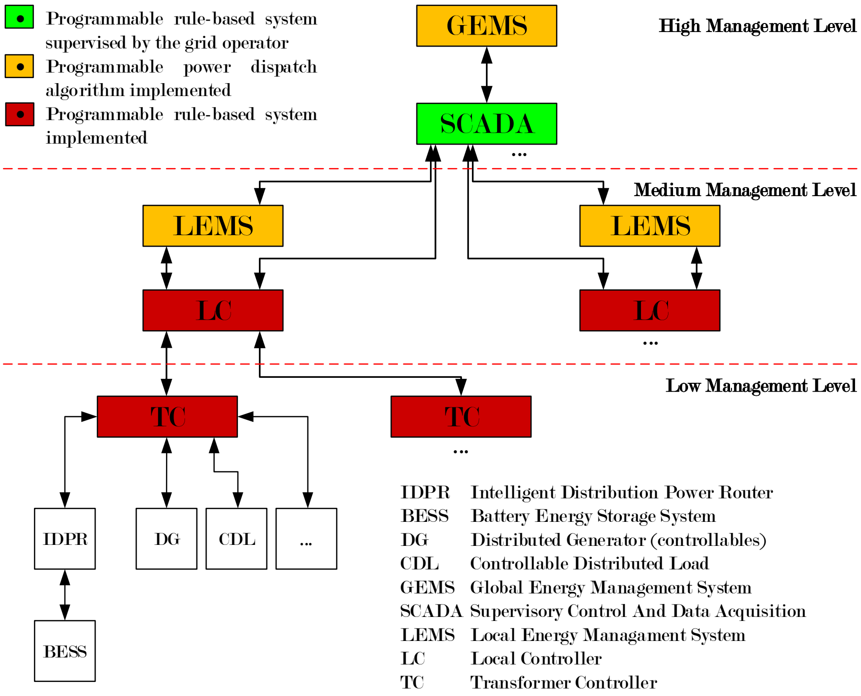


Figure 1. The multi-agent management system for the smart rural grid.

Finally, the LCs and TCs are programmable rule-based devices that exchange information and setpoints with the back-up resources, DGs, CDLs, GSs, as well as with control and protection devices. It is important to note that the programmable rule-based systems implemented in LCs and TCs ensure a proper operation during an eventuality in the communications' network.

This paper focus on the GEMS agent while managing the whole DN. To do so, this agent optimizes the operation of the network in two main steps. The first step—called economic optimization hereinafter, solves an optimal economic dispatch for the controllable sources and loads in the network. Since economic, the optimization is based on market aspects, availability and cost of DGs and back-up resources. The second step, and from the inputs of the first one, adjusts the active and reactive power dispatch for DGs and back-up resources considering technical aspects such as power losses and voltage variations, thus performing an Optimal Power Flow (OPF) [42]. This paper develops these two management steps performed by GEMS under the operational circumstance that the rural grid being managed is not isolated, but connected to the main grid of the rest of the territory.

So more in detail, the GEMS performs the following tasks: (i) generates the consumption and generation forecasts for the whole system and for a time horizon of 24 h; (ii) with this time horizon, executes the global economic optimization; (iii) executes the optimal power flow function of the global economic optimization setpoints and network technical constrains; (iv) outputs a file with the setpoints for controllable sources and loads for the following 24 h, in time steps of 15 min. Such time step is convenient for the integration of GEMS in some electrical markets worldwide [43,44]. The following Section 3 develops the presented objectives for GEMS step-by-step.

3. The Global Energy Management System

This section introduces the GEMS operation. Internally, the GEMS has three different modules addressing its objectives. The first module carries out forecasts. In particular, it determines the generated and consumed forecasts for active and reactive power for each SS. The second module (the Global Economic Optimization (GEO)) processes the price of electricity pool and sends it to SCADA. Also the GEO module calculates through a Mix Integer Lineal Programming (MILP) determines the power setpoints for controllable generators, loads and storages addressing an economic criterion. These setpoints are named global economic setpoints. Finally, these setpoints are processed in the third module of the GEMS, which is called the Global Technical Optimization (GTO) module. The GTO module adjusts through a Non-Lineal Programing (NLP) the global setpoints are according to the technical constraints, applying curtailments if required and adapting the reactive power, in order to smooth voltage variations and reduce the electrical losses. Finally the resulting setpoints, the global technical setpoints are sent to SCADA. The Figure 2 collects the described modules of GEMS and the time horizon for the processes they carry out. The following gives a deeper description of the GEMS.

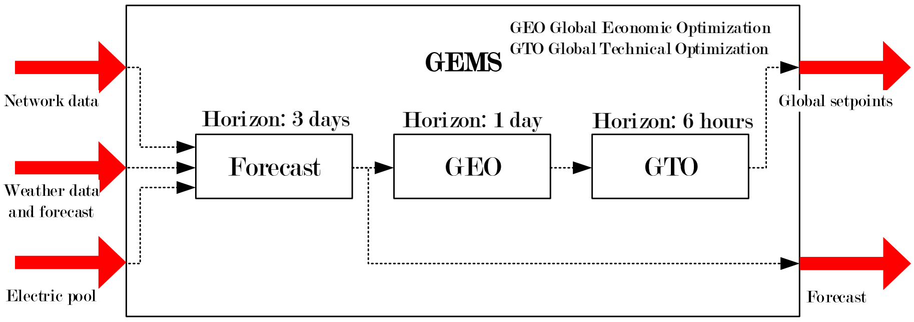


Figure 2. Global Energy Management System (GEMS) in detail.

3.1. Forecasts for the Whole System

Currently, the models to forecast the electrical consumption and generation, are tools that are developed for specific areas. They function in several aspects like, economic, weather, industry, population, market, technological development, among others [9]. In addition, in the literature there are several techniques that related all these inputs to determine the outputs. Commonly they can be classified into static or dynamic, univariate or multivariate and for the technique that they use. The most simple and frequent techniques are times series and regression models [9].

The aim of the article is not to advance in the knowledge field of the forecast methods. So the required forecasted data for GEMS operation has been derived from real data adding a random variability according real standard deviation. The root-mean-square of the error for simulated forecasted data is 10%. This is consistent with usual error magnitude provided by state-of-the art forecasting methods for wind and sun resources [9].

3.2. Global Economic Optimization Formulation

The Global Economic Optimization formulation is a MILP model that pursues DSO's goals. As noted in Figure 2, the GEO is the first optimization block in the GEMS algorithm. Its objective is to solve with an minimum energy cost for grid participants, and this is translated into a quarter-hourly dispatch for distributed resources. For GEO formulation the following hypotheses are considered:

- It optimizes the dispatch of active power for controllable elements in the network, assuming that the reactive power management is treated by the GTO.
- It assumes that the DN operates as a three-phase balanced system, so power flows among three phases of the DN are aggregated for optimization purposes. Such a balanced system is ensured by the action of the previously introduced IDPRs. The IDPR makes the unbalanced power flow downstream (i.e., in the low voltage network, where dispersed consumers and generators are located) as an aggregated balanced power flow upstream to be exchanged with the medium voltage DN.

- It also assumes that voltage levels remain in an acceptable range, thanks to the subsequent GTO actuation.
- It does not take into account the electrical losses of lines and transformers.
- It takes into account the performance of storage technologies. The efficiency in charging and discharging processes as well as the self-discharge phenomena are considered.
- The number and consumption of controllable loads is known.
- The number and output of programmable generators is known.
- The consumption and generation at SS feeder is aggregated, representing the behaviour of low voltage network.

Following contents present the input data, variables, mathematical constraints and the objective function for the GEO.

3.2.1. The Input Data

The input data for the mathematical problem is divided into sets (see Table 1), constants (see Table 2), costs (see Table 3), load parameters (see Table 4), DG parameters (see Table 5), and BESS (see Table 6).

Table 1. Summary of input data (sets).

Data	Description
T	Set of time periods $\{t_1, t_2, ...\}$
S	Set of locations $\{s_1, s_2, ...\}$
L	Set of distributed loads $\{l_1, l_2, ...\}$
L_C	Subset of CDL $\{l_{c1}, l_{c2}, ...\}$
G	Set of distributed generation $\{g_1, g_2, ...\}$
G_S	Subset of SDG $\{g_{s1}, g_{s2}, ...\}$
G_A	Subset of ADG. $\{g_{a1}, g_{a2}, ...\}$
G_P	Subset of PDG. $\{g_{p1}, g_{p2}, ...\}$
G_{PA}	Subset of PADG $\{g_{pa1}, g_{pa2}, ...\}$
B	Set of BESSs $\{b_1, b_2, ...\}$

Table 2. Summary of input data (constants).

Data	Description
$K_{\Delta t}$	Interval of time (h).
$K_{RP_{EG}}$	Rated power of EG transformer (kW).
$K^s_{RP_T}$	Rated power of transformer from SS s (kW), $[s \in S]$.

Table 3. Summary of input data (costs).

Data	Description
$K^t_{CNS_{DL}}$	Cost of energy non-supplied to DLs (also NCDGs) at time t (€ /kWh), $[t \in T]$.
$K^t_{CI_{EG}}$	Cost of energy imported from EG at time t (€ /kWh), $[t \in T]$.
$K^t_{CNG_{SDG}}$	Cost per energy non-generated by SDGs at time t (€ /kWh), $[t \in T]$.
$K^t_{CNG_{ADG}}$	Cost per energy non-generated by ADGs at time t (€ /kWh), $[t \in T]$.
$K_{CNG_{PDG}}$	Cost per energy non-generated by PDGs (€ /kWh).
$K^{g,s}_{CF}$	Cost per litre of fuel for generator g in a SS s (€ /l), $[g \in G_{PA}, s \in S]$.

Table 4. Summary of input data (DL parameters).

Data	Description
$K^{s,t}_{E_{NCDL}}$	Energy consumed by Non-Controlled Load (NCDL) from SS s at time t (kWh), $[s \in S, t \in T]$.
$K^{s,t}_{E_{IDPR}}$	Energy consumed by IDPRs from SS s at time t (kWh), $[s \in S, t \in T]$.
$K^{l,s}_{RP_{CDL}}$	Rated power of CDL l from SS s (kW), $[l \in L_C, s \in S]$.
$K^{l,s}_{N\Delta t_{CDL}}$	Number of steps required by CDL l_c from SS s (-), $[l \in L_C, s \in S]$.
$K^{l,s}_{TS_{CDL}}$	Start-up time of CDL l from SS s (h), $[l \in L_C, s \in S]$.
$K^{l,s}_{TE_{CDL}}$	End time of CDL l from SS s (h), $[l \in L_C, s \in S]$.

Table 5. Summary of input data (Distributed Generators (DG) parameters).

Data	Description
$K^{s,t}_{P_{NCDG}}$	Power generated by NCDG from SS s at time t (kW), $[s \in S, t \in T]$.
$K^{g,s,t}_{P_{SDG}}$	Power generated by SDG g from SS s at time t (kW), $[g \in G_S, s \in S, t \in T]$.
$K^{g,s,t}_{P_{ADG}}$	Power generated by ADG g from SS s at time t (kW), $[g \in G_A, s \in S, t \in T]$.
$K^{g,s,t}_{P_{PDG}}$	Power generated by SDG g from SS s at time t (kW), $[g \in G_P, s \in S, t \in T]$.
$K^{g,s}_{RP_{PDG}}$	Rated power of PDG g from SS s (kW), $[g \in G_P, s \in S]$.
$K^{g,s}_{N\Delta t_{PDG}}$	Number of steps required by PDG i from SS s (-), $[g \in G_P, s \in S]$.
$K^{g,s}_{TS_{PDG}}$	Start-up time of PDG g from SS s (h), $[g \in G_P, s \in S]$.
$K^{g,s}_{TE_{PDG}}$	End time of PDG g from SS s (h), $[g \in G_P, s \in S]$.
$K^{g,s}_{LRP_{PADG}}$	Lower rated power of PADG g from SS s (kW), $[g \in G_{PA}, s \in S]$.
$K^{g,s}_{URP_{PADG}}$	Upper rated power of PADG g from SS s (kW), $[g \in G_{PA}, s \in S]$.
$K^{g,s}_{FB_{PADG}}$	Fuel consumption related to the operation of PADG g from SS s (l/kW), $[g \in G_{PA}, s \in S]$.
$K^{g,s}_{FR_{PADG}}$	Fuel consumption related to the output of PADG g from SS s (l/kW), $[g \in G_{PA}, s \in S]$.
$K^{g,s}_{LFC_{PADG}}$	Lower fuel consumption limit of PADG g from SS s (l), $[g \in G_{PA}, s \in S]$.
$K^{g,s}_{UFC_{PADG}}$	Upper fuel consumption limit of PADG g from SS s (l), $[g \in G_{PA}, s \in S]$.

Table 6. Summary of input data (Battery Energy Storage Systems (BESS) parameters).

Data	Description
$K^{b,s}_{RP_{BS}}$	Rated power of BESS b from SS s (kW), $[b \in B, s \in S]$.
$K^{b,s,t}_{LSoC_{BS}}$	Lower SoC limit of BESS b from SS s at time t, $[b \in B, s \in S, t \in T]$.
$K^{b,s,t}_{USoC_{BS}}$	Upper SoC limit of BESS b from SS s at time t, $[b \in B, s \in S, t \in T]$.
$K^{b,s}_{C_{BS}}$	Capacity of BESS b from SS s (kWh), $[b \in B, s \in S]$.
$K^{b,s}_{0SoC_{BS}}$	Initial SoC of BESS b from SS s, $[b \in B, s \in S]$.
$K^{b,s}_{\sigma_{BS}}$	Self-discharging performance of BESS b from SS s, $[b \in B, s \in S]$.
$K^{b,s}_{\eta C_{BS}}$	Charging performance of BESS b from SS s, $[b \in B, s \in S]$.
$K^{b,s}_{\eta D_{BS}}$	Discharging performance of BESS b from SS s, $[b \in B, s \in S]$.

3.2.2. Variables

In turn, variables of global economic optimization problem are presented and classified into SS and EG variables (see Table 7), DSM variables (see Table 8), DG variables (see Table 9), and battery energy storage system variables (see Table 10).

Table 7. Summary of variables (secondary substations (SS) and EG variables).

Variable	Description
$x^{s,t}_{E_{SS}} \in \mathbb{R}$	Energy exchanged by a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{E_{DL}} \in \mathbb{R}^+$	Energy consumed by all DLs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{E_{DG}} \in \mathbb{R}^+$	Energy generated by all DGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{E_{BS}} \in \mathbb{R}$	Energy provided by all BESSs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{t}_{EI_{EG}} \in \mathbb{R}^+$	Energy imported from the EG at time t (kWh), $[t \in T]$
$x^{t}_{EE_{EG}} \in \mathbb{R}^+$	Energy exported to the EG at time t (kWh), $[t \in T]$
$x^{t}_{B_{EG}} \in \mathbb{B}$	Boolean variable indicating that the systems is importing energy from the EG at time t (-), $[t \in T]$

Table 8. Summary of variables (Demand-Side Management (DSM) variables).

