Faculdade de Engenharia da Universidade do Porto

Dynamic Distribution System Reconfiguration to Improve System Reliability Considering Renewables and Energy Storage

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Resumo

O desenvolvimento económico e o crescente uso de novas tecnologias por parte dos consumidores fazem com que o fornecimento de energia, bem como a qualidade da mesma, se torne uma séria preocupação. Uma forma de abordar essa preocupação é implementando sistemas de distribuição automatizados com tecnologias inteligentes para melhorar a fiabilidade e a eficiência da operação de sistema. Os sistemas elétricos atuais estão em evolução devido às novas funcionalidades que o sistema elétrico deverá ter, nomeadamente a integração de fontes de energia renováveis em grande escala, a integração de veículos elétricos, a implementação de tecnologias de redes inteligentes, entre outras. Neste cenário, os Sistemas de Distribuição Inteligentes (SDI) devem operar e restaurar o serviço interrompido aos consumidores. Para que o sistema ganhe esta capacidade, é necessário substituir os interruptores manuais por interruptores controlados de forma remota, melhorando a capacidade de restauração do sistema tendo em vista a implementação de redes inteligentes. Este trabalho tem como objetivo desenvolver um novo modelo, determinando o conjunto mínimo de interruptores a substituir para automatizar o sistema, juntamente com uma análise de sensibilidade sobre a posição dos novos interruptores, que podem ser colocados no mesmo local dos substituídos ou num novo local. Neste trabalho as topologias são também otimizadas tendo em conta índices de fiabilidade e perdas de energia. A otimização do sistema é feita considerando a integração de fontes de energia renováveis na rede e sistemas de armazenamento de energia, simultaneamente com os requisitos económicos e funcionais do sistema. A ferramenta computacional é testada usando o sistema de teste IEEE 119 Bus, onde são considerados vários tipos de carga (residencial, comercial e industrial).

Palavras-chave— Automação de Distribuição, Sistemas de Distribuição Inteligentes, Fiabilidade, Redes Inteligentes, Restauração de Serviço

Abstract

Economic development and the use of more and more technologies by consumers pushing upwards the demands of consumers for reliable and quality energy supply. And, this is becoming critical concern for service providers. The increasing penetration of variable energy sources is even exacerbating the situation further; system operators in general are finding it increasingly difficult to deliver energy that meets the standards set by regulators and consumers themselves. Novel solutions should be at the system operators' disposal, particularly at distribution levels. One way to partly address this concern is through the implementation of automated distribution systems with intelligent technologies which improves the systems reliability and efficiency during operation. The present electrical systems are evolving due to the new functionalities that the electrical system is expected to have, namely the integration of renewable energy sources in large-scale, the integration of electric vehicles, enable smart grid technologies, among others. In this scenario, Distributed Smart Systems (DSSs) should operate and restore discontinued service to consumers. In order for the system to gain such ability, it is necessary to replace the manual switches for remotely controlled switches, improving the system restoration capability having in view the Smart Grids implementation. This thesis aims to develop a new model, determining the minimal set of switches that have to be replaced in order to automate the system, along with a sensitivity analysis on the position of the new switches, whether it should be placed in the same place as the manual switch or in a new location. In this work, different topologies are assessed taking into account different reliability indices and power losses. *The optimization of the system is made considering the renewable energy sources integration in the grid, energy storage systems simultaneously with the economic and functional requirements of the system, in order to improve the system reliability. The computational tool is tested and validated on the IEEE 119 Bus test system, where different types of load are considered (residential, commercial and industrial).*

Keywords—Distribution Automation, Distributed Smart Systems, Reliability, Self-healing, Smart Grid, Service Restauration.

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Cláudio Santos

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Abbreviation and Symbols

List of Abbreviations

CAIDI	Customer Average Interruption Duration Index
DDSR	Dynamic Distribution System Reconfiguration
DER	Distributed Energy Resources
DG	Distributed Generation
DN	Distribution Network
DSR	Distribution System Reconfiguration
ESS	Electrical Storage System
EPS	Electrical Power System
EU	European Union
LCC	Life Cycle Cost
NEDO	New Energy and Industrial Technology Development Organization
PCS	Power Converter System
RCS	Remote Control Switch
RES	Renewable Energy Sources
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
TCC	Total Capital Cost
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

List of Symbols

Sets/Indices

s/Ω^{s}	Index/set of scenarios
h/Ω^{h}	Index/set of hours
g/Ω^{g}	Index/set of generators
es/Ω^{es}	Index/set of energy storage
$\varsigma/\Omega^{\varsigma}$	Index/set of substations
l/Ω^{l}	Index/set of lines

Parameters

ρ_s	Probability of scenario s
OC_g	Cost of unit energy production
λ^{CO_2}	Emission rate of Substation
ER_g^{DG}	Emission rate of DG's
ER_ς^{SS}	Emission rate of energy purchased from substation
$PD_{s,h}^n$	Demand at node *n* (MW)
$QD_{s,h}^n$	Demand at node *n* (MVAr)
V_{nom}	Nominal voltage (kV)
η_{es}^{ch}	Charging efficiency
η_{es}^{dch}	Discharging efficiency
$E_{es,n}^{min}$	Energy Storage limit
$E_{es,n}^{max}$	Energy Storage limit
μ_{es}	Scaling factor
$P_{g,n,s,h}^{DG,min}$, $P_{g,n,s,h}^{DG,max}$	Power generation limits (MW)
pf_g	Power factor of DG's
pf_{ss}	Power factor of substation

Variables

$P_{\varsigma,s,h}^{SS}$, $Q_{\varsigma,s,h}^{SS}$	Imported power from grid (MW, MVAr)
$E_{es,n,s,h}$	Reservoir level of ESS (MWh)
$I_{es,n,s,h}^{dch}$, $I_{es,n,s,h}^{ch}$	Charging and discharging binary variables
$P_{g,n,s,h}^{DG}$, $Q_{g,n,s,h}^{DG}$	DG power (MW, MVAr)
$P_{\varsigma,n,s,h}^{SS}$	Imported power from grid (MW)
$\Delta V_{n,s,h}$	Voltage deviation magnitude (kV)
$\chi_{l,h}$	Binary switching variable of line l
$f_{l,h}$	Fictitious current flows through line l
$g_{n,h}^{SS}$	Fictitious current injections at substation nodes
$d_{n,h}$	Fictitious nodal demand
n_{DG}	Number of candidate nodes for installation of distributed generation

Functions

SWC	Switching cost term (€)
TEC	operation cost (€)
TENSC	Power not supplied cost (€)
TEmiC	Emissions cost (€)

Chapter 1

Introduction

This chapter presents a brief introduction to the topic, the problem definition and motivation, and the research objectives. This chapter also presents the methodology used in the work as well as the structure of the dissertation.

1.1 Background

Over the last century, the structure of the electric power system has been viewed, from the operation point of view, as a hierarchical structure. This traditional way of looking at the electric power system has 4 levels: production, transmission, distribution and consumption. This hierarchical system implies that the energy flow is unidirectional, from the highest levels of the hierarchy (large-scale production) to the lowest levels (consumption), both interconnected by the intermediate levels transport and distribution. This has several advantages, namely in terms of the production efficiency of large plants and the simplicity of transport and, above all, distribution. However, this structure has some disadvantages:

- The long distance between the points of production and consumption causes large infrastructural expenses on transmission networks and increases energy losses by transmission, which are as big as the distance traveled;
- Usually large production plants exploit resources that cause major environmental damage with the emission of harmful gases into the atmosphere, thus increasing the negative environmental impact;
- The networks hierarchical structure implies that, if there is a problem at a higher level, a large part of the network and its elements at lower levels are also affected.