Variable	Description
$x^{s,t}_{E_{CDL}} \in \mathbb{R}^+$	Energy consumed by all CDLs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{l,s,t}_{B_{CDL}} \in \mathbb{B}$	Boolean variable indicating that the CDL l associated to a SS s is consuming energy at time t (-), t, $[l \in L_C, s \in S, t \in T]$
$x^{s,t}_{ENS_{DL}} \in \mathbb{R}^+$	Energy not supplied to DLs associated to a SS s at time t (kWh), $[s \in S, t \in T]$

Table 9. Summary of variables (DG variables).

Variable	**Description**
$x^{s,t}_{E_{SDG}} \in \mathbb{R}^+$	Energy generated by all SDGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{E_{ADG}} \in \mathbb{R}^+$	Energy generated by all ADGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{E_{PADG}} \in \mathbb{R}^+$	Energy generated by all PADGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{s,t}_{ENG_{NCDG}} \in \mathbb{R}^+$	Energy not supplied by NCDGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{g,s,t}_{B_{SDG}} \in \mathbb{B}$	Boolean variable indicating that the SDG g associated to a SS s is generating energy at time t (-), $[g \in G_S, s \in S, t \in T]$
$x^{s,t}_{ENG_{SDG}} \in \mathbb{R}^+$	Energy not generated by SDGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{g,s,t}_{R_{ADG}} \in \mathbb{R} : [0,1]$	Proportion of energy generated by the ADG g associated to a SS s at time t (kWh), $[g \in G_A, s \in S, t \in T]$
$x^{s,t}_{ENG_{ADG}} \in \mathbb{R}^+$	Energy not generated by ADGs associated to a SS s at time t (kWh), $[s \in S, t \in T]$
$x^{g,s,t}_{B_{PDG}} \in \mathbb{B}$	Boolean variable indicating that the PDG g associated to a SS s is generating energy at time t (kWh), $[g \in G_P, s \in S, t \in T]$
$x^{s}_{ENG_{PDG}} \in \mathbb{R}^+$	Energy not generated by PDGs associated to a SS s (kWh), $[s \in S, t \in T]$
$x^{g,s,t}_{B_{PADG}} \in \mathbb{R}^+$	Boolean variable indicating that the PADG g associated to a SS s is generating energy at time t (-), $[g \in G_{PA}, s \in S, t \in T]$
$x^{g,s,t}_{R_{PADG}} \in \mathbb{R} : [0,1]$	Proportion of energy consumed by PADG g associated to a SS s at time t (-), $[g \in G_{PA}, s \in S, t \in T]$
$x^{g,s}_{F_{PADG}} \in \mathbb{R}^+$	Fuel consumed PADG g associated to a SS s (l), $[g \in G_{PA}, s \in S, t \in T]$
$x^{g,s}_{FUU_{PADG}} \in \mathbb{R}^+$	Fuel saved by PADG g associated to a SS s (l), $[g \in G_{PA}, s \in S]$

Table 10. Summary of variables (BESS variables).

Variable	**Description**
$x^{b,s,t}_{EC_{BS}} \in \mathbb{R}^+$	Energy consumed by BESS b associated to a SS s at time t (kWh), $[b \in B, s \in S, t \in T]$
$x^{b,s,t}_{ED_{BS}} \in \mathbb{R}^+$	Energy discharged from BESS b associated to a SS s at time t (kWh), $[b \in B, s \in S, t \in T]$
$x^{b,s,t}_{SoC_{BS}} \in \mathbb{R} : [0,1]$	State of Charge of BESS b associated to a SS s at time t (-), $[b \in B, s \in S, t \in T]$

3.2.3. GEO Constraints

In turn constraints are also divided and formulated in four groups, (i) SSs and the EG, (ii) DSMs, (iii) DGs and (iv) BESSs constraints.

(i) SSs and EG constraints

The power balance constraint (1) determine the energy exchanged by each SS. This must be equal to the sum of the energy consumed and generated by customers, and the energy supplied (or consumed) by the storage systems. In addition, this also is bounded by the rated power of the SS transformer in (2). Then, in (3), the sum of all exchanged energy is equal to the difference between the imported and the exported energy from the EG. Finally, imported and exported energy from the EG are limited by the rated power of the EG transformer through (4) and (5), also ensuring that when one is positive the other is zero and vice versa.

$$x^{s,t}_{E_{SS}} = x^{s,t}_{E_{DL}} - x^{s,t}_{E_{DG}} - x^{s,t}_{E_{BS}} \quad \forall s, \forall t \tag{1}$$

$$-K^{s}_{RP_T} K_{\Delta t} \leq x^{s,t}_{E_{SS}} \leq K^{s}_{RP_T} K_{\Delta t} \quad \forall s, \forall t \tag{2}$$

$$x^{t}_{EI_{EG}} - x^{t}_{EE_{EG}} = \sum_{s \in S} x^{s,t}_{E_{SS}} \quad \forall t \tag{3}$$

$$x^{t}_{EE_{EG}} \leq K_{RP_{EG}} K_{\Delta t} x^{t}_{B_{EG}} \quad \forall t \tag{4}$$

$$x^{t}_{EI_{EG}} \leq K_{RP_{EG}} K_{\Delta t}(1 - x^{t}_{B_{EG}}) \;\; \forall t \tag{5}$$

(ii) DSM constraints

The energy consumed, as detailed in the (6), is the sum of the energy from non-controllable and controllable distributed loads, as well as the energy not supplied to loads. Typically, CDLs are characterized by their rated power and the time they are consuming energy. These two variables are bounded by Equation (7) (power) and Equation (8) (time). Finally, the Equation (9) restricts the consumption of CDLs for the time interval $[K^{l,s}_{TS_{CDL}}, K^{l,s}_{TE_{CDL}}]$ addressing starting times.

$$\begin{aligned} x^{s,t}_{E_{DL}} = K^{s,t}_{E_{NCDL}} + K^{s,t}_{E_{IDPR}} + x^{s,t}_{E_{CDL}} \\ - x^{s,t}_{ENS_{DL}} \;\; \forall s, \forall t \end{aligned} \tag{6}$$

$$x^{s,t}_{E_{CDL}} = \sum_{l \in L_C} K^{l,s}_{RP_{CDL}} K_{\Delta t} x^{l,s,t}_{B_{CDL}} \;\; \forall s, \forall t \tag{7}$$

$$K^{l,s}_{N\Delta t_{CDL}} = \sum_{t \in T} x^{l,s,t}_{B_{CDL}} \;\; \forall l \in L_C, \forall s \tag{8}$$

$$\begin{aligned} x^{l,s,t}_{B_{CDL}} = 0 \;\; \forall l \in L_C, \forall s, \\ \forall t \mid ((K^{l,s}_{TS_{CDL}} < K^{l,s}_{TE_{CDL}}) \cap (t < K^{l,s}_{TS_{CDL}} \cup t > K^{l,s}_{TE_{CDL}})) \\ \cup (((K^{l,s}_{TS_{CDL}} \geq K^{l,s}_{TE_{CDL}})) \cap (t > K^{l,s}_{TS_{CDL}} \cap t < K^{l,s}_{TE_{CDL}})) \end{aligned} \tag{9}$$

(iii) DG constraints

Equation (10) sums the energy generated by all different DG sources. Equation (11) fixes the generated and the non generated energy from NCDGs according to forecasts. The generated and non generated energy from SDGs are quantified by Equations (12) and (13), respectively. Similarly, generated and non generated energy by ADGs are quantified by Equations (14) and (15). Similarly to CDL Equations (7)–(9), Equations (16)–(19) determine the generated and non generated energy from PDGs in function of their rated power and operating times $[K^{g,s}_{TS_{PDG}}, K^{g,s}_{TE_{PDG}}]$. Finally, the energy generated by PADGs are determined by Equations (20)–(23). The total generation for each SS is determined by Equation (20), and Equation (21) limits the output power of PADGs according to their limitations. Further, the fuel consumption per each unit is calculated by Equation (22) and limitations in fuel usage are imposed by Equation (23).

$$\begin{aligned} x^{s,t}_{E_{DG}} = x^{s,t}_{E_{NCDG}} + x^{s,t}_{E_{SDG}} + x^{s,t}_{E_{ADG}} + x^{s,t}_{E_{PDG}} \\ + x^{s,t}_{E_{PADG}} \;\; \forall s, \forall t \end{aligned} \tag{10}$$

$$x^{s,t}_{E_{NCDG}} + x^{s,t}_{ENG_{NCDG}} = K^{s,t}_{P_{NCDG}} K_{\Delta t} \;\; \forall s, \forall t \tag{11}$$

$$x^{s,t}_{E_{SDG}} = \sum_{g \in G_S} K^{g,s,t}_{P_{SDG}} K_{\Delta t} x^{g,s,t}_{B_{SDG}} \;\; \forall s, \forall t \tag{12}$$

$$x^{s,t}_{ENG_{SDG}} = \sum_{g \in G_S} K^{g,s,t}_{P_{SDG}} K_{\Delta t}(1 - x^{g,s,t}_{B_{SDG}}) \;\; \forall s, \forall t \tag{13}$$

$$x^{s,t}_{E_{ADG}} = \sum_{g \in G_A} K^{g,s,t}_{P_{ADG}} K_{\Delta t} x^{g,s,t}_{R_{ADG}} \;\; \forall s, \forall t \tag{14}$$

$$x^{s,t}_{ENG_{ADG}} = \sum_{g \in G_A} K^{g,s,t}_{P_{ADG}} K_{\Delta t}(1 - x^{g,s,t}_{R_{ADG}}) \;\; \forall s, \forall t \tag{15}$$

$$x^{s,t}_{E_{PDG}} = \sum_{g \in G_P} K^{g,s}_{RP_{PDG}} K_{\Delta t} x^{g,s,t}_{B_{PDG}} \;\; \forall s, \forall t \tag{16}$$

$$k^{g,s}_{N\Delta t_{PDG}} \geq \sum_{t \in T} x^{g,s,t}_{B_{PDG}} \quad \forall g \in G_P, \forall s \tag{17}$$

$$\begin{aligned} x^{g,s,t}_{B_{PDG}} &= 0 \;\; \forall g \in G_P, \forall s, \\ \forall t \mid ((K^{g,s}_{TS_{PDG}} < K^{g,s}_{TE_{PDG}}) &\cap (t < K^{g,s}_{TS_{PDG}} \cup t > K^{g,s}_{TE_{PDG}})) \\ \cup \, (((K^{g,s}_{TS_{PDG}} \geq K^{g,s}_{TE_{PDG}})) &\cap (t > K^{g,s}_{TS_{PDG}} \cap t < K^{g,s}_{TE_{PDG}})) \end{aligned} \tag{18}$$

$$\begin{aligned} x^{s}_{ENG_{PDG}} = \sum_{g \in G_P} K^{g,s}_{RP_{PDG}} K_{\Delta t} \Bigg(& k^{g,s}_{N\Delta t_{PDG}} \\ & - \sum_{t \in T} x^{g,s,t}_{B_{PDG}} \Bigg) \;\; \forall s \end{aligned} \tag{19}$$

$$x^{s,t}_{E_{PADG}} = \sum_{g \in G_{PA}} K^{g,s}_{URP_{PADG}} K_{\Delta t} x^{g,s,t}_{R_{PADG}} \quad \forall s, \forall t \tag{20}$$

$$\begin{aligned} K^{g,s}_{LRP_{PADG}} x^{g,s,t}_{B_{PADG}} &\leq K^{g,s}_{URP_{PADG}} x^{g,s,t}_{R_{PADG}} \\ &\leq K^{g,s}_{URP_{PADG}} x^{g,s,t}_{B_{PADG}} \forall g \in G_{PA}, \forall s, \forall t \end{aligned} \tag{21}$$

$$\begin{aligned} x^{g,s}_{F_{PADG}} = \sum_{t \in T} K^{g,s}_{URP_{PADG}} (& K^{g,s}_{FB_{PADG}} x^{g,s,t}_{B_{PADG}} \\ & + K^{g,s}_{FR_{PADG}} x^{g,s,t}_{R_{PADG}}) \;\; \forall g \in G_{PA}, \forall s, \forall t \end{aligned} \tag{22}$$

$$\begin{aligned} K^{g,s}_{LFC_{PADG}} - x^{g,s}_{FUU_{PADG}} &\leq x^{g,s}_{F_{PADG}} \\ &\leq K^{g,s}_{UFC_{PADG}} \;\; \forall g \in G_{PA}, \forall s \end{aligned} \tag{23}$$

(iv) BESS constraints

Completing the description of the constraints for the problem, BESS-related constraints are introduced in the following. Equation (24) defines E_{BS} as the subtraction between the energy consumed and injected to the grid by storages. In turn, these terms are limited by Equations (25) and (26), which are function of the rated power of the battery ($K^{b,s}_{RP_{BS}}$). In addition, the State of Charge (SoC) is bounded by Equation (27). The SoC is in function of the capacity of the battery ($K^{b,s}_{C_{BS}}$), the initial SoC ($K^{b,s}_{0SoC_{BS}}$), the self-discharge constant ($K^{b,s}_{\sigma_{BS}}$), and the charging and discharging efficiencies, ($K^{b,s}_{\eta C_{BS}}$) and ($K^{b,s}_{\eta D_{BS}}$) respectively.

$$x^{s,t}_{E_{BS}} = \sum_{b \in B} x^{b,s,t}_{ED_{BS}} - x^{b,s,t}_{EC_{BS}} \quad \forall s, \forall t \tag{24}$$

$$x^{b,s,t}_{EC_{BS}} \leq K^{b,s}_{RP_{BS}} K_{\Delta t} x^{b,s,t}_{B_{BS}} \quad \forall b, \forall s, \forall t \tag{25}$$

$$x^{b,s,t}_{ED_{BS}} \leq K^{b,s}_{RP_{BS}} K_{\Delta t} (1 - x^{b,s,t}_{B_{BS}}) \quad \forall b, \forall s, \forall t \tag{26}$$

$$K^{b,s,t}_{LSoC_{BS}} \leq x^{b,s,t}_{SoC_{BS}} \leq K^{b,s,t}_{USoC_{BS}} \quad \forall b, \forall s, \forall t \tag{27}$$

$$\begin{aligned} K^{b,s}_{C_{BS}} x^{b,s,t}_{SoC_{BS}} &= K^{b,s}_{C_{BS}} (K^{b,s}_{0SoC_{BS}} - K^{b,s}_{\sigma_{BS}}) \\ + x^{b,s,t}_{E_{BSC}} K^{b,s}_{\eta C_{BS}} &- \frac{x^{b,s,t}_{E_{BSD}}}{K^{b,s}_{\eta D_{BS}}} \;\; \forall b, \forall s, \exists t = t_0 \end{aligned} \tag{28}$$

$$\begin{aligned} K^{b,s}_{C_{BS}} x^{b,s,t}_{SoC_{BS}} &= K^{b,s}_{C_{BS}} (x^{b,s,t-\Delta t}_{SoC_{BS}} - K^{b,s}_{\sigma_{BS}}) \\ + x^{b,s,t}_{E_{BSC}} K^{b,s}_{\eta C_{BS}} &- \frac{x^{b,s,t}_{E_{BSD}}}{K^{b,s}_{\eta D_{BS}}} \;\; \forall b, \forall s, \forall t \neq t_0 \end{aligned} \tag{29}$$