It is in this context that, in recent years, a change of perspective of the electric energy system arises. The substantial increase in the interest of exploring more and more renewable energy sources is not compatible with the conventional form of the electrical system, so a restructuring of the electrical industry was necessary, which led to the separation of the different sectors previously integrated vertically, favoring the access to networks and creating competitive markets. Thus, the evolution to a liberalized market, along with the benefits of renewable exploration, has led the world governments to actively promote the adoption of distributed generation.

Recent technological developments have also contributed to the development of well-adapted applications in the field of distributed generation (wind generators and photovoltaic panels), but not only. From the technical point of view, the increasing penetration of distributed generation has strong implications such as problems at the stability levels of the operation and changes on the voltage profiles, resulting from the injection of energy into the distribution networks. As possible solutions to some of these problems, other technologies of interest appeared to improve the system's stability and reliability. An example of such technologies are energy storage systems, which together with the increasing penetration of renewable energy sources based distributed generation (RESs-based DGs) have helped to make the system smarter, moving more and more towards what it is today called a smart grid.

Another developed technology that helps this transformation and increases the system automation was the creation of the remotely controlled switches. Replacing the manual switches with these smart switches helps increase system reliability. The restoration of networks is a very important technique and must be done as quickly as possible so as not to compromise the energy supply to consumers. In Figure 1.1 are presented several key technologies and important aspects to develop the future smarter infrastructure grid.

Thus, it has been concluded that the distribution system automation has become very important in recent years in an attempt to make the grid as reliable as possible, while at the same time increasing in renewable energies exploitation.

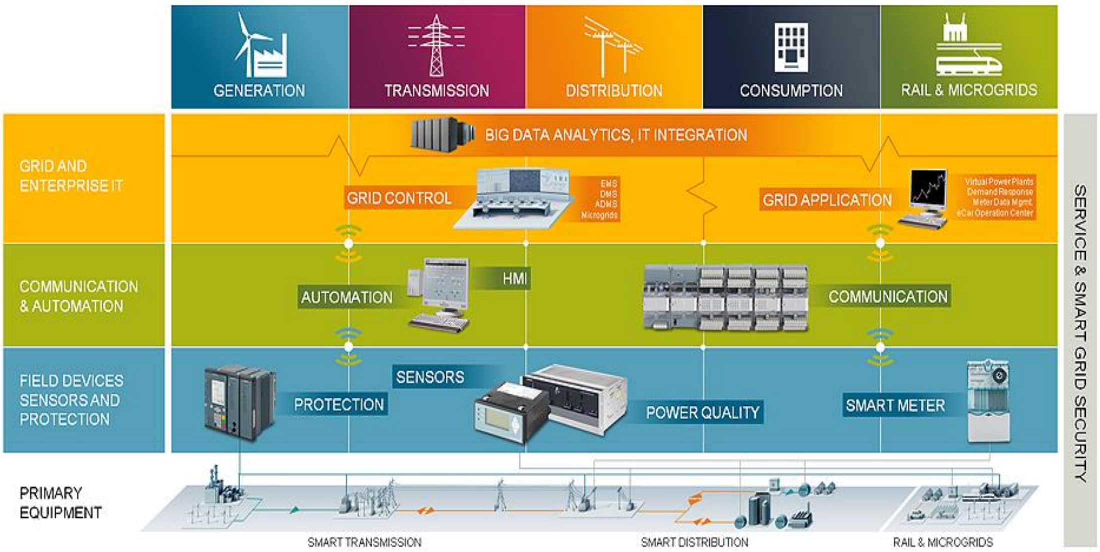

Figure 1.1- Future smarter infrastructure grid technologies [1].

1.2 Problem Definition

The economic development and the increase use of new technologies by consumers make the energy supply and the quality of energy a serious concern. One way to address this concern is to implement automated distribution systems with intelligent technologies to improve the reliability and efficiency of system operation. Current electrical systems are evolving due to the new features that the electrical system should have, namely the integration of large-scale renewable energy sources, the integration of electric vehicles, the implementation of smart grid technologies, among others. At the same time, there is the integration problem of RESs, especially with regard to the uncertainty and variability of these resources that affect the operation of the system on a large scale.

In this scenario, intelligent distribution systems must operate and restore the discontinued service to consumers. In order for the system to gain this capability, it is necessary to replace the manual switches with remotely controlled switches, improving the system restoration capability for the implementation of smart grids. Therefore, one of the problems is how identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration. Once the previous problem is solved, a new problem arises in terms of system operation due to the new network topological options. Which is the best topology to be used considering several reliability indices and system power losses at different hours throughout the day?

In this framework it is therefore necessary to develop operational models to solve the problems raised taking into account the system operational, economic and reliability constraints as well as meet international environmental objectives.

1.3 Research Objectives

The main objectives of this dissertation are:

- To develop an improve stochastic mixed integer linear programming (SMILP) operation model considering the presence of Distributed Generation based renewables, Energy Storage Systems and dynamic reconfiguration.
- Create a methodology on the system sensitivity analysis to identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration.
- Identify whether the automate switches will be placed, if only in places were manual switches exist or also in other places.
- Identify switches that require more maintenance due to dynamic reconfiguration.

- To study and optimize the network different topologies taking into account different reliability indices (System Average Interruption Duration Index- SAIDI- and System Average Interruption Frequency Index- SAIFI) and power losses.

1.4 Research Methodology

The proposed optimization model is a stochastic mixed integer linear programming (SMILP) type, for which there are quite many efficient off-the-shelf solvers. The model aims to optimally operate distribution network systems, featuring large-scale DERs, during the course of a day (i.e. over a period of 24-hours). The problem is programmed in GAMS 24.0 and solved using the CPLEX 12.0 solver. All the simulations are conducted in an HP Z820 workstation with two E5-2687W processors, each clocking at 3.1GHz frequency, and 256 GB of RAM.

1.5 Thesis Structure

This dissertation is divided in six chapters. Chapter 2 presents the state of art and the related concepts on the topic being studied. In Chapter 3 it is established the mathematical model developed, from the objective functions to the constraints used. Chapter 4 lists the electrical system data used, as well as all the assumptions taken to solve the problem. All the results of the simulations are presented and discussed in Chapter 5. Finally, Chapter 6 highlights the main conclusions of this work, the future works that can be done as well as the contributions of this dissertation.

Chapter 2

State of Art

This chapter presents the state of art and the concepts related to the automation of the electrical distribution system, with respect to the Distribution System Reconfiguration (DSR), in the presence of Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs), as well as the electrical system transformation and restoration process. Finally, an overview of the bibliographic review is also presented, focusing on the works most directly related to the present work, where the contribution of this work is evidenced in relation to those present in the bibliography.

2.1 Distribution System Reconfiguration (DSR)

2.1.1 Introduction and Definition

The distribution network is the electrical power system infrastructure section responsible for connecting the energy coming from the transmission network to the final consumers. The operation of these systems comes with a set of challenges, namely in terms of power losses. The power losses in the distribution network represent about 60-70% of the total losses in the electrical power system, which means that the reduction of those losses is a major priority in operational and economical terms. In addition, the increasing integration of variable loads and RES make conventional system operation strategies less efficient and more difficult to operate. One of the solutions to minimize the losses and help to integrate more RESs is the DSR [2]-[4].

DSR can be defined in a generic way, as a set of real-time procedures performed in order to lead to the change of the electrical network topology, so that it better adapts to the changes occurred in the energy production and/or consumption. These changes are ensured by the switching operations of the various switches installed in the network that enable or disable specific branches [4]-[9].

DSR objectives can have several objectives, such as [10]:

- Power losses reduction;
- Reliability improvement;
- Line maintenance costs reduction;
- Energy quality improvement;
- Voltage stability margin improvement.

2.1.2 Technology and Requirements

As mentioned earlier, DSR is ensured by the switches installed in the network, which allow to change the topology of the distribution network. There are two types of switches: those normally open, known as tie switches, and those that are normally closed, the sectionalized switches. DSR can operate both in normal or emergency conditions and, although it was created with the purpose of obtaining a network radial topology that leads to the least losses possible, today is also used to reduce system interruptions that affect consumers, with the goal to improve the system global reliability. The DSR contributes to improve system reliability can be seen in Figure 2.1. [11]:

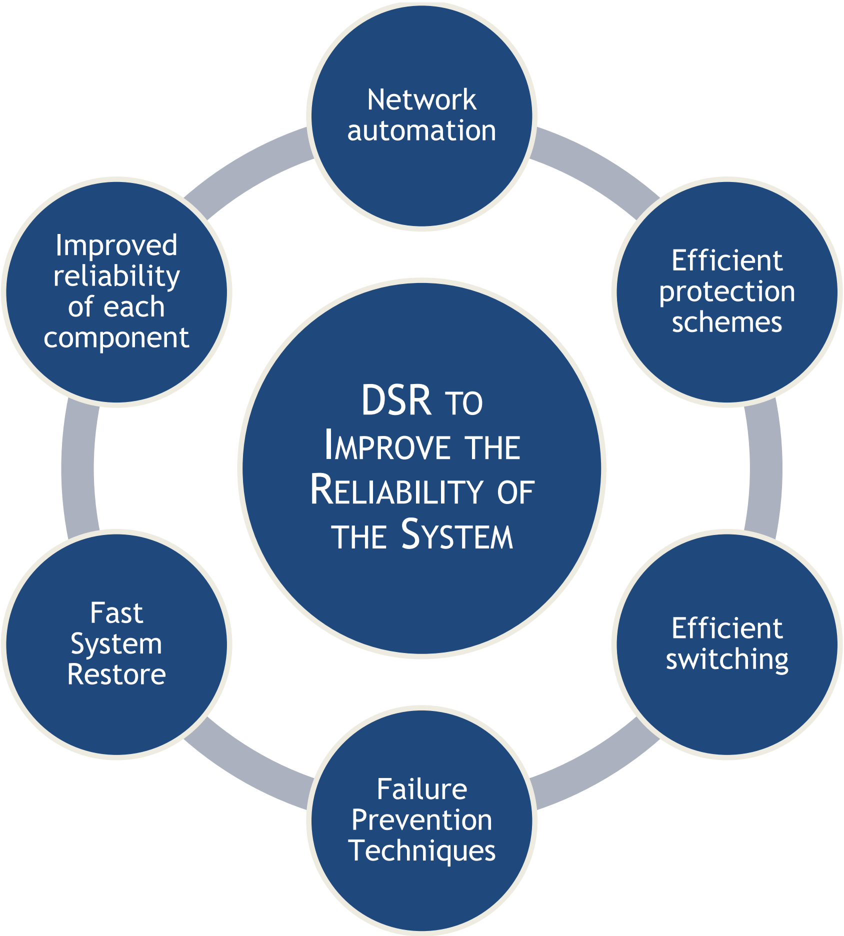

Figure 2.1- DSR contributes to improve system reliability.

2.1.3 Advantages and Challenges

Reconfiguration is an important task since by changing the grid topology it allows the operator to reduce the operational power losses as well as allows the network to accept a greater amount of RESs, unlike static networks. Furthermore, it also helps the network operator to avoid network capacity violations or overvoltage's. At the distribution network level, DSR can also help the network operator to restore service after accidents that lead to service failure and help prevent other service interruptions and corresponding penalties. In the case of networks with DGs, reconfiguration can also help reduce losses and prevent current and voltage violations that may be caused by the presence of DGs itself [9], [11], [12].

A reconfigurable network can change its topology by switching operations, whose positions determine the active or inactive operation of a line. However, the network topology depends on several parameters and needs to be updated according to the data received on a daily, weekly, monthly or seasonal basis, to be correctly adapted to the changes it is subjected to throughout its operation [6]–[8], [10], [13], [14].

DSR has had as its main objective the reduction of electrical power losses. However, when considering real-time automatic reconfiguration (dynamic reconfiguration), there are some challenges to consider, such as [15]:

- A cost-benefit relationship needs to be established to determine the need and the effectiveness of the reconfiguration;
- The network must be flexible enough to allow reconfiguration;
- The technical viability of the switching operations must be studied in real time, considering the availability of real-time measurements of the network.

Agents involved in a distribution network can be identified by buses where power is injected or consumed and lines, which serve as a link between several buses [13].

2.1.4 Switching Frequency

The DSR has a great economic potential of cost reduction if the switching operations are optimized for an optimum frequency. In order to analyze daily, weekly, monthly, and seasonal reconfiguration plans for a consecutive year, studies were carried out in which manual switches were replaced by intelligent control switches and, according to the results, the changing of the switching frequency led to great economic savings [10].

2.2 Renewable Energy Sources (RES)

2.2.1 The Need for Change

Recently, the introduction of RESs has become a global need, given the great technical, economic and environmental advantages of its integration [16]-[20]. Three of the main reasons for this shift in the energy paradigm are [21]:

1. Environmental problems leading to increasing concerns;
2. The large transmission distances between production and consumption points, which result in high electrical power losses;
3. The demand increase that leads to more congestion in feeders.

As the years pass by, there are more and more government measures in countries all around the world that are conducting their efforts with the common goal of replacing all large traditional fossil-based power plants with RES-based generating units [21], [22].

One technique used to reduce energy losses in the distribution system is the interconnection of a local generation unit, since a production closer to consumption will reduce the losses that normally occur in the transport of energy between generation and consumption points. Examples of these local production units are the small generators that exploit renewable energy resources (mainly solar and wind farms, but also mini-hydro and biomass). Typically, this type of generation is known as distributed generation, which consists of lower power generators that are strategically connected directly to the distribution network [5], [17]-[19], [21], [22]. The energy generated from RES-based DGs is constantly growing, as [5] shows in Figure 2.2.

This growth is expected to continue, with RES penetration expected to exceed 25% of the total energy capacity generated soon in developed countries. Studies also show that the use of RES can reduce carbon emissions by 60% by the year 2050 [5].

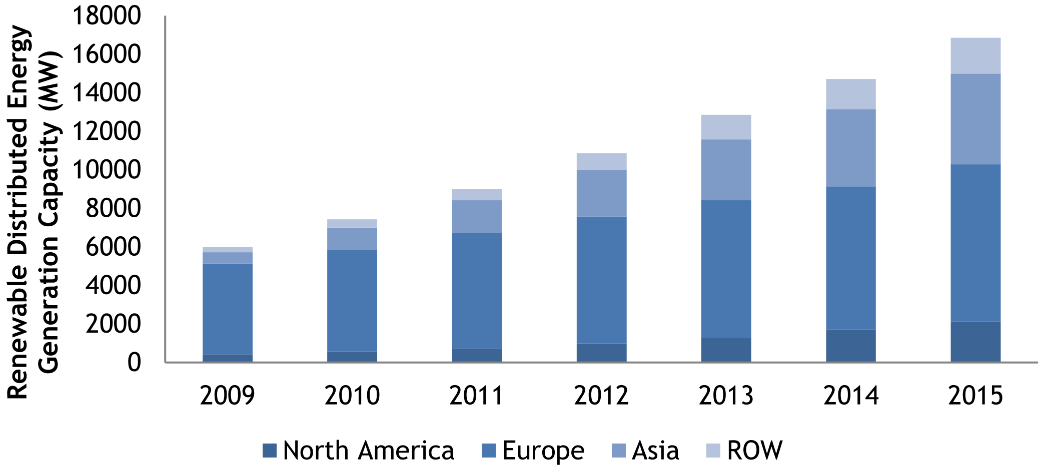

Figure 2.2- RESs-based energy generation annual capacity [5].