3.2.4. The GEO Objective Function

The global economic objective function z_{GEO} has been chosen incorporating diverse criteria. Addressing the obligation for DSOs to cover the demand, the first summation of the objective function calculates the cost for the energy not supplied to DLs (including the non controllable DG). Note that the second to fourth summations are included in order to maximize DGs generation and manage them efficiently. Further, the fifth summation aims to minimize the cost related to fuel usage (including the wasted fuel). Finally, the last summation is added so as to minimize the cost related to energy imported from the EG.

$$
\begin{aligned}
[\min] z_{GEO} = & \sum_{s \in S, t \in T} K^{t}_{CNS_{DL}} (x^{s,t}_{ENS_{DL}} + x^{s,t}_{ENG_{NCDG}}) \\
& + \sum_{s \in S, t \in T} K^{t}_{CNG_{SDG}} x^{s,t}_{ENG_{SDG}} \\
& + \sum_{s \in S, t \in T} K^{t}_{CNG_{ADG}} x^{s,t}_{ENG_{ADG}} \\
& + \sum_{s \in S} K_{CNG_{DG}} x^{s}_{ENG_{PDG}} \\
& + \sum_{s \in S, g \in G_{PA}} K^{g,s}_{CF} (x^{g,s}_{F_{PADG}} + x^{g,s}_{FUU_{PADG}}) \\
& + \sum_{t \in T} K^{t}_{CI_{EG}} x^{t}_{EI_{EG}}
\end{aligned}
\tag{30}
$$

3.3. Global Technical Optimization

As noted in Figure 2, the Global Technical Optimization is the last optimization procedure in the GEMS. It receives the outputs from GEO and perform a process based on a NLP that provides the final setpoints for distributed resources according to the DSO's technical constraints. The GTO minimizes losses in the DN guaranteeing the dispatch solved by the GEO. The GTO also adjusts the reactive power from the IDPRs, and also readjust the active power from DGs and BESS in order to keep the voltage within acceptable range. The GTO goes under the following assumptions:

- The DN voltages and currents are balanced.
- Consumption and generation profiles are aggregated at each SS's feeder.
- The electrical loses of medium voltage lines and transformers are considered for optimization purposes.

The following presents the input data, variables, mathematical constraints and the objective function for the GTO.

3.3.1. The Input Data

The input data for the mathematical problem is divided into sets (see Table 11), constants and general (see Table 12), external grid parameters(see Table 13), and secondary substation parameters (see Table 14).

Table 11. Summary of input data (sets).

Data	Description
N	Set of nodes (all types)
N_{SS}	Subset of nodes from N that correspond to SSs.
N_{EG}	Subset of a node from N that corresponds to EG.

Table 12. Summary of input data (constants and general parameters).

Data	Description
K_{VW}	Weighting factor.
$K_{YG}^{c,d}$	Real part of admittance between node b and node c (S), $[c, d \in N]$.
$K_{YB}^{c,d}$	Imaginary part of admittance between node b and node c (S), $[c, d \in N]$.

Table 13. Summary of input data (EG parameters).

Data	Description
$K_{VM_{EG}}$	Voltage module of EG node c (kV), $[c \in N_{EG}]$.
$K_{VA_{EG}}$	Voltage angle of EG node c (kV), $[c \in N_{EG}]$.
$K_{RP_{EG}}$	Rated power of EG transformer from node c (kVA), $[c \in N_{EG}]$.

Table 14. Summary of input data (SS parameters).

Data	Description
$K_{RP_T}^c$	Rated power of transformer from node c (kVA), $[c \in N_{SS}]$.
$K_{RP_{BS}}^c$	Rated power of IDPR from node c (kVA), $[c \in N_{SS}]$.
K_{VM}^c	Desired voltage module for SS node c (kV), $[c \in N_{SS}]$.
K_{PC}^c	Active power consumed in node (includes the power consumed by NCDL, CDL and IDPRs) c (kW), $[c \in N_{SS}]$.
K_{QC}^c	Reactive power consumed in node (includes the power consumed by NCDL and CDL) c (kvar), $[c \in N_{SS}]$.
$K_{LPG_{DG}}^c$	Minimum threshold value for active power generation from DGs (NCDG) at node c (kW), $[c \in N_{SS}]$.
$K_{UPG_{DG}}^c$	Maximum threshold value for active power generation from DGs (total) at node c (kW), $[c \in N_{SS}]$.
$K_{LPG_{BS}}^c$	Minimum threshold value for active power generation from BESSs (charging) at node c (kW), $[c \in N_{SS}]$.
$K_{UPG_{BS}}^c$	Maximum threshold value for active power generation from BESSs (discharging) at node c (kW), $[c \in N_{SS}]$.

3.3.2. Variables

In turn, variables of global technical optimization problem are presented and classified into voltage and total power variables (see Table 15), EG variables (see Table 16), and SS variables (see Table 17).

Table 15. Summary of variables (voltage and total power variables).

Variable	Description
$x_{VM}^c \in \mathbb{R}^+$	Voltage module for node c (kV), $[c \in N]$
$x_{VA}^c \in \mathbb{R} : [-\pi, \pi]$	Voltage angle for node c (rad), $[c \in N]$
$x_{PT}^c \in \mathbb{R}$	Total active power from node c (kW), $[c \in N]$
$x_{QT}^c \in \mathbb{R}$	Total reactive power from node c (kvar), $[c \in N]$

Table 16. Summary of variables (EG variables).

Variable	Description
$x_{PI_{EG}} \in \mathbb{R}$	Imported active power from the EG (kW)
$x_{QI_{EG}} \in \mathbb{R}$	Imported reactive power from the EG (kvar)

Table 17. Summary of variables (SS variables).

Variable	Description
$x_{VE}^c \in \mathbb{R}$	Voltage excess for node c (kV), $[c \in N]$
$x_{PG_{DG}}^c \in \mathbb{R}^+$	Active power generated by DGs in node c (kW), $[c \in N]$
$x_{PG_{BS}}^c \in \mathbb{R}$	Active power injected by BESSs in node c (kW), $[c \in N]$
$x_{QG}^c \in \mathbb{R}$	Reactive power generated by IDPRs in node c (kvar), $[c \in N]$

3.3.3. GTO Constraints

In turn constraints are also divided and formulated in three groups, (i) voltage and total power, (ii) EG, (iii) SS constraints.

(i) Voltage and total power constraints

The voltage for all buses are calculated by Equations (31) and (32).

$$\begin{aligned} x^c_{PT} = x^c_{VM} \sum_{d \in N} x^d_{VM} \Big(& K^{c,d}_{YG} \cos(x^c_{VA} - x^d_{VA}) \\ & + K^{c,d}_{YB} \sin(x^c_{VA} - x^d_{VA}) \Big) \quad \forall c \in N \end{aligned} \tag{31}$$

$$\begin{aligned} x^c_{QT} = x^c_{VM} \sum_{d \in N} x^c_{VM} \Big(& K^{c,d}_{YG} \sin(x^c_{VA} - x^d_{VA}) \\ & - K^{c,d}_{YB} \cos(x^c_{VA} - x^d_{VA}) \Big) \quad \forall c \in N \end{aligned} \tag{32}$$

(ii) Constraints related to the EG bus

Active and reactive power balances at the EG bus are ensured by Equations (33) and (34), respectively. The active and reactive power balance for the rest of buses are ensured by Equations (35) and (36). Equation (37) establishes that the active and reactive power exchanged with the EG is less than the rated power of the EG transformer. The voltage module and angle of the EG bus is fixed by Equations (38) and (39), respectively.

$$x^c_{PT} = x_{PI_{EG}} + x^c_{PG_{DG}} + x^c_{PG_{BS}} - K^c_{PC} \quad \exists c \in N_{EG} \tag{33}$$

$$x^c_{QT} = x_{QI_{EG}} + x^c_{QG} - K^c_{QC} \quad \exists c \in N_{EG} \tag{34}$$

$$x^c_{PT} = x^c_{PG_{DG}} + x^c_{PG_{BS}} - K^c_{PC} \quad \forall c \notin N_{EG} \tag{35}$$

$$x^c_{QT} = x^c_{QG} - K^c_{QC} \quad \forall c \notin N_{EG} \tag{36}$$

$$K_{RP_{EG}}{}^2 \geq x_{PI_{EG}}{}^2 + x_{QI_{EG}}{}^2 \quad \exists c \in N_{EG} \tag{37}$$

$$x^c_{VM} = K_{VM_{EG}} \quad \exists c \in N_{EG} \tag{38}$$

$$x^c_{VA} = K_{VA_{EG}} \quad \exists c \in N_{EG} \tag{39}$$

(iii) Constraints related to SS buses

An excessive voltage level at SS buses is quantified by Equation (40). The active power generated by DGs is bounded by Equation (41). Similarly, the Equation (42) limits the active power injected from BESSs of IDPRs. The active power term can be negative and this means that the battery is consuming power. Therefore, the DG production could be reduced, the BESSs could dispatch or absorb energy. Finally, the active and reactive power supplied by IDPR is bounded by Equation (43) and the total power exchanged by a SS is bounded by the rated power of transformer through Equation (44).

$$x^c_{VE} = x^c_{VM} - K^c_{VM} \quad \forall c \in N_{SS} \tag{40}$$

$$K^c_{LPG_{DG}} \leq x^c_{PG_{DG}} \leq K^c_{UPG_{DG}} \quad \forall c \in N_{SS} \tag{41}$$

$$K^c_{LPG_{BS}} \leq x^c_{PG_{BS}} \leq K^c_{UPG_{BS}} \quad \forall c \in N_{SS} \tag{42}$$

$${K^c_{RP_{BS}}}^2 \geq {x^c_{QG}}^2 + {x^c_{PG_{BS}}}^2 \quad \forall c \in N_{SS} \tag{43}$$

$$K_{RP_T}^{c}{}^{2} \geq x_{PT}^{c}{}^{2} + x_{QT}^{c}{}^{2} \;\; \forall(c \in N_{SS} \cup c \notin N_{EG}) \tag{44}$$

3.3.4. The GTO Objective Function

The technical objective function z_{GTO} is divided into terms, the first one minimizes the imported energy from EG, thus indirectly minimizing the electrical losses and maximizing the active power generation from distributed resources. The second penalizes any excess or deficit in voltage for all buses through the weighting factor. This factor penalizes an excess of voltage in terms of active power ($K_{VW} >> 1$).

$$[\text{min}] \;\; z_{GTO} = \sum_{c \in N} x_{PT}^{c}{}^{2} + K_{VW} x_{VE}^{c}{}^{2} \tag{45}$$

4. Study Cases

For GEMS performance evaluation, different computational scenarios and metrics are proposed, and these are presented in the following.

4.1. Definition of Computational Scenarios

Twenty computational scenarios are proposed for evaluation. The scenarios are distributed in four blocks:

- **Case (i)**: The DN neither includes IDPRs neither BESSs, nor management tools.
- **Case (ii)**: The DN is equipped with IDPRs and BESSs, and the GEO, as a management tool.
- **Case (iii)**: The DN is equipped with IDPRs and BESSs and the GTO, as a management tool.
- **Case (iv)**: The DN is equipped with IDPRs and BESSs, as well as the GEO and the GTO as management tools.

Doing this, it is possible to evaluate the impact in network operational performance of adopting both the energy management algorithms proposed in this paper as well as the IDPRs, as distributed energy storage capabilities.

For each of the above presented blocks, five scenarios are proposed, each proposing different levels of renewables' penetration. In particular, DG penetration varies from 10% to 50% with respect to total contracted power in the network.The DG penetration is bounded in Spain up to 50% of total contracted power by current regulation [45].

The adopted DN is located in a rural zone of Catalonia [46]. This grid is actually being utilized as a demonstration site for the management tools and power electronics (the IDPR) presented in this paper. These demonstrations are being carried out in the frame of the FP7 European research project Smart Rural Grid. Figure 3 presents a single-phase diagram of this DN.

As can be noted, this is a rural distribution grid including 13 SSs. The consumers are of different types, including DLs, NCDLs and CDLs. The CDLs refers to electrical vehicles, water heaters, refrigerators. A penetration of about 25% of CDLs are integrated in each SS. Moreover, several types of DGs are included in the network: (i) non-controllable DGs (small or micro renewable generation like flow-hydraulic generation, photovoltaics and wind-based generation); (ii) switchable and adjustable DGs (renewable sources governed by microcontroller that regulate their power output; (iii) programmable DGs (fully governable generators such as combined heat and power generation systems); and iv) programmable and adjustable DGs (auxiliary sources like diesel, biomass, gasifiers, waste-to-energy generators). A representative daily profile for aggregated generation and consumption are presented in Figure 4.