Traditionally, the DGs was dedicated to the energy production close to the loads or in an isolated way, being defined as a source of energy directly connected to the distribution network or to the consumer. However, DGs are becoming increasingly important in the context of the energy production decentralization and the high RESs penetration, contributing to the network with technical, economic and environmental benefits. Among them [23]:

- Power losses reduction in feeders;
- Voltage levels stability improvement;
- Fuel cost reduction;
- Independence of large traditional producers;
- Lower electricity price;
- CO_2 emissions reduction

2.2.2 RESs-based DGs Integration Challenges

Given the passive configuration of the distribution networks, integrating DGs on a large scale is not technically feasible, since it brings major challenges for the system operation, especially in terms of energy quality and stability [16], [17]. Therefore, the disadvantages of integrating DGs into the network are due to the changes in the distribution system, since in most cases the network isn't technically prepared to receive de DGs or to lead with the effects of its integration. The main challenges for the RES-based DG integration are [23]:

- Bi-directional power flow;
- Higher system frequency oscillations;
- Need to redesign all network protection systems;
- Uncertain production (due to the stochastic nature of the sources).

These limitations can, however, be mitigated as soon as the distribution networks complete its evolution process to active grids (smart grids) [16].

2.2.3 DGs Size and Installation Optimization

Given the technical-economic factors, the integration of RESs in the electrical system cannot be delayed [24]. However, although the use of RESs contributes positively to the environment, they also contribute to considerable uncertainty as regards to the energy production.

Therefore, it's very important for the distribution system that optimal models are developed to best resolve DG planning. In case of an energy demand rise, distribution companies invest in feeders, DG units or any combination of them. One of the great challenges is the optimally allocating and dimensioning of the new DG units in the network [17], [18], [21]-[23], [25].

Given the challenges that come with the high RESs penetration, their integration into the network still requires adaptation processes to improve network flexibility. From the network stability and reliability perspective, the integration of RESs-based DG creates major technical challenges, given the great variability of operation that makes it difficult to control the planning and operation of the system. In this context, mathematical models are developed considering the design and location of ESSs and reactive power sources that, together, favor the penetration of RESs. In addition, energy losses, carbon emissions and their costs can be reduced, and the network can also benefit from an improved voltage stability [17], [26].

2.2.4 RES-based DGs Integration: current world position

The need for electricity is increasing, given the fast fossil resources depletion that have always been exploited as the main source of energy. Moreover, the fact that a large number of producing countries are located in unstable geopolitical areas, together with global warming, lead to the search for new energy sources [18], [27].

In this context, governments all over the world direct all their efforts in an attempt to promote the RESs exploitation, since they are resources with no shelf life and that they don't have great risks of accident associated with their exploitation and maintenance [27]. To cope with the climate change and achieve acceptable levels of carbon gas emissions, developed countries must develop strategies to adapt to a new pattern of economic development based on a perspective of reducing environmental damage and thus create a new and sustainable way of looking at energy [28], [29].

Despite having considerable installation costs, renewables are the key element of the new priorities of the European energy policy. The significant potential for exploration in Europe, given the large resources available, gives the European Union (EU) the possibility of creating an energy sector that can be competitive and reliable, while at the same time sustainable. In addition, other political advantages are [27]:

- Reducing dependence on energy imports;
- Energy security of supply improvement;
- Carbon emissions reduction.

World leaders demand an immediate reduction in the emission of polluting gases into the atmosphere, setting very ambitious targets for 2050. The EU states have already established that by 2050 gas emissions must be 80-95% below 1990 levels. Another European strategy is to reduce the same levels by 20% by 2020 [27]. For example, in Germany the high number of renewables installed is also causing changes in the system operation and influencing coal-fired power plants, traditionally the largest source of energy in that country. In 2034, the total power capacity extracted from wind and sun is predicted to be approximately 173 GW double the current peak in the country [28].

In the United States, a country known by its high energy consumption, most part of energy comes from thermal power plants (68.4%). However, according to plans for energy announced by the US Department of Energy in 2030, 20% of the country's electricity will be generated from the wind and 10% from solar photovoltaic systems [28].

2.3 Energy Storage Systems

2.3.1 The need for ESSs

The increased exploration and penetration of RESs into the network is a major step in promoting energy savings and reducing carbon emissions. Nowadays there is a great concern to integrate more RESs, in order to solve problems of great worldwide concern as [30]:

- Increased energy demand;
- Reduced energy security;
- High dependence on fossil fuels;
- High carbon emissions into the atmosphere.

However, the truth is that a lot of installed RES cannot be fully charged, leading to huge waste of energy [28], [31].

Although the purpose of the DGs is to supply energy to local loads, where production exceeds demand at certain times, DGs units may be interconnected to the grid thus providing excess power and causing grid stability problems [32]. Moreover, given the stochastic nature of RESs units, their high penetration into the grid can cause stability problems in network operation and control. These problems can be mitigated with the help of ESSs [30]-[33].

Thus, coordinating the integration of RESs with ESSs, as well as with the reconfiguration capability of the network, can significantly improve the system's ability to increase the penetration of RESs reliably and safely [30], [32]-[35]. After the installation of large-scale energy and performance storage technologies, electricity will become a commodity and can be stored when the generation capacity exceeds the level of consumption [28]. In addition, ESSs help to control a secure supply of energy and improve the overall stability of the electric power system [36].

2.3.2 ESSs Challenges

ESSs are a viable solution to help increase the RESs penetration into the power grid as discussed above. There are several application technologies for these systems, differing greatly in investment costs depending on the system capacity, their useful life, storage losses, efficiency and reaction times. Of all the challenges of integrating ESSs, the cost of this equipment is the one that stands out more [33].

The costs of ESS systems can be divided into two types: total capital cost (TCC) and life cycle costs (LCCs) [36]. TCC involves all costs of purchasing, installing and delivering the storage unit, including energy storage costs and energy balance costs. On the other hand, the LCC is an important indicator to evaluate and compare different ESS, since it includes all the expenses related to its operation and maintenance [36].

2.3.3 Technology and Operation

To solve the problems previously presented associated with the large-scale integration of RESs, several technologies were created within the scope of the electric grid innovation - smart grid - that are implemented in the network always coordinated with the integration of RESs, in order to increase the network's capacity to integrate renewable sources. One of those technology is the so-called ESSs, which has proven to be a highly feasible solution in favor of increasing the integration of RES-based DGs units, reducing its negative side effects to the network [30], [37].

In general, ESSs technologies include 2 main areas: a power conversion system (PCS) and a power storage section. PCS is used to adjust voltage, current, and other storage characteristics, always based on load requirements [36].

Looking at the ESSs technical and economic characteristics, the different technologies can be divided into:

- Mechanical energy storage systems;
- Electrochemical storage batteries;
- Electromagnetic energy storage systems;
- Gas energy storage system.

In addition to helping to compensate the injected power in the local load and the absorbed power from the generators [30], the ESSs implementation in the network helps to balance RESs production and demand levels by storing energy in periods of too low demand or too high production and using this stored energy to power loads when the demand is too high or the production is too low [32]-[35].

The ESSs performance mainly depends on the application requirements that are specific to each level of energy and voltage, such as power, conversion efficiency and charge and discharge times [28].

2.3.4 ESS integration: Current world position

Since ESSs must be strategically positioned, a number of countries have contributed to studies and projects in the search for new storage techniques that optimize the process. In 2013, Japan's Technological Development and New Energy Development Organization (NEDO) developed a plan for all types of ESSs techniques, with special focus on the development of lithium batteries. Late in 2014, the United States Department of Energy released relevant technical reports on the development and application of all types of advanced batteries, also with special attention to lithium batteries and advanced energy storage technologies through compressed air [28]. In the circle graph on Figure 2.3 it can be seen the installed energy storage capacity worldwide in 2016.