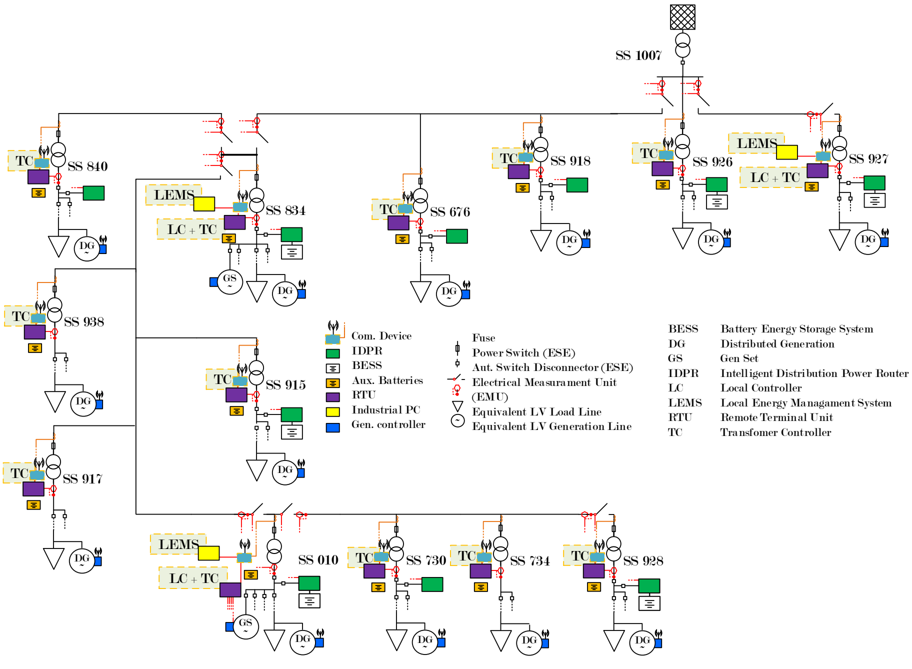
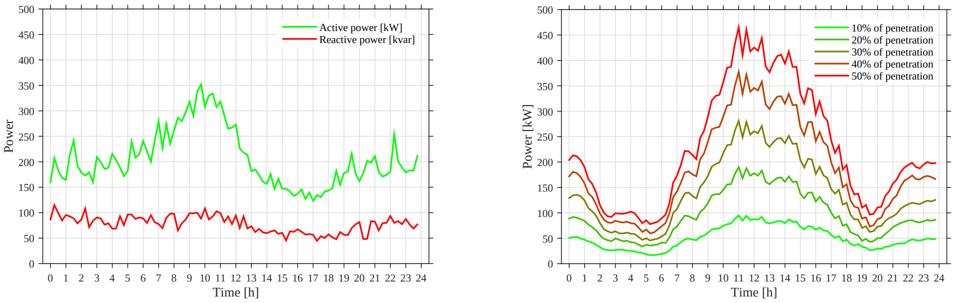


Figure 3. The whole rural distribution grid.



(**a**) (**b**)

Figure 4. Input data. (**a**): Total active and reactive power consumption of the whole DN. (**b**): Total active power generated by DGs of the whole DN per different renewables' penetration.

4.2. Power Quality Indicators and Metrics

This section introduces diverse quality indicators so as to evaluate the impact of including the management tools proposed in this paper. Similarly as for parameters and variables, quality indicators are divided into two groups, (i) secondary substation indicators (I_{SS}) (see Table 18), and (ii) distribution network indicators (I_{DN}) (see Table 19).

Table 18. SS related metrics (I_{SS}).

Indicator	Description
$I^s_{SS_1} \in \mathbb{R}^+$	Daily voltage variation at SS s (%), $[s \in S]$
$I^s_{SS_2} \in \mathbb{R}^+$	Daily reactive power respect to consumptions at SS s (%), $[s \in S]$
$I^s_{SS_3} \in \mathbb{R}^+$	Daily useful energy stored in BESSs at SS s (%), $[s \in S]$
$I^s_{SS_4} \in \mathbb{R}^+$	Daily curtailed from DGs at SS s (%), $[s \in S]$

Table 19. DN related metricss (I_{DN}).

Indicator	Description
$I_{DN_1} \in \mathbb{R}^+$	Daily distribution electrical losses (passive elements) (%)
$I_{DN_2} \in \mathbb{R}^+$	Daily electrical consumption of IDPRs (active elements) (%)
$I_{DN_3} \in \mathbb{R}^+$	Daily energy imported from the EG (%)

(i) SS related metrics

The indicator $I^s_{SS_1}$ expresses through Equation (46) the voltage width of the 95% of SS voltage module of a day ($x^{s,t}_{VM}$). This metric is formulated as in the EN 50160 standard [47]. Note in Equation (46) that K_{VM^b} is the nominal value of voltage for this bus. Analogously, the SS indicator $I^s_{SS_2}$ is related to the total reactive power over the active power consumption, and the SS indicator $I^s_{SS_3}$ determines the average energy discharged by batteries for each SS. Finally, the SS $I^s_{SS_4}$ expresses how much power is curtailed from the maximum power available from DGs for each SS.

$$I^s_{SS_1} = \Big(\text{Quantile}_{97.5\%}\left\{x^{s,t}_{VM}, \forall t\right\} - \text{Quantile}_{2.5\%}\left\{x^{s,t}_{VM}, \forall t\right\}\Big)\frac{100}{K_{VM^b}} \tag{46}$$

$$I^s_{SS_2} = \text{mean}\left\{\frac{K^{s,t}_{PC}}{x^{s,t}_{SC}}, \forall t\right\}100 \tag{47}$$

$$x^{s,t}_{SC} = \sqrt{{K^{s,t}_{PC}}^2 + {x^{s,t}_{QT}}^2} \tag{48}$$

$$I^s_{SS_3} = \frac{\sum_{t\in T} x^{s,t}_{ED_{BS}}}{K^s_{C_{BS}}}100 \quad \forall s : K^s_{C_{BS}} \neq 0 \tag{49}$$

$$I^s_{SS_4} = \frac{x^s_{ENG_{DG}}}{x^s_{ENG_{DG}} + \sum_{t\in T} x^{s,t}_{E_{DG}}} \tag{50}$$

$$x^s_{ENG_{DG}} = x^s_{ENG_{PDG}} + \sum_{t\in T}\left(x^{s,t}_{ENG_{SDG}} + x^{s,t}_{ENG_{ADG}}\right) \tag{51}$$

(ii) DN related metrics

The DN indicator $I^s_{DN_1}$ is calculated from the total electrical losses of the whole DN (from passive elements) divided by the total power consumption. Note that the energy losses from passive elements is determined by the Equation (53). The DN indicator $I^s_{DN_2}$ presents the percentage of the consumption of IDPRs and BESSs respect to the total power consumption. Note that the energy losses from the active elements is determined by the Equation (55). The DN indicator $I^s_{DN_3}$ determines how much power is imported from the EG respect to the total power consumption through Equation (56).

$$I_{DN_1} = \frac{\sum_{t\in T} x^t_{E_{PI_s}}}{\sum_{s\in S, t\in T} x^{s,t}_{PC}\Delta t}100 \tag{52}$$

$$x^{t}_{E_{PIs}} = \mathrm{Re}\left\{ \sum_{b\in B} x^{b,t}_{VM} e^{j x^{b,t}_{VA}} \left(\sum_{c\in B} (K^{b,c}_{YG} + jK^{b,c}_{YB}) x^{c,t}_{VM} e^{j x^{c,t}_{VA}} \right)^{*} \right\} \Delta t \tag{53}$$

$$I_{DN_2} = \frac{\sum_{t\in T} x^{t}_{E_{PIs}}}{\sum_{s\in S, t\in T} x^{s,t}_{PC} \Delta t} 100 \tag{54}$$

$$x^{t}_{E_{AIs}} = \sum_{s\in S} \left(K^{s,t}_{E_{IDPR}} + (1 - K^{i,s}_{\eta D_{BS}}) x^{s,t}_{E_{BSD}} + (1/K^{i,s}_{\eta C_{BS}} - 1) x^{s,t}_{E_{BSC}} + K^{i,s}_{C_{BS}} K^{i,s}_{\sigma_{BS}} \right) \tag{55}$$

$$I_{DN_3} = \frac{\sum_{t\in T} K_{\Delta t} x^{t}_{PI_{EG}}}{\sum_{s\in S, t\in T} x^{s,t}_{PC} \Delta t} 100 \tag{56}$$

4.3. Simulation Results

This subsection depicts the simulation results for the four blocks of scenarios, which in turn include five levels of DG penetration. As a reminder, each of the four cases are characterized by including different energy management tools and energy storage devices.

Graphical results are structured in the following Figures (Figures 5–8). Figure 5 plots the power exchanged (both active and reactive) with the EG for each of the four cases of scenarios. Analogously, Figure 6 plots the power losses. In addition, Figure 7 presents the the voltage in SS 834, 915, 010 and 928. Figure 8 plots the SoC of BESS at SS 834, 915, 010 and 928.

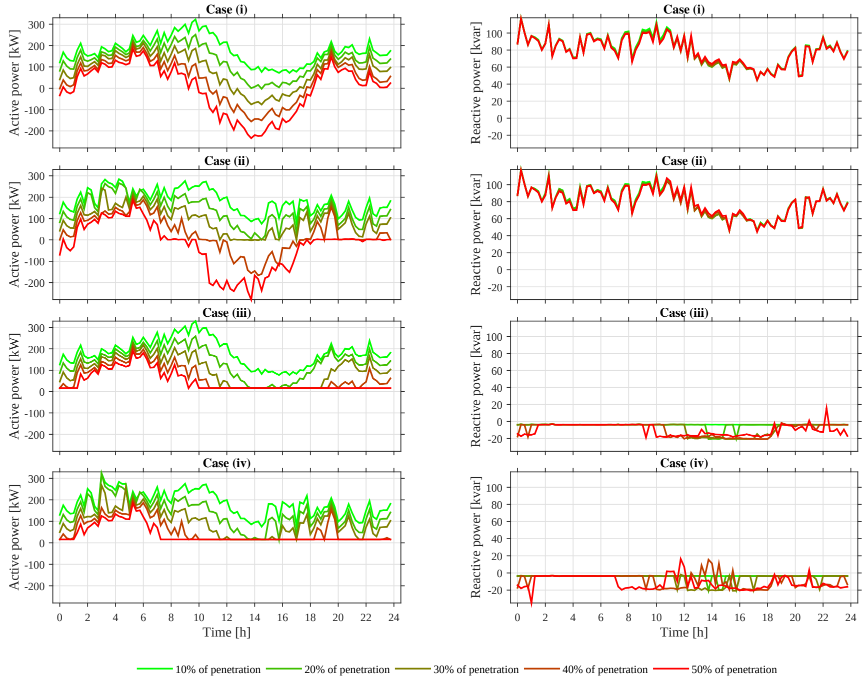


Figure 5. Active and reactive power exchanged with the EG (first and second column, respectively) for each block (rows) and for all penetrations (colour scale, legend depicted in Figure 4).

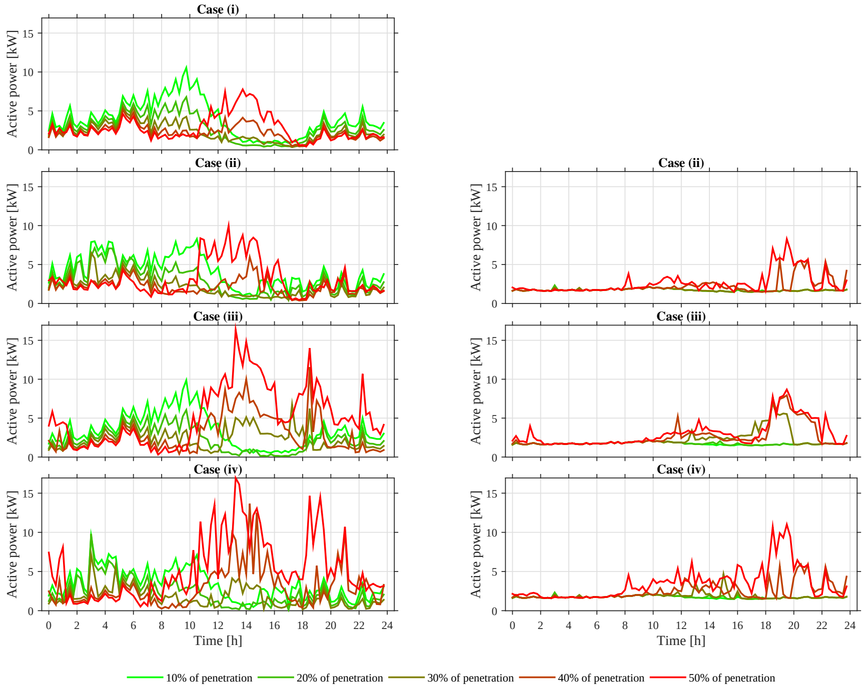


Figure 6. In the first column: Power losses of DN passive elements for each case. In the second column: Power losses of DN active elements for each case.

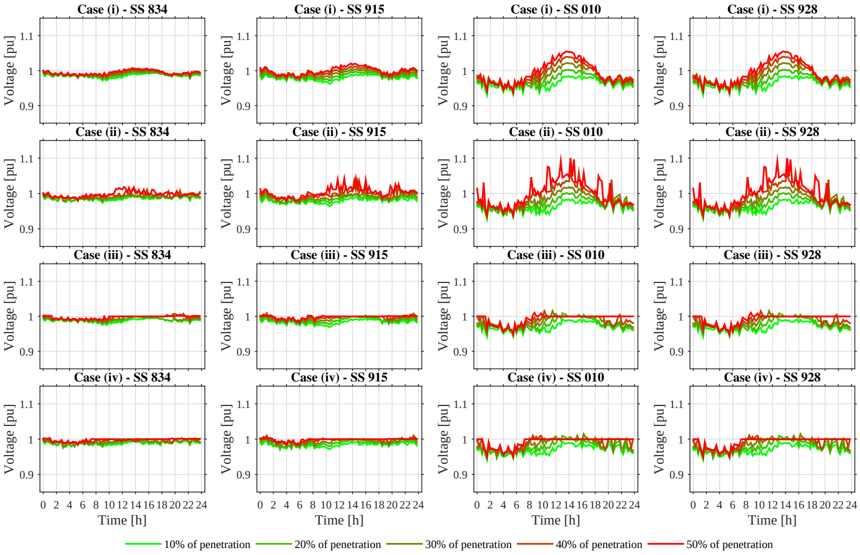


Figure 7. Voltage at SS 834, SS 915, SS 010 , SS 928 for each case (rows) and for all DG penetrations (colour scale).

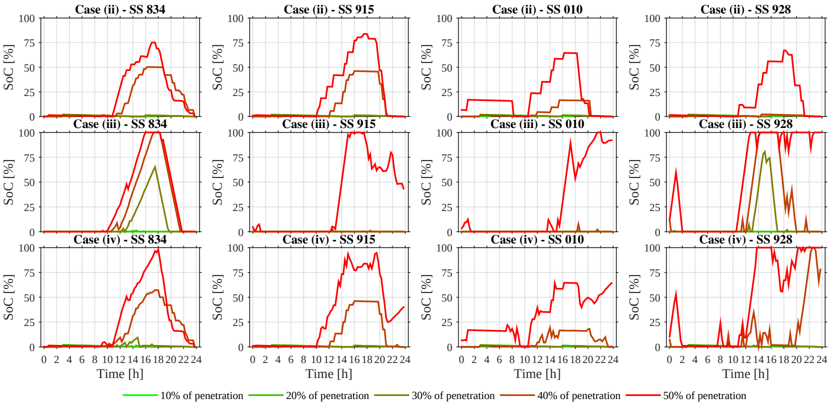


Figure 8. SoC of BESSs at SS 834, SS 915, SS 010 , SS 928 for cases (ii) to (iv) (rows) and for all DG penetrations (colour scale).

To sum up, SS and DN indicators, and objective functions (are defined in Sections 3.2 and 3.3) are calculated and presented in Tables 20–22, respectively. Note that there are many SSs, so Table 20 only presents average and peak values from SSs.

Further, it is interesting to note that assessing the impact of forecasting errors for generation and demand in indicators included in the above mentioned tables, additional simulations were performed, in which no forecasting errors were considered. The comparison of the results indicate a little influence in the indicators. For instance, the indicator associated to the usage of batteries ($I^{s}_{SS_3}$) has experienced a variation around 1.97% (so less than 2% on average) from these two simulations. Similarly, the indicator addressing the renewables' curtailment ($I^{s}_{SS_4}$) has varied about 1% on average. Indicators addressing voltage quality ($I^{s}_{SS_1}$), power factor ($I^{s}_{SS_2}$) and power losses ($I^{s}_{DN_1}$ and $I^{s}_{DN_2}$) has remained almost equal for the two simulations.

Table 20. Summary of SS indicators.

I_{SS}	Case	Level of Penetration									
		10%		20%		30%		40%		50%	
		Mean [%]	Peak [%]	Mean [%]	Peak [%]	Mean [%]	Peak [%]	Mean [%]	Peak [%]	Mean [%]	Peak [%]
(1)	(i)	2.585	4.896	2.745	5.899	3.176	7.557	3.714	9.189	4.234	10.767
	(ii)	2.256	4.665	2.752	6.255	2.824	7.574	3.682	9.846	4.793	14.732
	(iii)	2.288	4.361	2.440	5.091	2.286	5.112	2.287	4.985	1.871	4.558
	(iv)	2.093	4.050	2.516	5.915	2.373	5.684	2.048	5.235	1.638	4.300
(2)	(i)	90.486	84.547	90.486	84.547	90.486	84.547	90.486	84.547	90.486	84.547
	(ii)	90.486	84.547	90.486	84.547	90.486	84.547	90.486	84.547	90.486	84.547
	(iii)	98.964	89.203	98.383	89.203	92.328	82.624	87.535	77.808	79.032	63.563
	(iv)	98.96	89.203	98.566	89.203	95.920	89.203	87.004	72.431	78.175	60.636
(3)	(i)	0	0	0	0	0	0	0	0	0	0
	(ii)	0	0	0	0	0	0	11.369	39.654	27.426	66.883
	(iii)	0.001	0.005	0.260	2.186	18.175	75.727	31.123	137.399	39.612	110.192
	(iv)	0.001	0.004	0.201	2.429	2.736	14.936	27.509	125.810	62.720	210.840
(4)	(i)	0	0	0	0	0	0	0	0	0	0
	(ii)	0	0	0	0	0	0	0	0	0	0
	(iii)	0	0.001	0.005	0.027	1.219	5.362	6.865	19.126	12.897	32.197
	(iv)	0	0.001	0.011	0.095	0.398	3.105	2.044	8.030	8.251	20.019

Table 21. Summary of DN indicators.

I_{DN}	Case	Level of Penetration				
		10% **Rate [%]**	**20%** **Rate [%]**	**30%** **Rate [%]**	**40%** **Rate [%]**	**50%** **Rate [%]**
(1)	(i)	1.937	1.377	1.118	1.111	1.361
	(ii)	1.977	1.419	1.024	1.054	1.53
	(iii)	1.660	1.095	1.172	1.461	2.559
	(iv)	1.623	1.083	0.844	1.453	2.594
(2)	(i)	0	0	0	0	0
	(ii)	3.329	3.329	3.329	4.276	5.076
	(iii)	3.329	3.361	4.443	5.143	5.874
	(iv)	3.329	3.360	3.580	4.803	6.793
(3)	(i)	85.934	63.543	46.158	32.293	23.199
	(ii)	88.380	65.980	44.353	23.063	13.066
	(iii)	88.985	66.614	47.257	31.173	22.667
	(iv)	88.948	66.603	45.599	26.468	18.153
(1) + (2)	(i)	1.937	1.377	1.118	1.111	1.361
	(ii)	5.306	4.748	4.353	5.330	6.610
	(iii)	4.989	4.456	5.615	6.604	8.433
	(iv)	4.952	4.444	4.424	6.257	9.387

Table 22. Summary of objective function value.

QI_C	Case	Level of Penetration				
		10% **Sol. [€/day]**	**20%** **Sol. [€/day]**	**30%** **Sol. [€/day]**	**40%** **Sol. [€/day]**	**50%** **Sol. [€/day]**
z_{GEO}	(i)	158.636	117.399	85.223	59.395	42.485
	(ii)	161.916	120.658	81.036	41.792	23.410
	(iii)	164.239	123.044	87.395	57.443	42.975
	(iv)	162.870	121.721	83.337	48.050	33.683
		Sol. [$10^5 kW^2$]	Sol. [$10^5 kW^2$]	Sol. [$10^5 kW^2$]	Sol. [$10^5 kW^2$]	Sol. [$10^5 kW^2$]
z_{GTO}	(i)	33.737	20.718	13.262	10.397	12.435
	(ii)	34.754	21.840	11.705	7.582	12.295
	(iii)	35.953	22.360	13.092	6.923	4.286
	(iv)	35.333	22.360	12.030	5.598	2.947

5. Discussion of Results

This section presents a discussion of the optimization results. The optimization is carried out through Julia software [48,49] using the mathematical language called Jump [50] and optimization solvers called Gurobi [51] and Ipopt [52]. Then, the obtained data is thread and depicted through mathematical software (Matlab) [53]. The discussion of results is in terms of the indicators previously defined, which focus on the secondary substations (SS indicators) and of the rest of the elements of the distribution network (DN indicators).

5.1. SS Related Metrics

(i) Voltage quality related metric (I_{SS_1})

The voltage metric is directly related with Figure 7. This reflects that the quality of the voltage at the SSs tends to decrease with the distance of these SSs to the point of interconnection with the transmission system. It is remarkable to note that this trend is accentuated if the network is operated from just an economic criterion, i.e., through the GEO (see the results for case (ii) in Figure 7). However, if it is applied the technical operation strategies –the GTO– (see cases (iii) and (iv), the metric I_{SS_1} results clearly improved with respect to base cases (i.e., case (i) with respect to case (iii); and case (ii) with respect to the case (iv)). This can be clearly observed in Figure 9, upper left subplot.

(ii) Reactive power related metric (I_{SS_2})

It is considered that the reactive power is only associated to the loads of the network; generators are operated with an unitary power factor. Therefore, this metric does not depend on the DG penetration level for cases where there is not reactive power management –the GTO– (cases (i) and (ii)). However, when there is reactive power management (cases (iii) and (iv)), there is a dependency between DG penetration and the reactive power metric I_{SS_2}. This can be reflected in Figure 9, upper right subplot. For low levels of DG penetration, the reactive power management focuses on reducing electrical losses. As a reminder, this reactive power management is performed by the IDPRs, not by DG. Conversely, for DG penetration levels above the threshold level of 30%, from which active power flows through the network are highly variable, the reactive power management is under the criterion of smoothing voltage variations. As a consequence, the reactive power metric decreases. This progressive worsening of metric I_{SS_2} is also appreciated in Figure 9, upper right subplot.

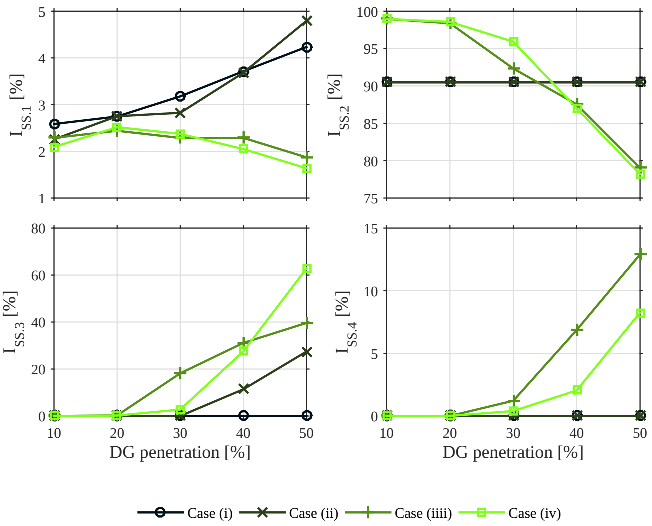


Figure 9. Trend of diverse SS related metrics with respect to DG penetration level.

(iii) Battery related metric (I_{SS_3})

The battery usage is directly related with the level of DG penetration (see SoC variations for all cases evaluated in Figure 8, clearly showing how batteries are more and more operated with increasing DG penetration levels). For all cases and regardless the usage level of the battery, they are charged with surplus of DG. Still keeping the attention in Figure 8, we can observe two additional aspects. First, for the case in which the network is operated under an economic criterion, i.e., case (ii), the GEO decides to let batteries completely discharged at the end of the day for economic purposes. This way, batteries are charged in sunny hours, with surplus of renewables, and discharged at night, when electricity is costly and there is no surplus of renewables. Second, for the case in which the network is operated also under the technical criterion (i.e., cases (iii) and (iv)), batteries are also operated so as to improve the power quality of the network (for instance to smooth out voltage variations). As a consequence, the usage of the batteries is higher than in the case (ii), specially for DG penetrations above 30%.

(iv) Curtailment related metric (I_{SS_4})

The curtailment related metric is directly associated to the level of DG penetration and management tools applied. For low DG penetration levels, the curtailment is not relevant (see Figure 9, bottom right subplot). Conversely, for DG penetration levels above 30%, curtailment is an issue and a matter being dealt by solely the GTO (case (iii)) or both the GTO and the GEO (case (iv)). For the case (iii), and as shown in Figure 9, a noticeable share of DG generation results curtailed with the objective of maintaining a minimum power quality in the network. Note for instance in this regard, that up to 12% of renewables should be curtailed considering a DG penetration level of 50%. For the case (iv), in which the network is operated by both the GTO and the GEO, this latter management algorithm decides to reduce the amount of energy curtailed so as to minimize economic costs of network operation, while still respecting the technical optimization proposed by GTO.

5.2. DN Related Metrics

(i) Distribution electrical losses (cables and transformers) (I_{DN_1})

Passive losses are proportional to the square of current. As can be observed in Figure 6, they are significant during peaks of demand and/or generation. Also in the above mentioned figure, for the case (i), when the DG penetration level is low the major part of electrical losses are during peak demand hours (i.e., in the morning). Conversely, while the DG penetration level is high, the major part of electrical losses are gathered during the midday (as a result of PV generation).

More in detail, Figure 10, upper left subplot, presents the evolution of metric I_{DN_1} (so the magnitude of distribution losses) function of DG penetration levels. As can be observed, for low shares (below 30%) and considering the application of the advanced management tool GTO (case (iii) and case (iv)), passive losses become lower than for the base case (case (i)). However, for penetration levels above the threshold of 30%, the actuation of the GTO, which is focused on smoothing voltage variations, affects distribution losses increasing them above the base case. It is important to highlight that active losses remain almost constant during the day. However, in the evening, they experience an increment as a result of the process of batteries discharging. Finally, in case (i) there are not active elements involved, such as IDPRs and BESSs, so there are not associated electrical losses to compute.

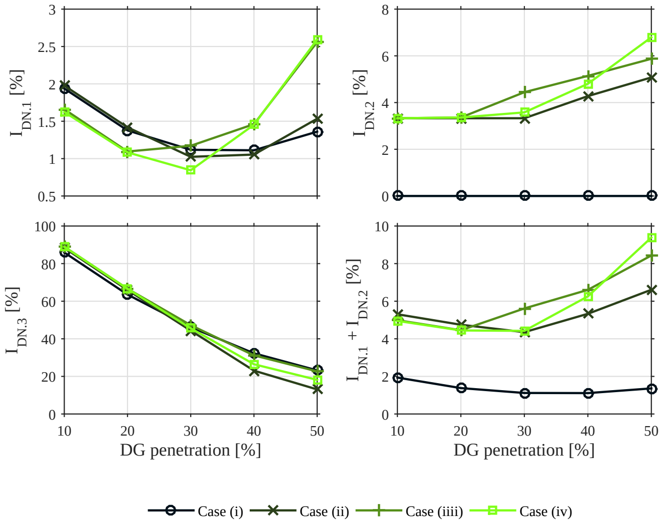


Figure 10. Trend of diverse DN related metrics with respect to DG penetration level.

(ii) Electrical consumption of IDPRs (active elements) (I_{DN_2})

This electrical consumption is additional to the base case. This is a toll that smart grids have to pay in order to include additional equipment as power electronics and batteries. However, it represents a small percentage of all consumptions, similar to cables and transformers. As can be observed in Figure 10, in general terms, the higher the DG penetration is, the more we utilize batteries and power electronics, and thus the higher the associated losses are. Finally, note that this usage of batteries is mainly bounded at night, since is in this time frame in which batteries are discharged (see Figure 6).

(iii) External dependency (I_{DN_3})

It is noted that the dependency with the EG is inversely proportional to DG penetration level. Such dependency with the EG is even lower if the network is managed by the GEO (please compare cases (i) and (ii) in Figure 10 bottom left subplot). From this comparison, it can be observed that I_{DN_3} is improved up to 10% approximately at most while considering the GEO. This can also be observed in Table 21. Even though this improvement could seem relatively small, the impact of including the GEO as the management tool results much more important in economic terms, as analysed later in Section 5.3. In addition, an important aspect to highlight at this point is the effect of CDLs and PDGs in external grid dependency. The management of such resources permit time shift consumption and generation according to electricity prices. In other words, CDLs consume when there is an energy surplus or when the energy is cheap, and PDGs generate when there is an energy deficit or when it is expensive. The effect on this management is reflected in Figure 9, comparing cases (i) and case (iii) (cases with no management of CDLs and PDGs), with cases (ii) and (iv), in which there is management for such controllable resources. It can be observed how demand peaks are moved to off-peak periods (for instance, see the load peak reduction in the morning for cases with renewables penetration of 10% and 20%).

5.3. Evaluation of Objective Functions

(i) The GEO objective function (z_{GEO})

As a reminder, the GEO tries to minimize the operational costs of the DN. As can be appreciated in Figure 11, left subplot, the costs, i.e., z_{GEO}, decreases as proportional to DG penetration levels for all cases. This makes sense, since less power is imported from the EG. Such trend is even accentuated for cases (ii) and (iv), where the economic management is applied. In addition, it is worth noting that for low DG penetration levels, the cost is slightly higher than for considering high shares due to the toll associated to the losses incurred in batteries and power electronics. It is important to remark that from 30% of DG penetration on, this additional losses are compensated via the savings from the economic management performed by the GEO. Finally, the cost reduction from cases (ii) and (iv) with respect to the case base (case (i)), is almost 45% and 21%, respectively.