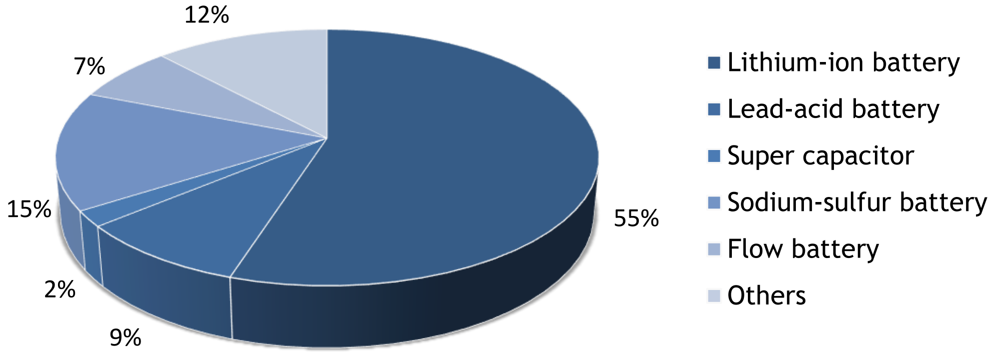

Figure 2.3- Installed energy storage capacity worldwide in 2016 [28].

Recently, the energy storage industry has highly grown. In December 2016, 1227 energy storage projects were conducted throughout the world, and the total installed capacity exceeded 1930 MW. In these projects, most of the systems used are based on lithium batteries (approximately 55%) [28].

2.4 Restoration and Transformation of the Electric Power System

2.4.1 Restoration of the Electric Power System

Service failures and outages are inevitable in a distribution network. Consequently, the zone where they occur (and other zones) are momentarily out of power. DSR can be used to restore as many loads as possible by reallocating power flows without violating network operation [38]-[40].

In an electrical power system, most failures occur in the distribution network, usually resulting in the interruption of service to some consumers. Traditionally, when the failure occurs and the service stops, consumers call the respective distribution company. Upon receiving a service failure notification, a field crew is sent to search for the exact location of the fault and isolate it via manual switches, restoring the service to as many consumers as possible while repairing the failure [41]–[45]. There are 3 main factors in the origin of the occurrence of distribution network failures: tree fall, animal and atmospheric interference, as can be seen in Figure 2.4. In most current distribution networks, the restoration is done manually, with the opening and closing of switches. However, with an automated system, restoration can be performed in less time and even decrease the number of members of the field crew [7], [8], [43], [46], [47].

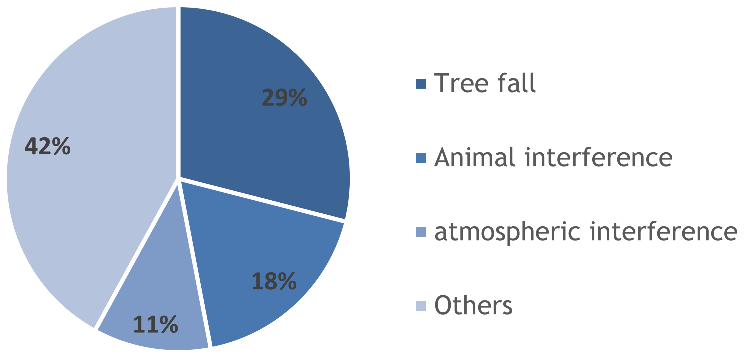

Figure 2.4 - Accidents that cause network failure **[46]**.

To evaluate the performance of electrical systems, some indices such as the System Average Interruption Frequency Index (SAIFI), the System Average Interruption Duration Index (SAIDI) and the Customer Average Interruption Duration Index (CAIDI) are usually used. These indices include the so-called extended service outlets, which are those that last longer than five minutes. An automated system reduces the number of these service outlets and also locates and isolates the fault automatically and almost instantaneously, thus preventing service outlets in zones that do not belong to the fault zone [42], [43], [46], [48], [49].

2.4.2 The Smart-grid and the Self-healing

Energy production in large power plants and their delivery at points of consumption constitute the classic tasks of a power grid. However, the technology advance and the evolution of the human need have raised some difficulties in terms of operation, control, efficiency and reliability, which require a change of perspective, including [50]:

- Large number of components interconnected to the distribution network;
- Any failure of a component can easily affect another component instantly;
- Several connections and dependencies between components and networks, which make the creation of mathematical models a complex challenge.

The distribution network automation helps the DSR process, because it makes it possible the respond to possible problems more quickly. This reduces the number of interventions by the operator and leaves the network less subject to human error [49]. In addition, for large-scale systems with a more complex topology, the computational load of only one control center is quite high, which makes DSR decision slower, limiting the system restoration performance. The grid evolution to a smart grid, with the integration of sensor-based technology, control methods and better (bilateral) communication among network components, among others, is view has a possible solution to this complex challenge. This new grid will adopt a decentralized control method, increasing the flexibility of the network and improving DSR processes, restoration and even fault detection, coordination of protections and voltage control [20], [38], [40], [50]-[53]. The Table 2.1 shows the main differences between the traditional perspective of the network and the new way of facing the electric system - the smart grid.

Table 2.1- Differences between the traditional network and the smart grid **[20]**.

Traditional Grid	Smart Grid
Mechanization	Digitization
One-way communication	Two-way real-time communication
Centralized power generation	Distributed power generation
Radial Network	Dispersed Network
Less data involved	Large volumes of data involved
Small number of sensors	Many sensors and monitors
Less or no automatic monitoring	Great automatic monitoring
Manual control and recovery	Automatic control and recovery
Less security and privacy concerns	Prone to security and privacy issues
Human attention to system disruptions	Adaptive protection
Simultaneous production and consumption	Use of storage systems
Limited control	Extensive control system
Slow response to emergencies	Fast response to emergencies
Fewer user choices	Vast user choices

The smart-grid, when prepared with self-healing and subjected to a failure, can automatically detect it and act according to make the restoration process more quickly and automatically, improving the overall reliability of the system. The goal of self-healing is to minimize the duration of service outputs as well as interruptions felt by consumers, increasing the reliability of the system [40], [46], [51]-[53].

2.4.3 Switches

A smart grid should restore service to consumers who saw it interrupted as quickly as possible after a service exit. Remote-controlled switches (RCSs) can be operated by the system operator in the distribution center, which makes DSR much faster when compared to manual switches by field crews. Replacing manual switches by RCSs improves the restoration capacity of the network and must be done in a functional and economical way. The maximum restoration capacity must be obtained by replacing the minimum possible number of switches so as not to excessively increase the costs associated with the replacement [54]-[56].

The Dynamic Reconfiguration of Distribution Systems (DRDS) consists on real-time RCS operations. To support the operation and control of the RCS's, a distribution automation system is still required, as can be seen in Figure 2.5 [56], [57].

The effectiveness of DRDS in DGs integration has been studied based on two aspects:

- Use DRDS to maximize the exploitation capacity of existing DGs units and the penetration of new DGs units;
- Use DSDR to optimize other objectives, canceling out the negative effects of DG.

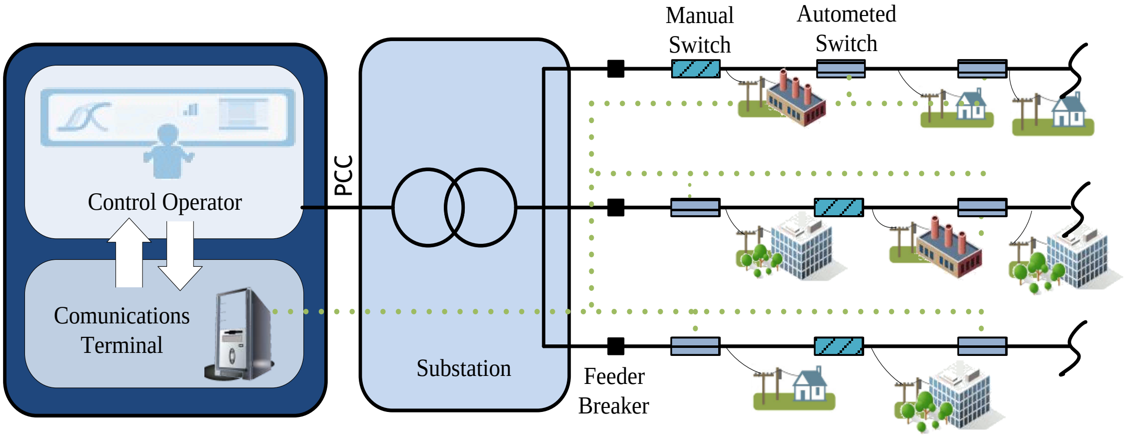

Figure 2.5 - Distribution automation system structure.