(ii) The GTO objective function (z_{GTO})

As a reminder, the term z_{GTO} is related to the magnitude of the power flows between the DN and the EG, and also to the severity of voltage variations within the DN from the desired values. So from a technical perspective, z_{GTO} should be as low as possible, indicating somehow minimum power losses and voltage deviations. As depicted in Figure 11, right subplot, in general terms z_{GTO} decreases with the DG penetration level. This clearly depicts the progressively dependency reduction with the EG. For the base case though, and also for the case (ii), in which the GTO are not working, there is point, around 40% in DG penetration, that voltage variations are remarkably high, and this makes z_{GTO} to increase. On the other hand, for these scenarios in which the penetration of DG is above 40%, the operation of the GTO keeps such voltage deviations low, thus ensuring a minimum z_{GTO}.

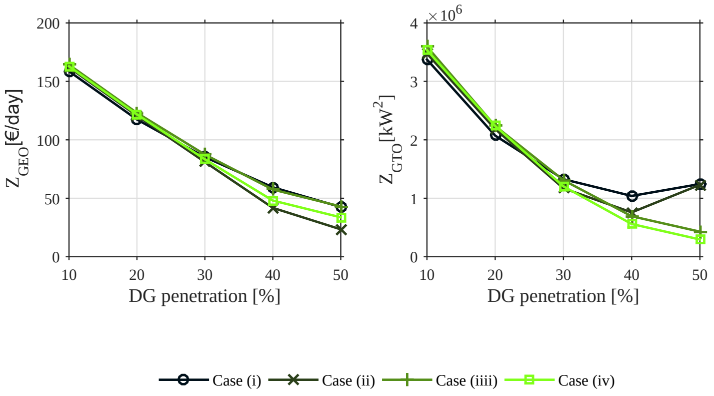


Figure 11. The operational costs of the DN for diverse DG penetration levels.

6. Conclusions

This paper addressed the impact of including different advanced techniques for managing electrical rural grids. These techniques combine the application of ICT tools and power electronics with embedded energy storage capability. The analysis was based on a real grid, in which different scenarios have been evaluated and these are characterized by progressively increasing the penetration of renewable energy generation from a base, current case. In these analyses, the temporal profiles for the demand have been also derived from the current ones, and adopted with a 15 min time step resolution.

The new advanced management techniques included: (i) an algorithm named as GEO, able to dispatch the charge and discharge of the energy storage devices throughout the grid, as well as the controllable loads and programmable energy generation capabilities, all of these from an economic criterion; (ii) an algorithm named as GTO, able to dispatch the charge and discharge the energy storage devices, the programmable energy generation capabilities as well, and all addressing active power flows, as for the GEO, but also the reactive power flows throughout the distribution grid. In this sense, the GTO performs the operation of the network in terms of a technical criterion; and (iii) a new power electronics-based device with embedded energy storage capacity named here as IDPR. This device effectively executes the charge and discharge of the storage capabilities throughout the grid (i.e., batteries), and also performs a proper management of reactive power flows according to GTO setpoints.

The obtained results, in general terms, demonstrate that for the adopted grid as the case study, the inclusion of these advanced management techniques from both a technical point of view (i.e., an improvement of the power quality of the network) and an economic perspective (i.e., a reduction of the costs incurred in importing energy from the exterior of the distribution network), is justified with a penetration of renewables higher than the threshold level of 30%. From this level of penetration on, the reduction of the costs due to the energy imported with the external grid compensates the toll to be paid in the form of the additional losses of the new energy storage devices integrated into the grid. To emphasize, such thereshold level in penetration of renewables is particular for the adopted study case and cannot be generalized. However, the performed management tools and related metrics could be directly applied for analyzing other networks.

Also from this level of penetration on, the inclusion of these new management tools (ICTs and energy storages) does improve the techno-economic operation of the grid. This means that the voltage profiles throughout the network result much more consistent and smoothed, and that the dependency with the external network is much lower than in the case of not considering such management tools. For instance, the included energy storage systems, properly managed by the GTO and the GEO, permit to reduce the operation costs, which are mainly affected by the energy imported from the external grid, from 42.5 € /day (case (i), or base case) to 23.4 € /day (case (ii), GEO working), for the case of 50% of renewables' penetration. Further even, the operating costs of the network as calculated by the sum of the cost of the energy imported from the external grid, the distribution losses and the investments in power electronics as well, result lower while managed by the GEO than in the base case.

More in particular, the inclusion of just the GTO algorithm (not in combination with the GEO) cannot be justified in economic terms. In the same manner, the inclusion of the GEO can be justified from an economic perspective, but not from a technical point of view. The combined actuation of both algorithms yields satisfactory results from both perspectives.

The inclusion of such management tools from a technical perspective can be justified for weak and radial networks concerning long distances, which is the typical case for rural networks. These networks experiences high variations in voltage levels and these become accentuated with the distance from the point of interconnection with the main external grid. These problems are further accentuated with the inclusion of renewables, since voltage variations can be noticeable especially at the end of lines.

Finally, it is worth noting that the analysis proposed in this paper is representative of a case with growing importance of renewables in rural distribution grids. So it is, without any doubt, a timely exercise and in response to the urgent energy transition the electrical power sectors are currently undergoing.

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Abbreviations

The following abbreviations are used in this manuscript:

ADG	Adjustable Distributed Generator
BESS/BS	Battery Energy Storage System
CDL	Controllable Distributed Load
DER	Distributed Energy Resources
DG	Distributed Generator
DL	Distributed Load
DN	Distribution Network
DSM	Demand-Side Management
DSO	Distribution System Operators
EG	External Grid
EMS	Energy Management System
GEMS	Global Energy Management System
GEO	Global Economic Optimization
GS	Diesel Generator
GTO	Global Technical Optimization
ICT	Infomation and Communation Technologies
IDPR	Intelligent Distribution Power Router
LC	Local Controller
LEMS	Local Energy Management System
MAS	Multi-Agents Systems
MILP	Mix Integer Lineal Programming
NCDG	Non-Controllable Distributed Generator

NCDL	Non-Controllable Distributed Load
NLP	Non-Lineal Programing
OPF	Optimal Power Flow
PADG	Programmable and Adjustable Distributed Generator
PDG	Programmable Distributed Generator
SCADA	Supervisory Control and Data Acquisition
SDG	Switchable Distributed Generator.
SG	Smart Grid
SoC	State of Charge
SS	Secondary Substation
TC	Transformer Controller
TSO	Transmission System Operator

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3.3 Summary

This chapter has studied the impact of including different advanced techniques for managing electrical rural grids. These techniques merge the application of ICT tools and power electronics with embedded energy storage capability. The advanced techniques combine an algorithm named as Global Economic Optimization, which is able to dispatch the charge and discharge of the energy storage devices throughout the grid, as well as the controllable loads and programmable energy generation capabilities, all of these from an economic criterion; and an algorithm named as Global Technical Optimization, which is able to dispatch the charge and discharge the energy storage devices, the programmable energy generation capabilities as well, and all addressing active power flows, as for the economic optimization, but also the reactive power flows throughout the distribution grid. The results have demonstrated that the inclusion of an Energy Management System for the adopted grid is justified with a penetration of renewables higher than the threshold level of 30%. From this level of penetration on, the reduction of the costs due to the energy imported with the external grid compensates the toll to be paid in the form of the additional losses of the new energy storage devices integrated into the grid. At the economic level and from the threshold value in renewable' penetration, the EMS reduces the energy costs for the grid participants, minimizing imports from the external grid and compensating the toll to be paid in the form of the losses incurred by including additional equipment in the network. At the technical level, the inclusion of the EMS permits us to significantly increase the power quality. Finally, the inclusion of such management tools from a technical perspective can be justified for weak and radial networks concerning long distances, which is the typical case for rural networks.

Chapter 4

Conclusions

4.1 Contributions

The Thesis goals have been completely aligned with the idea of transforming a radial and dumb distribution grid into a meshed intelligent system through the application of innovative management systems and power electronics with embedded storage. These depict a novel architecture for modernizing traditional rural networks into Smart Grids and include innovations on both the power and management planes of the grid.

In the power plane, innovations included the development and integration of the so-called Intelligent Distribution Power Router (IDPR). An IDPR is a modular power electronics device that can integrate a storage system that provides different services such as harmonic and reactive currents' compensation, current balancing, energy back-up and network restoration, among others. The IDPR is the key technology for enhancing the power quality and security of supply, the grid operation and performance, the useful life of grid infrastructures, the distributed generation hosting capacity and the electrical vehicle integration; and reducing the digital divide phenomena and the technological uncertainty.

In the management plane, innovations included the design and implementation of a management architecture that can be easily replicated along other rural environments. This management architecture has permitted to decentralize the operation of the network while either in grid connected or isolated modes. It was developed as scattered intelligence into diverse agents that can even act autonomously in case of mains fault or other circumstances. Therefore, the reliability and self-healing and self-reliant capabilities of the network have been increased. Such contents are included in Chapter 2 of the present Thesis.

The design of the management architecture included advanced techniques for managing rural and radial distribution networks with distributed and renewable generation, electrical vehicles and IDPRs with embedded storage as well. In particular, two intelligent novel agents were deployed for optimizing the operation of the rural grid while connected to the main distribution one, and while operated as isolated.

The first agent is in charge of managing the whole grid and combines three important services. The first service is the energy forecasting. Every 15 minutes, it provides the consumption and generation time series for the execution of related optimization algorithms. The second service is a mixed-integer linear programing algorithm that solves the dispatch (i.e. the charge and discharge of) the energy storage systems throughout the grid, as well as of the controllable loads and programmable energy generation capabilities. This dispatch optimization is done pursuing best active power flows. The third service is realized through a non-linear programing algorithm that further modifies the previous dispatch, but addressing other technical restrictions that modifies reactive power flows throughout the grid. Such contents are included in Chapter 3 of the present Thesis.

In turn, the second management agent solves the dispatch of controllable assets in the local grid (not the whole grid) while in both isolated and grid-connected modes. Because of managing a local area, the involved optimizations were solved adopting a lower level of aggregation for consumption and generation assets than in the first agent explained above. While in grid connected mode, it is based on non-linear programing algorithms that input real time network data (with time step 1 minute), and output the dispatch for controllable assets addressing technical constraints (not market-based ones). In turn, while in isolated mode, the goal is to enhance the power quality and security of supply for consumers. Such contents are included in Appendix A of the present Thesis.

The performance of the management agents has been tested through simulations. Their application has proved beneficial for weak and radial networks concerning long distances, which is typical for rural networks, and the benefits are from both technical and economic perspectives. In this regard, it is worth noting that the inclusion and proper management of energy storage systems permits to reduce the grid operation costs (i.e. distribution losses).

In addition, the performance of the innovative grid architecture has been tested in the Smart Rural Grid project. Along with the management agents, the deployment of related technologies such as advanced meters (telecommunications network in general), distributed energy resources, IDPRs with embedded storage, evolved into an advanced distribution grid with improved self-healing, reliability, power quality, interoperability, resilience and efficiency. Contributions in this regard can be noted in Chapter 2 and Appendix B.

To sum up, the developed architecture and related technology has gone beyond the traditional concept of rural grids. Developed algorithms and technologies can also be suitable for other type of distribution systems for improving the quality of service and the hosting capacity, without the need of network reinforcement or expensive investments for the new grid deployment.

4.2 Future work

The present Thesis, has introduced an innovative Smart Grid architecture for rural grid taking into account rural environment limitations and features. In addition, the Thesis has also defined advanced algorithms for that system and for managing new power electronics, renewable and distributed energy resources and electrical storage system. In this sense, future work may be done in the following directions:

(i) To standarize the proposed architecture for the management of the rural grid according to Smart Grid Architecture Model methodology, so as to maximize impact and ease replicability.

(ii) To explore a broad catalog of potential use cases for the developed power electronics with embedded storage in distribution grids, as a way of promoting exploitation of the contributions of the present thesis.

(iii) To research other ways to increase the low voltage hosting capacity by combining the proposed power electronics with embedded storage with enhanced network observability and network reconfiguration.

(iv) To develop new algorithms at both centralized and decentralized level in order to automate even more the DSO operation, respond optimally against any electrical phenomena and ensure the power quality and security of supply.

(v) To improve the local management of power electronics and electrical storage system in order to integrate more storage technologies enabling advanced services to the grid at enhanced performance.

Chapter 5

Publications

5.1 Publications as first author

Journal articles

- Francesc Girbau-Llistuella, Andreas Sumper, Francisco Díaz-González, Samuel Galceran-Arellano. “Flicker mitigation by reactive power control in wind farm with doubly fed induction generators”, International Journal of Electrical Power & Energy Systems, Elsevier 2014, 285-296, February 2014.
  doi.org/10.1016/j.ijepes.2013.09.016

- Francesc Girbau-Llistuella, Francisco Díaz-González, Andreas Sumper. “Optimization of the Operation of Smart Rural Grids through a Novel Energy Management System”, Energies 2018, MDPI, 11(1), 9, December 2017.
  doi.org/10.3390/en11010009

- Francesc Girbau-Llistuella, Francisco Díaz-González, Andreas Sumper, Ramon Gallart-Fernández, Daniel Heredero-Peris. “Smart Grid Architecture for Rural Distribution Networks: Application to a Spanish Pilot Network”, Energies 2018, MDPI, 11(4), 844, April 2018.
  doi.org/10.3390/en11040844

Book chapter

- Francesc Girbau-Llistuella, Andreas Sumper, Ramon Gallart-Fernández, Santi Martinez-Farrero. “Smart Rural Grid Pilot in Spain”, in “The Energy Internet: An Open Energy Platform to Transform Legacy Power Systems Into Open Innovation and Global Economic Engines”, Elsevier 2018, to be published in September 2018.
  ISBN-13: 978-0081022078

Conference papers

- Francesc Girbau-Llistuella, Joan Marc Rodriguez-Bernuz, Eduardo Prieto Araujo, Andreas Sumper. “Experimental Validation of a Single Phase Intelligent Power Router ”, in Innovative Smart Grid Technologies Conference

Europe (ISGT-Europe), 2014 IEEE PES, Istambul, Turquia, 1-6, October 2014.
doi.org/10.1109/ISGTEurope.2014.7028775

- Francesc Girbau-Llistuella, Andreas Sumper, Ramon Gallart-Fernández, Volker Buehner. "Operation of rural distribution grids with intermittent generation in connected and island mode using the open source EMS solver SCIP", in 2015 International Conference on Renewable Energy Research and Applications (ICRERA), 2015 IEEE, Palermo, Italia, 1-6, November 2015.
doi.org/10.1109/ICRERA.2015.7418557

- Francesc Girbau-Llistuella, Andreas Sumper, Francisco Díaz-González, Antoni Sudrià-Andreu, Fernando Castro Cervera, Ramon Gallart-Fernández. "Arquitectura de una Red Inteligente Rural", in 2015 Congreso Iberoamericano sobre microrredes de generación distribuïda de renovables (MIGEDIR), Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), Liberia, Costa Rica, 64-72, December 2015.
MIGEDIR2015 Memoria

- Francesc Girbau-Llistuella; Andreas Sumper; Daniel Heredero-Peris; Marc Pagès-Giménez; Cristian Chillón-Antón; Josep Andreu Vidal-Clos; Francisco Díaz-González; Ramon Gallart-Fernández. "Demonstration and experience of the smart rural grid project", in Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2016 IEEE PES, Ljubljana, Slovenia, 1-6, October 2016.
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Appendix A

Local performance of the Smart Rural Grid through the Local Energy Management System

A.1 Introduction

This Appendix details the operational contribution of an Energy Management System during the grid-connected and grid-disconnected operation [47]. It adjusts and determines active and reactive power setpoints, with a minute resolution, according to high-level setpoints and real-time measurements. It is one of key elements from the Smart Rural Grid for increasing its interoperability, resilience, efficiency and robustness of the existing rural distribution network by the utilization of Smart Grid technologies, power electronics and embedded storage systems.

A.2 Publication

Local performance of the Smart Rural Grid through the Local Energy Management System

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***Abstract*—This paper aims to detail and illustrate the operation of the Local Energy Managament System during the grid-connected and grid-disconnected mode of the Smart Rural Grid (SRG) project. The SRG project is focused on Distributed System Operator's capabilities to increase the interoperability, resilience, efficiency and robustness of the existing rural distribution network by the utilization of new Smart Grid technologies. This project is founded by the European Union and it is constituted by an eight partners consortium mixing their know-how in a hybrid smart solution; therefore, power electronics, control theory, telecommunications, distribution system operator energy managing, supervisory systems and end-users coexist in a pilot network. This pilot network includes four rural secondary substations up to 200 kVA interconnected by means of medium voltage rural overhead lines in Vallfogona, Catalonia, Spain.**

***Index Terms*—Intelligent power distribution router, power quality, rural distribution network, smart rural grid.**

I. INTRODUCTION

Rural distribution networks are more vulnerable than urban distribution grids. The aged infrastructure of rural distribution networks combined with other habitual challenges in this location kind such as lower quality indices (number or time of interruptions), difficulty of access after electric contingencies or scattered consumptions requires updated solutions and cutting edge technologies to face them. The increasing penetration of small distributed power plants can contribute to overcome these weaknesses defining a new electric paradigm. However, the flow of the locally produced electric energy must be controlled for the optimal use of available energy "credits". The particular conditions and operation boundaries of rural distribution grids need a new type of thinking that includes assisting technologies to enhance the operation [1]–[3].

The Smart Rural Grid (SRG) project emerges to face those challenges and helps to answer the different technical and operational issues for the particular case of rural grids. In this sense, the SRG project explores and shows how to exploit the convergence between electricity and telecommunications networks. The undertaken work aims to point out how utilities can operate more efficiently their available electric resources and manifests how to interconnect energy prosumers to enable a multi-directional energy flow [4]. It also examines the best way to make the transition from the present rural distribution network to a new electric operational framework by using Smart Grid (SG) technologies without losing sight of the corresponding associated business concepts [5]–[7].

The main objective of this paper is to present grid-connected and grid-disconnected operation contributions. The paper is divided into five sections, the Section II presents the SRG project; the Section III introduces and exposes the Local Energy Management System (LEMS) operation, and its contribution to the pilot SRG; the Section IV presents a study case in order to show the LEMS operation; the Section V presents results of the grid-connected and grid-disconnected operation; and finally the Section VII enumerates the conclusions. In addition, it is added an Annex in order to explain the electrical configurations of SRG.

II. SMART RURAL GRID PROJECT

The SRG project focuses on a real rural distribution grid with substantial potential of improvement in efficiency, particularly, in continuity of supply terms. The project is developed on a 5 kV distribution network at EyPESA's rural exploitation region. It should be highlighted that the pilot area is low population dense. There are 25 costumers distributed into four low level secondary substations (see in Fig. 1) being, in this particular case, residential or agrarian [8]. It is important to consider that initially, the present network was a non-manageable radial grid where safety operation is only guaranteed through manual switch-disconnectors and fuses. Furthermore, failure detection and difficulty of access to the exploitation area is complex making problematic a robust operation of the system.

As a consequence of addressing new management tools and cutting edge technologies, the pilot network has been deeply transformed, resulting in the scheme depicted in Fig. 2. Following, the above actions to upgrade the rural grid are listed [8], [9]:

- **Promotion of Distributed Energy Resources (DERs)**. Photovoltaic is the most favourable DER due to the network orography, the weather conditions, and the technology cost. In this regards, the Distributed System Operator (DSO) helps to co-finance DER to increase the penetration at local generation and the role of prosumers.
- **Inclusion of new protection devices**. In the initial situation, the protection elements of the pilot network

Apendix A: Local performance of the Smart Rural Grid

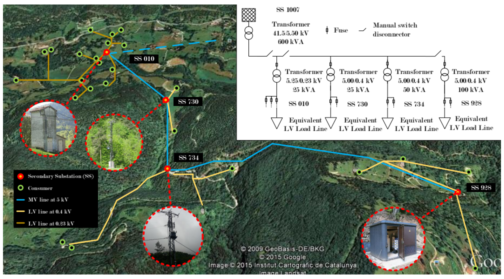


Fig. 1: SRG Pilot Project Located at Catalonia, Spain

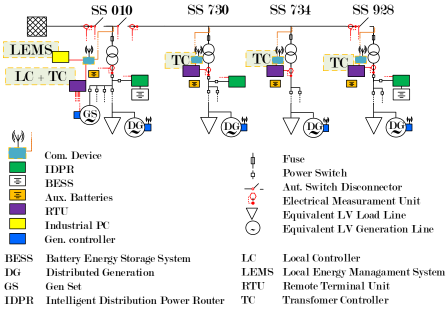
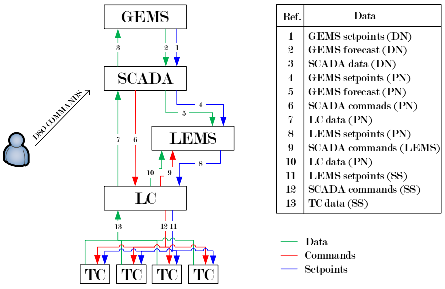


Fig. 2: Single Line Diagram of SRG Project



Ref.	Data
1	GEMS setpoints (DN)
2	GEMS forecast (DN)
3	SCADA data (DN)
4	GEMS setpoints (PN)
5	GEMS forecast (PN)
6	SCADA commads (PN)
7	LC data (PN)
8	LEMS setpoints (PN)
9	SCADA commands (LEMS)
10	LC data (PN)
11	LEMS setpoints (SS)
12	SCADA commands (SS)
13	TC data (SS)

Fig. 3: The Control and the Management Hierarchy of SRG Project

are not equipped with automatic re-closing. The new rural grid adds degrees of freedom offering new electrical configurations and new operation modes [10].

- **Install back-up resources**. Several types of back-up resources can be adopted to improve continuity of supply. One alternative is the inclusion of diesel gen-sets (GS). Likewise, it is possible to adopt power electronic-based solutions. In this regard, the SRG project develops the named Intelligent Distribution Power Router (IDPR) [11], [12].
- **Deploy a proper telecommunications network**. A new telecommunication infrastructure is proposed with the aim of guaranteeing the efficient integration and management of DERs, storage systems and new protection and control devices through Remote Terminal Units (RTU).
- **Create new control and management agents**. It is necessary to create agents to coordinate all above mentioned technologies allowing to interact between themselves, exchanging data and commands. From a bottom-up approach, the management hierarchy is configured by the so-called Transformer Controller (TC), the Local Controller (LC), the LEMS, the Supervisory Control and Data Acquisition (SCADA) and, finally, at the top of the management structure is the Global Energy Management System (GEMS). The hierarchy and relationships are depicted in Fig. 3.

III. LEMS OPERATION

In this section aims to introduce the LEMS operation. The LEMS enables the operational optimization of the PN. The LEMS calculates, in a one minute basis, the setpoints to back-up resources and Distributed Generators (DGs), from data collected by the LC, SCADA constraints and commands, and GEMS setpoints and forecast. The PN data comes from LC via Modbus TCP/IP each minute, while SCADA contraints and commands are updated asynchronously through the LC. Conversely, GEMS setpoints and forecasts come through the SCADA via File Transfer Protocol (FTP). Furthermore, the LEMS records the most relevant information of the PN, in order to be checked when there is an eventuality. The LEMS is the last level of the management architecture included in the PN environment. Due to the complexity of the calculations carried out by LEMS, it is implemented in an industrial PC. This has been selected because it has a high computing power, and also it has an extended temperature range, does not have fans and is a compact design in order to protect it from dirt, dust and humidity, supporting harshest conditions.

The designed LEMS is simple and robust for operating continuously under different conditions. Fig. 4 presents the state machine of LEMS. It is constituted by four states: (i) start up, (ii) stand by, (iii) run, (iv) run and data logger, (v) error states, and (vi) off. In addition, the LEMS is always communicating with the LC and the SCADA, via Modbus TCP/IP and FTP TCP/IP, respectively. In this sense, commands came from the SCADA, via Modbus, and data came from the LC and the SCADA, via Modbus and FTP. Similarly, alarms are sent to the SCADA, via Modbus.

The initial state of LEMS, considering that the LEMS is electrically supplied, is "start up", this state is a momentary step between the absence of supply – "off" state – and the "stand by" state. Therefore, The LEMS evolves automatically from "start up" state to "stand by" state. When the LEMS is in the "stand by" state, it is expecting a *turn on* command, while it is continuously refreshing its Modbus table. In addition, if an error occurred the LEMS state would evolve to the "error"

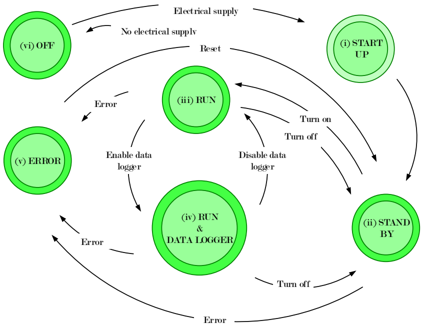


Fig. 4: LEMS state machine

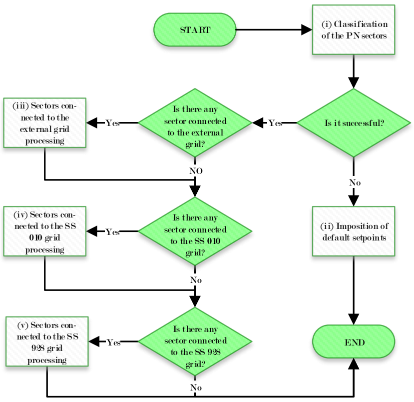


Fig. 5: LEMS algorithm

state.

Similary to the "stand by" state, the error state is continuously refreshing its Modbus table, including the detected issue or error. In addition, it requests a *reset* command from the SCADA, in order to progress to "stand by" state again. When the DSO sends a turn on command, while the LEMS remains in "stand by", the LEMS state becomes "run" state. The "run" state enables the operational optimization of the PN, it is explained in detail later. Then, if the SCADA sends a *turn off* command, the LEMS goes again to "stand by" state, either, if the SCADA sends *enable data logger* command, the LEMS goes to "run and data logger" state. Similarly to "run" state, this state enables the operation optimization and in parallel it is saved relevant data about the pilot SRG.

The "run" state is the most significant state, because the LEMS manages locally IDPRs and their Battery Energy Storage Systems (BESS), and distributed generators. In addition, the LEMS takes into account the electrical configuration of the pilot SRG, and depending on it configure IDPRs to support the connected-grid operation, or disconnected-grid operation. The LEMS executes a cyclic algorithm each minute, depicted in Fig. 5. The first process (i) of the algorithm classifies SRG sectors. The SRG sectors and the electrical configuration are presented in Annex. It is important to emphasize, according to [7], that there are only two electrical sectors could operate isolated from the external grid and the rest of electrical sectors. They are first and third electrical sectors, because they have an IDPR with a Battery Energy Storage System (BESS). The second electrical sector is totally dependent from the external grid or others sectors, because its IDPR does not manage a BESS. Therefore, the classification process determine which sectors are connected to the external grid, to the grid created in Secondary Substation (SS) 010, or to the grid created in SS 928. Then, if the classification is successful or not, the LEMS determines a collection of setpoints through processes (iii) to (v), or imposes a collection of default setpoints through process (ii), which have been determined previously by the DSO.

In case that there is any electrical sector connected to the external grid, it is executed the third process (iii) with specific sectors. The LEMS takes the hierarchically superior energy management systems quarter setpoints –GEMS– and it adjusts them trough the local optimization operation process described below. Mainly, the local optimization manages the reactive power flows in order to guarantee stable the voltage, ensuring in second term a few distribution losses, because the external grid and active power setpoints are fixed by the superior optimization.