It has been proven that RCSs bring network advantages to the flexibility of operation and speed of response to urgent and instant needs. However, it is not as simple as replacing all manual switches with RCSs: these are considerably more expensive at both installation and maintenance level. This is where the critical switch concept emerges: the ideal manual switches to be replaced by RCSs in order to optimize the cooperation with the installation of DG in the network in the most economical way possible [57].

2.5 Bibliographic Review

Existing works on system reconfiguration mainly focus on reducing energy losses as its main objective, and also distributed energy generation through renewable energy sources [3], [58]. However, in recent years, DSR has been gaining more notoriety due to the electrical networks technologic evolution, from static to dynamic networks in the sense of their smartification, both in normal system operation and in contingency mode. On the smartification side, the DSR stands out with the system automation, to make it dynamic in the perspective of an optimized operation. Similarly, the DSR in contingency operation stands out from the perspective of self-healing, being a key element for the autonomous and more efficient recovery, from the system in contingency state to a normal operating state.

In this perspective, there is a very restricted set of works on the DSR operation. Regarding the analysis of reliability indices, *Paterakis et al.* presents in [59] a study on system reconfiguration formulated through a multi-objective problem that aims to minimize energy losses, while also optimizing some reliability indices. In the same context, Chen et al. presents in [60] a method that analyzes some reliability indices taking into account the total supply capacity of the distribution network, the reconfiguration of the network and the daily demand curves.

Regarding switches and their central role in system reconfiguration and restoration, several papers address optimal ways to allocate switches along system lines [61], [62]. One of the most important points about switches is the replacement of manual switches with RCS. *Bernardon et al.*, in [15], presents a new methodology for the DSR to be done automatically, incorporating DGs units in the operation of the system and only considering RCS. The problem in this method is that it is not practical to consider all switches as RCS, since the price of replacing them all would be exorbitant. In this way, Lei *et al.* introduces in [57] the concept of "critical switch", which represents the minimum number of manual switches to be replaced by RCSs that will make dynamic reconfiguration more efficient. Thus, this paper studies the application of the DRDS with DGs integration and seeking to minimize energy losses, while also identifying which key switches to replace at the lowest possible cost. Despite this, *Lei et al.* does not solve in this work the problem of the optimal allocation of RCSs.

Therefore, after knowing how many and which switches to replace, the biggest problem lies on where to place the RCSs to maximize their performance. Lei *et al.* in [55], [63] have looked for new methods that allow to optimally allocate the RCSs so that the system restoration performance can be improved, as well as the overall system reliability, all at the lowest possible cost. In [55], *Ray et al.* defends that the optimization of the number and location of RCSs must take into account three different main objectives: to reduce the interruption cost to the consumer as much as possible, to minimize the interruption duration index (SAIDI), and to maximize the quantity of loads that can be restored using the RCSs. A model formulated as a Mixed Integer Conic Programming (MICP) is proposed that seeks to optimize the number and location of the switches so that the system restoration is automatic and as fastest as possible.

The present work focuses on two objectives: performing the DRDs while improving the system restoration capacity after a failure. Therefore, initially, the system is dynamically reconfigured, and then the goal is to identify the minimum number of switches that must be updated for RCSs to improve the system overall performance as well as the ability to restore. In addition, an analysis is also made of SAIDI and SAIFI reliability indices. A sensitivity analysis is made based on hourly reconfiguration topologies, the number of consumers affected during a fault, the power supplied to the consumer and the energy losses in the system. With this analysis, it is also intended to identify the switches that will require greater maintenance actions.

2.6 Chapter Summary

In this chapter, the state of art was structured in five main sections. The first section presents the concept of DSR, its objectives, requirements, advantages and disadvantages. The second section addresses the need to integrate renewable-based distributed generation resources, the challenges underlying this integration together with the current state of play of this resource. The third section is dedicated to ESSs, presenting the technologies that facilitate the creation of smart grids. Also, the main challenges, technologies and the current state of integration of these resources in the network are discussed in this section. The fourth section presents the problems about system restoration, and the evolution of the electrical system from static to dynamic in the perspective of the distribution network, focusing on smart-grids and self-healing. Finally, in the fifth section provides an overview of the bibliographic review, based on the works present in the literature that are related to the present work. Here the contributions of this work are also presented.

Chapter 3

Mathematical Formulation

In this chapter it is described and demonstrated the algebraic formulation of a model to make it possible to identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration, in the presence of renewable energy sources based distributed generators and energy storage systems. The problem is formulated as a stochastic mixed integer linear programming and it aims to minimize the total cost. In addition, the formulation to study and optimize the network different topologies taking into account different reliability indices is presented.

3.1 Objective Function

The objective of the current work is to minimize the set of switches to be updated from manual to automatic based on dynamic reconfiguration while considering the technical and economic constraints. The objective function was formulated as the sum of the most relevant cost terms (3.1), namely, the costs related to network reconfiguration (switching, SWC), the costs of operation (TEC), the costs of emissions ($TEmiC$) and cost of power not supplied ($TENSC$).

$$MinTC = SWC + TEC + TENSC + TEmiC \tag{3.1}$$

The switching cost term is presented in (3.2). This equation represents the switching costs sum of all lines in the operating period (24 hours). The switching cost of a line SW_l, at a given time is multiplied by a binary variable that for programming reasons is divided into two $y_{l,h}^{+}$ and $y_{l,h}^{-}$ allowing to count if one line change its status from the previous hour to the current time.

$$SWC = \sum_{l \in \Omega^l} \sum_{h \in \Omega^h} SW_l * (y^+_{l,h} + y^-_{l,h}) \tag{3.2}$$

The total operation cost (3.3) is given by the sum of costs of power produced by DGs, discharged from ESSs and imported from upstream grid. In this equation $\rho_s$represents the probability of a scenario to occurrence. The parameters OC_g, λ^{es} and λ^{ς}_h represent the cost of production from the DGs, the cost of discharging from ESSs and the cost of the energy that come from the upstream network over the several hours, respectively. The variables $P^{DG}_{g,n,s,h}$, $P^{dch}_{es,n,s,h}$ and $P^{SS}_{\varsigma,n,s,h}$ are DGs power, ESSs discharging power and imported power from grid, respectively.

$$\begin{aligned} TEC = & \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{g \in \Omega^g} OC_g P^{DG}_{g,n,s,h} \\ & + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{es \in \Omega^{es}} \lambda^{es} P^{dch}_{es,n,s,h} \\ & + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{\varsigma \in \Omega^{\varsigma}} \lambda^{\varsigma}_h P^{SS}_{\varsigma,n,s,h} \end{aligned} \tag{3.3}$$

The cost of power not supplied, given by *TENSC*, in (3.4), where $v^P_{s,h}$ and $v^Q_{s,h}$ are penalty terms corresponding to active and reactive power demand curtailment, $P^{NS}_{n,s,h}$ and $Q^{NS}_{n,s,h}$ are the active e reactive unserved power.

$$TENSC = \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} (v^P_{s,h} P^{NS}_{n,s,h} + v^Q_{s,h}\, Q^{NS}_{n,s,h}) \tag{3.4}$$

Finally, equation (3.5) refers to the total cost of emissions as a result of power either supplied by DGs or imported from upstream. The first equation term is the sum of the product of emissions cost λ^{CO_2}, emissions rate of DGs (ER^{DG}_g) and DGs power ($P^{DG}_{g,n,s,h}$). The second equation term models the expected emission costs of power imported from the grid, given by the sum of the emissions cost λ^{CO_2}, emission rate of energy purchased (ER^{SS}_{ς}) and energy imported from grid ($P^{SS}_{\varsigma,s,h}$).

$$\begin{aligned} TEmiC = & \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{g \in \Omega^g} \sum_{n \in \Omega^n} \lambda^{CO_2}\, ER^{DG}_g P^{DG}_{g,n,s,h} \\ & + \sum_{s \in \Omega^s} \rho_s \sum_{h \in \Omega^h} \sum_{\varsigma \in \Omega^{\varsigma}} \sum_{n \in \Omega^n} \lambda^{CO_2}\, ER^{SS}_{\varsigma} P^{SS}_{\varsigma,s,h} \end{aligned} \tag{3.5}$$

3.2 Constraints

3.2.1 Kirchhoff’s Law

The sum of all incoming flows to a node should be equal to the sum of all outgoing flows, which is given by the *Kirchhoff’s Law*. This is applied to both active (3.6) and reactive (3.7) power flows, and must be always respected:

$$\sum_{g\in\Omega^{g}} P^{DG}_{g,n,s,h} + \sum_{es\in\Omega^{es}} \left(P^{dch}_{es,n,s,h} - P^{ch}_{es,n,s,h}\right) + P^{SS}_{\varsigma,s,h} + P^{NS}_{n,s,h} + \sum_{in,l\in\Omega^{l}} P_{l,s,h} - \sum_{out,l\in\Omega^{l}} P_{l,s,h} = PD^{n}_{s,h} + \sum_{in,l\in\Omega^{l}} \frac{1}{2} PL_{l,s,h} + \sum_{out,l\in\Omega^{l}} \frac{1}{2} PL_{l,s,h}\,, \forall\varsigma \in i \tag{3.6}$$

$$\sum_{g\in\Omega^{g}} Q^{DG}_{g,n,s,h} + Q^{c}_{c,n,s,h} + Q^{SS}_{\varsigma,s,h} + Q^{NS}_{n,s,h} + \sum_{in,l\in\Omega^{l}} Q_{l,s,h} - \sum_{out,l\in\Omega^{l}} Q_{l,s,h} = QD^{n}_{s,h} + \sum_{in,l\in\Omega^{l}} \frac{1}{2} QL_{l,s,h} + \sum_{out,l\in\Omega^{l}} \frac{1}{2} QL_{l,s,h} \, \forall\varsigma \in i \tag{3.7}$$

In these equations $P_{l,s,h}$ and $Q_{l,s,h}$ represent the active and reactive power flow in the line respectively, $PD^{n}_{s,h}$ and $QD^{n}_{s,h}$ and represent the active and reactive demand at the nodes and $PL_{l,s,h}$ and $QL_{l,s,h}$ represent the active and reactive energy losses in the lines.

3.2.2 Kirchhoff’s Voltage Law

Inequalities (8) and (9) present the linearized AC power flows through each feeder, which are governed by the *Kirchhoff’s Voltage Law*. Note that $\theta_{l,s,h}$ refers to the angle difference $\theta_{n,s,h} - \theta_{m,s,h}$ where n and m are bus indices corresponding to the same line l. The process of linearization is shown in Annex A.

$$\left|P_{l,s,h} - (V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)g_{k} - V^{2}_{nom} b_{k} \theta_{l,s,h}\right| \leq MP_{l}(1 - \chi_{l,h}) \tag{3.8}$$

$$\left|Q_{l,s,h} - (-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)b_{k} - V^{2}_{nom} g_{k} \theta_{l,s,h}\right| \leq MQ_{l}(1 - \chi_{l,h}) \tag{3.9}$$

It is important to note that, due to the reconfiguration problem, equations (3.8) and (3.9), have binary variables to make sure the flow through a given line is zero when its switching variable is zero (line is disconnected). Moreover, the introduction of those variables results in bilinear products which can result in undesirable non-linearity. For that reason, it’s important to use the big-M formulation, set to the maximum transfer capacity, to avoid the non-linearity.

3.2.3 Power Limits

The maximum amount of flow that can pass through a line is given by inequality (3.10). Equations (3.11) and (3.12) represent active and reactive power losses in a given line l.

$$P_{l,s,h}^{2} + Q_{l,s,h}^{2} \leq \chi_{l,h}(S_{l}^{max})^{2} \tag{3.10}$$

$$PL_{l,s,h} = \frac{R_{l}\left(P_{l,s,h}^{2} + Q_{l,s,h}^{2}\right)}{V_{nom}^{2}} \tag{3.11}$$

$$QL_{l,s,h} = \frac{X_{l}\left(P_{l,s,h}^{2} + Q_{l,s,h}^{2}\right)}{V_{nom}^{2}} \tag{3.12}$$

3.2.4 ESSs model

ESSs are modeled by the expressions (3.13) - (3.18).

$$0 \leq P_{es,n,s,h}^{ch} \leq I_{es,n,s,h}^{ch} P_{es,n,h}^{ch,max} \tag{3.13}$$

$$0 \leq P_{es,n,s,h}^{dch} \leq I_{es,n,s,h}^{dch} P_{es,n,h}^{ch,max} \tag{3.14}$$

$$I_{es,n,s,h}^{ch} + I_{es,n,s,h}^{ch} \leq 1 \tag{3.15}$$

$$E_{es,n,s,h} = E_{es,n,s,h-1} + \eta_{es}^{ch} P_{es,n,s,h}^{cg} - \frac{P_{es,n,s,h}^{dch}}{\eta_{es}^{dch}} \tag{3.16}$$

$$E_{es,n}^{min} \leq E_{es,n,s,h} \leq E_{es,n}^{max} \tag{3.17}$$

$$E_{es,n,s,h0} = \mu_{es} E_{es,n}^{max}, E_{es,n,s,h24} = \mu_{es} E_{es,n}^{max} \tag{3.18}$$

The limits on the amount of power charged and discharged are given by (3.13) and (3.14), respectively, while (3.15) guarantees that charging and discharging processes do not simultaneously happen at any given time.

The state of charge is modelled as presented in (3.16). Inequality (3.17) ensures that the storage level is always within a permissible range. Finally, (3.18) sets the initial storage level and ensures the storage is left with the same amount at the end of the operational period. For sake of simplicity, both η_{es}^{ch} and η_{es}^{dch} are often set equal and their efficiencies are expressed in percentage of energy at the nodes where ESSs are connected to.