In case that there is any electrical sector connected to the SS 010 grid or SS 928 grid, it is executed the forth (iv) or fifth (v) processes with specific sectors. Similarly, the LEMS optimize the operation through the local optimization, but in this case the LEMS also manages the active power setpoints from DGs and other IDPR, which operate as slave, and the voltage setpoint of the IDPR that operates as a master. In addition, the reactive power flows are also manged in order to guarantee stable the voltage for the rest of grid, ensuring in second term a few distribution losses.

a) Optimal operation process: introduction: The local optimization operation is composed by a process based on a NLP that provides setpoints according to technical constraints. The idea of this process is minimizing losses guaranteeing that the consigned active power is dispatched, adjusting the reactive power from the IDPRs, readjusting the active power from DGs and BESS in order to keep the voltage within acceptable range. This local optimization goes under the following assumptions: (i) The DN voltages and currents are balanced, (ii) Consumption and generation profiles are aggregated at each SS's feeder. (iii) The electrical loses of MV lines and transformers are considered for optimization purposes. The input data for the mathematical problem is composed by a set of buses b (B)

b) Optimal operation process: formulation: Following, the formulation is presented, the voltage for all buses are determined by equations (1) and (2) linking the voltage module (x^b_{VM}) and angle (x^b_{VA}) through grid parameters ($K^{b,c}_{YG}$, $K^{b,c}_{YB}$) to the total active and reactive power (x^b_{PT}, x^b_{QT}).

$$\begin{aligned} x^b_{PT} = x^b_{VM} \sum_{c \in B} x^c_{VM} \Big(& K^{b,c}_{YG} \cos(x^b_{VA} - x^c_{VA}) \\ & + K^{b,c}_{YB} \sin(x^b_{VA} - x^c_{VA}) \Big) \quad \forall b \in B \end{aligned} \tag{1}$$

$$\begin{aligned} x^b_{QT} = x^b_{VM} \sum_{c \in B} x^c_{VM} \Big(& K^{b,c}_{YG} \sin(x^b_{VA} - x^c_{VA}) \\ & - K^{b,c}_{YB} \cos(x^b_{VA} - x^c_{VA}) \Big) \quad \forall b \in B \end{aligned} \tag{2}$$

Active and reactive power balance are ensured by equations (3) and (4), respectively, where both total power are composed by the imported power from the external grid ($x^b_{PI_{EG}}$, $x^b_{QI_{EG}}$), power generated by DGs ($x^b_{PG_{DG}}$, power injected by IDPRs ($x^b_{PG_{PR}}$, $x^b_{QG_{PR}}$), power consumed by consumers (K^b_{PC}, K^b_{QC}).

$$x^b_{PT} = x^b_{PI_{EG}} + x^b_{PG_{DG}} + x^b_{PG_{PR}} - K^b_{PC} \; \forall b \in B \tag{3}$$

$$x^b_{QT} = x^b_{QI_{EG}} + x^b_{QG_{DG}} + x^b_{QG_{PR}} - K^b_{QC} \quad \forall b \in B \tag{4}$$

Equation (5) establishes that the active and reactive power exchanged with the EG is less than the rated power of the EG transformer or EG interconnections ($K_{RP^b_{EG}}$). Note that if there is no interconnection at bus b the rated power is null.

$${K^b_{RP_{EG}}}^2 \geq {x^b_{PI_{EG}}}^2 + {x^b_{QI_{EG}}}^2 \quad \forall b \in B \tag{5}$$

In addition, the voltage and angle range of all buses (also the EG interconnections module and angle of the EG) are fixed by lower and upper bounds ($K^b_{VM_{LVM}}$, $K^b_{VM_{UVM}}$) and ($K^b_{VA_{LVA}}$, $K^b_{VA_{UVA}}$), through equations (6) and (7), respectively.

$$K^b_{VM_{LVM}} \leq x^b_{VM} \leq K^b_{VM_{UVM}} \quad \forall b \in B \tag{6}$$

$$K^b_{VA_{LVA}} \leq x^b_{VA} \leq K^b_{VA_{UVA}} \quad \forall b \in B \tag{7}$$

Similarly, the active and reactive power generated by DGs and injected by IDPRs are bounded by lower and upper bounds ($K^b_{LPG_{DG}}$, $K^b_{UPG_{DG}}$), ($K^b_{LQG_{DG}}$, $K^b_{UQG_{DG}}$), ($K^b_{LPG_{PR}}$, $K^b_{UPG_{PR}}$) and ($K^b_{LQG_{PR}}$, $K^b_{UQG_{PR}}$), through equations (8) to (11). Note, that active power setpoints are fixed by a hierarchically superior energy management system –GEMS– during the grid-connected operation.

$$K^b_{LPG_{DG}} \leq x^b_{PG_{DG}} \leq K^b_{UPG_{DG}} \quad \forall b \in B \tag{8}$$

$$K^b_{LQG_{DG}} \leq x^b_{QG_{DG}} \leq K^b_{UQG_{DG}} \quad \forall b \in B \tag{9}$$

$$K^b_{LPG_{PR}} \leq x^b_{PG_{PR}} \leq K^b_{UPG_{PR}} \quad \forall b \in B \tag{10}$$

$$K^b_{LQG_{PR}} \leq x^b_{QG_{PR}} \leq K^b_{UQG_{PR}} \quad \forall b \in B \tag{11}$$

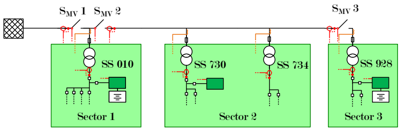


Fig. 6: Sectors of PN depending of the medium voltage switches (S_{MV})

Equations (12) and (13) establishes bound the active and reactive power generated by DGs and IDPRs according their rated power ($K^b_{RP_{DG}}$, $K^b_{RP_{PR}}$).

$${K^b_{RP_{BS}}}^2 \geq {x^b_{QG}}^2 + {x^b_{PG_{BS}}}^2 \quad \forall b \in B \tag{12}$$

$${K^b_{RP_{BS}}}^2 \geq {x^b_{QG}}^2 + {x^b_{PG_{BS}}}^2 \quad \forall b \in B \tag{13}$$

The following equation (14) tries to fix the voltage at bus b in a constant value, determining exceeded voltage (x^b_{VE}).

$$x^b_{VE} + x^b_{VM} = K^b_{VM} \quad \forall b \in B \tag{14}$$

c) Optimal operation process: objective function: The technical objective function z is divided in three terms, the first one minimizes the grid losses. The second is applied only in the disconnected operation, through disconnected factor (K_D) and penalizes the unused generation. The third penalizes any excess or deficit in voltage for all buses through the weighting factor. This factor penalizes an excess of voltage in terms of active power through a weighting factor (K_P)

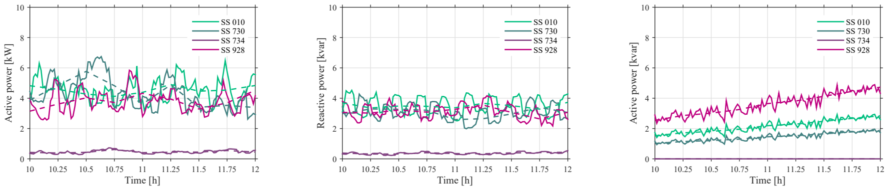
$$[\min] \quad z = \sum_{b \in B} x^b_{PT} - K_D x^b_{PG_{DG}} + K_P {x^b_{VE}}^2 \tag{15}$$

IV. STUDY CASE

This section presents a study case of the real pilot SRG, depicted in Fig.6, in order to validate the LEMS operation. The validation is carried out via two scenarios, the grid-connected operation (i) and the grid-disconnected operation (ii). In case (i), all sectors are interconnected and connected to the external grid (all S_{MV} are close). In addition, the high-level setpoints are supplied to the LEMS, therefore the LEMS has to adjust them and also determine reactive power setpoints. The case (ii) all the system is interconnected and disconnected from the external grid ($S_{MV}1$ is open), therefore the LEMS determine active and reactive power setpoints and low voltage setpoint for the IDPR which operates as a Master. The Figs. 7a and 7b depicts the real active and reactive power from the major substation for a day, in two sample times (LEMS resolution 1 min and GEMS resolution a quarter of hour), note the difference between them. Following, the Fig. 7c presents the active power setpoints for this interval.

V. RESULTS

This section depicts the performance of the LEMS in the low voltage grid. The optimization is carried out through Julia software [13] using the mathematical language called Jump [14] and the optimization solver called Ipopt [15] . Then,



(a) Real active power consumed by SS consumers (b) Real reactive power consumed by SS consumers (c) Real active power generated and quarter of hour active power setpoints for DGs

Fig. 7: Input data: with sample precision up to a minute (continuous line) and a quarter of hour (discontinuous line)

the obtained data is thread and depicted through mathematical software (Matlab) [16]. Figs. 8a and 8b present final active and reactive power setpoints for DGs and IDPRs, respectively, for the case (i). In addition, the Fig. 8c presents the expected voltage at SSs. Figs. 9a to 9c present final active and reactive power setpoints for DGs and IDPRs, which operate in slave mode, for the case (ii). Note, that the active power generated by DGs is not depicted because it is not enough to cover all the demand, therefore it is not curtailed. In addition, Fig. 9d depicts the expected active and reactive power injected by the IDPR master. Finally, Figs. 9e and 9f presents the voltage setpoint for IDPR master and the expected voltage for the rest of SSs.

VI. ACKNOWLEDGMENT

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VII. CONCLUSION

This paper has presented the LEMS operation. The LEMS is an energy management system for a determinate area, which can operate connected to the external grid either disconnected from it. Thus, the LEMS takes in account the pilot SRG configuration in order to operate. In addition, the LEMS collects the quarter of hour active power setpoints from a higher energy management system and modifies them according real-time measurements. In particular, the LEMS cycle spends only some seconds to complete the sequence.

The LEMS is a fundamental for the pilot SRG operation, because it adjusts and determines the final active and reactive power setpoints, with a minute resolution, improving the grid-response of DGs and IDPRs against load variations. In this sense, it has been observed that power consumed and generated variate rapidly, producing that quarter of hour septoints are not enough to perform correctly the SRG operation.

In addition, the DGs production is not enough to cover all the demand. Thus, it is required an additional contribution such as an emergency diesel generator, in order to operate continuously in island mode. However, if the fault or scheduled task do not require so many hours, the pilot SRG could survive this time.

ANNEX: PILOT SRG CONFIGURATIONS

This annex presents the pilot SRG configuration. Firstly, it is defined an electrical sector, which is an area that is formed by managing medium voltage switches, and it can collect more than one secondary substation. Therefore, a sector is an independent portion of electrical network that could operate isolated from external grid. Considering that there are three medium voltage switches (S_{MV}^1, S_{MV}^2, and S_{MV}^3) in the SRG pilot network, is be divided in three electrical sectors. Fig. 6 depicts three electrical sectors and medium voltage switches in the SRG pilot network scheme. In consequence, there are total of eight possible electrical configuration collected in the Table I.

TABLE I: SRG Electrical configurations

S_{MV}^1	S_{MV}^2	S_{MV}^3	Comments
open (0)	open (0)	open (0)	Sectors 1, 2 and 3 are disconnected from the external grid, and are isolated themselves.
open (0)	open (0)	close (1)	Sectors 1, 2 and 3 are disconnected from the external grid, sector 1 is completely isolated, and sectors 2 and 3 are interconnected themselves.
open (0)	close (1)	open (0)	Sectors 1, 2 and 3 are disconnected from the external grid, sector 3 is completely isolated, and sectors 1 and 2 are interconnected themselves.
open (0)	close (1)	close (1)	Sectors 1, 2 and 3 are disconnected from the external grid, and are interconnected themselves.
close (1)	close (1)	close (1)	All sectors (1, 2 and 3) are interconnected and are connected to the external grid
close (1)	close (1)	open (0)	Respected to the configuration (111), the sector 3 is isolated
close (1)	open (0)	close (1)	Respected to the configuration (111), sector 2 and 3 are isolated but interconnected between them
close (1)	open (0)	open (0)	The sector 1 is connected to the external grid, and sector 2 and 3 are isolated from the external grid and them

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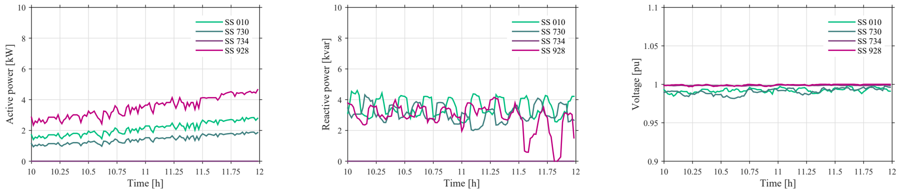
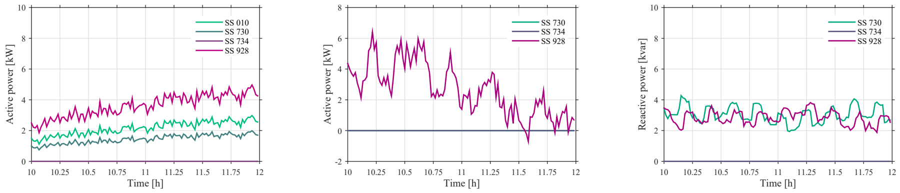
Apendix A: Local performance of the Smart Rural Grid

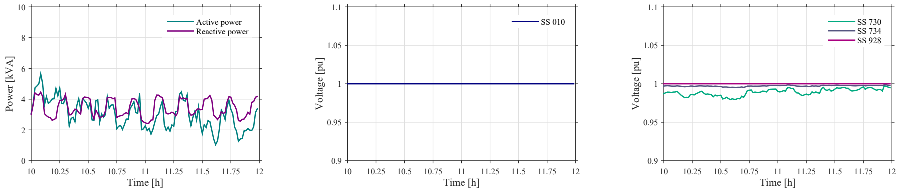


(a) DG active power setpoints (b) IDPR reactive power setpoint (c) Expected voltage

Fig. 8: Results for the case (i) with sample precision up to a minute



(a) DGs active power setpoints (b) IDPRs active power setpoints (slave) (c) IDPRs reactive power setpoints (slave)



(d) Expected IDPR active and reactive power (master) (e) Imposed voltage at IDPR master (f) Expected voltage

Fig. 9: Results for the case (ii) with sample precision up to a minute

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A.3 Summary

This Appendix has presented the Local Energy Management System operation. It runs both grid-connected and grid-disconnected operation. It processes the quarter of hour active power setpoints from a higher energy management system taking in account the network configuration and real-time measurements. Its cycle spends only some seconds to complete the optimization sequence and improves the grid-response of DGs and IDPRs against load variations. In this sense, it has been observed that the fast variations in power consumed and generated greatly affect the calculations of setpoints by the management system. Such setpoints, as calculated with a time step of 15 minutes, are not enough to perform correctly the grid operation.

Appendix B

Demonstration and Experience of the Smart Rural Grid Project

B.1 Introduction

This Appendix aims to illustrate an experience in grid-connected operation of the Smart Rural Grid project [48]. In particular, the presented experience focuses on the integration and management of an Intelligent Distribution Power Router together with a remote terminal unit, an industrial computer, and a robust telecommunications network.

B.2 Publication

ATTENTION ¡
Pages 118 to 123 of the thesis, containing the text mentioned above, are available at the editor's web
https://ieeexplore.ieee.org/document/7856257

B.3 Summary

This Appendix has presented how new devices are integrated to create a Smart Rural Grid, and how these devices can enhance the capabilities of existing rural grids. Focus is on the ability to manage the IDPR remotely through a console by means of an industrial computer and the remote terminal unit. In terms of performance, although it has been observed that the grid voltage at the point of common coupling is already good enough, total harmonic distortion at the secondary substation has been improved. Thus, it is concluded that the power quality for current waveforms can be greatly improved with the contribution of IDPRs.