3.2.5 Renewable Generation Power Limits

The active and reactive power limits of DGs are given by (3.19) and (3.20), respectively. Inequality (3.21) limits the DGs ability to inject or consume reactive power.

$$P_{g,n,s,h}^{DG,min} \leq P_{g,n,s,h}^{DG} \leq P_{g,n,s,h}^{DG,max} \tag{3.19}$$

$$Q_{g,n,s,h}^{DG,min} \leq Q_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG,max} \tag{3.20}$$

$$-\tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG} \leq tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \tag{3.21}$$

3.2.6 Conventional Generation Power Limits

The active and reactive power limits at the substations are given by (3.22) and (3.23), due to stability reasons.

$$P_{\varsigma,s,h}^{SS,min} \leq P_{\varsigma,s,h}^{SS} \leq P_{\varsigma,s,h}^{SS,max} \tag{3.22}$$

$$Q_{\varsigma,s,h}^{SS,min} \leq Q_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS,max} \tag{3.23}$$

The reactive power that is withdrawn from the substation is subject to the bounds presented in inequality (3.24).

$$-\tan\left(cos^{-1}(pf_{ss})\right)P_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS} \leq tan\left(cos^{-1}(pf_{ss})\right)P_{\varsigma,s,h}^{SS} \tag{3.24}$$

3.2.7 Radiality Constraints

The radial operation of the considered system is guaranteed by including the constraints in (3.25) through (3.31). Constraints (3.27)—(3.31) ensure radiality in the presence of DGs, and simultaneously avoid islanding.

$$\sum_{l \in \Omega^l} \chi_{l,h} = 1, \forall m \in \Omega^D, l \in n \tag{3.25}$$

$$\sum_{in,l\in\Omega^{l}} \chi_{l,h} - \sum_{out,l\in\Omega^{l}} \chi_{l,h} \leq 1, \forall m \notin \Omega^{D}, l \in n \tag{3.26}$$

$$\sum_{in,l\in\Omega^{l}} f_{l,h} - \sum_{out,l\in\Omega^{l}} f_{l,h} = g_{n,h}^{SS} - d_{n,h}, \forall n \in \Omega^{\varsigma}, l \in n \tag{3.27}$$

$$\sum_{in,l\in\Omega^{l}} f_{l,h} - \sum_{out,l\in\Omega^{l}} f_{l,h} = -1, \forall n \in \Omega^{g}, \forall n \in \Omega^{D} \tag{3.28}$$

$$\sum_{in,l\in\Omega^{l}} f_{l,h} - \sum_{out,l\in\Omega^{l}} f_{l,h} = \quad 0, \forall n \notin \Omega^{g}, \forall n \notin \Omega^{D} \forall n \notin \Omega^{\varsigma} \tag{3.29}$$

$$0 \leq \sum_{in,l\in\Omega^{l}} f_{l,h} + \sum_{out,l\in\Omega^{l}} f_{l,h} \leq n_{DG}, l \in n \tag{3.30}$$

$$0 \leq g_{n,h}^{SS} \leq n_{DG}, \forall n \in \Omega^{\varsigma}, l \in n \tag{3.31}$$

3.3 Reliability Indices

In this work some reliability indices are used after the optimization processes, as a tool to make decisions on the system daily operation. The reliability indices taken into account are the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI), which are calculated using equations (3.32) and (3.33).

3.3.1 SAIFI

SAIFI is given by the total number of consumers interruption duration by the total number of consumers, however this study focuses on the impact of branch failures to the customers served, as such this index is reformulated as (3.32).

$$SAIFI = \left(\frac{\sum_{l\epsilon\Omega}\, l \quad \lambda_{l} * |cf_{l}|}{M} \right) x_{l,h} \tag{3.32}$$

In this equation λ_l is the rate of the failure that affects N_n customers, $|cf_l|$ is the number of clients supplied by line l and M is the total number of customers. This equation is calculated for each line and for each hour, where if $x_{l,h}$ is zero, that is, if the line is not connected $(x_{l,h} = 0)$.

3.3.2 SAIDI

SAIDI is given by the total number of consumer interruption duration by the total number of consumers, in this study is calculated as a weighted mean of the duration of the interruptions assuming the number of customers as weights (3.33).

$$SAIDI = \left(\frac{\sum_{l \epsilon \Omega} l \quad \lambda_l * U_l * |cf_l|}{M} \right) x_{l,h} \tag{3.33}$$

In this equation U_l is the average repair time of line l. This equation is also calculated for each line and for each hour, where if $x_{l,h}$ is zero, that is, if the line is not connected $(x_{l,h} = 0)$.

3.4 TOPSIS Formulation

In this work the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) has been implemented (3.34) – (3.41). TOPSIS is a multi-criteria decision analysis method which is used to generate a Pareto front by evaluating *p*-objectives in a decision matrix. The TOPSIS method evaluates the following decision matrix (DM):

$$DM = \begin{bmatrix} x_{1,1} & \cdots & x_{1,m} & \cdots & x_{1,p} \\ \vdots & \ddots & \vdots & & \vdots \\ x_{n,1} & \cdots & x_{n,m} & \cdots & x_{p,m} \\ \vdots & & \vdots & \ddots & \vdots \\ x_{r,1} & \cdots & x_{r,m} & \cdots & x_{r,p} \end{bmatrix} \tag{3.34}$$

where m are the possible alternatives and n the criteria. $X_{i,j}$ represents the rating and performance of alternative n subject to criterion m. Each line of (3.34) represents an alternative solution, while each column is associated with an objective (minimization or maximization). In the general case, each objective is expressed in different units.

Thus, the next step of the TOPSIS method is to transform the decision matrix into a non-dimensional attribute matrix in order to enable a comparison among the attributes. The normalization process is performed through the division of each element by the norm of the vector (column) of each criterion.

An element $f_{n,m}$ of the normalized matrix is given by (3.35):

$$f_{n,m} = \frac{x_{n,m}}{\sqrt{\sum_{K=1}^{p} x_{km}^2}} \tag{3.35}$$

A set of weights (3.36), that express the relative importance of each objective (criterion) is provided by the Decision Maker at this point. The weighted normalized matrix with elements is created by multiplying each column of the matrix with elements by the weight.

$$w = \{w_1, \dots, w_{1m}, \dots w_p,\}, \sum\nolimits_m^n w_m = 1 \tag{3.36}$$

The next step is to specify the ideal and the negative-ideal solution vectors.
In (3.37) and (3.38), Ma is the set of objectives (criteria) to be maximized and Ma' is the set of objectives to be minimized. These artificial alternatives indicate the most preferable (ideal) solution and the least preferable (negative-ideal) solutions.

$$A^+ = \{(max_n(e_{n,m})|m \in Ma), (min_n(e_{n,m})|m \in Ma')\}, \forall n = 1, \dots, m \tag{3.37}$$

$$A^- = \{(min_n(e_{n,m})|m \in Ma), (max_n(e_{n,m})|m \in Ma')\} \forall n = 1, \dots, m \tag{3.38}$$

Then, the separation measure of each alternative from the ideal and the negative-ideal solution is measured by the dimensional Euclidean distance (3.39) and (3.40):

$$S_n^+ = \sqrt{\sum_{m=1}^{n} \left(e_{n,m} - e_m^+\right)^2, \forall n = 1, \dots, m} \tag{3.39}$$

$$S_n^- = \sqrt{\sum_{m=1}^{n} \left(e_{n,m} - e_m^-\right)^2, \forall n = 1, \dots, m} \tag{3.40}$$

The final step in the application of the TOPSIS method is the calculation of the relative closeness to the ideal solution. In (3.41), these distances are operated in order to create a rank (from highest to lowest value) of hourly topologies.

$$C_n^+ = \frac{S_n^-}{S_n^+ + S_n^-}, \quad 0 < C_n^+ < 1, \forall n, \dots, m \tag{3.41}$$

3.5 Chapter Summary

This chapter has presented the mathematical formulations used in this dissertation. The objective function and the constraints are described fully. The aim is to minimize the total system costs and identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration. In this model DGs and ESSs are considered to be present and the problem is developed as a stochastic mixed integer linear programming (MILP) optimization. Additional formulation to study and optimize the network different topologies taking into account different reliability indexes is also presented. In the following chapter, the IEEE 119-bus distribution network system data and assumptions are demonstrated as well as the scenarios considered in the optimization process.

Chapter 4

Case Study, Results and Discussion

In chapter 4 it is presented the case study, describing all the system data and assumptions that will be used to test the mathematical formulation demonstrated in the previous chapter. It also contains a scenarios description section, that analyzes all the scenarios considered in the optimization process. In this chapter, it is also presented and discussed all the numerical results obtained from the simulated operational mathematical model. The goal is to analyze the total costs, the reconfiguration results and a sensitivity analysis on the affected consumers, as well as the switches that need to be updated and its maintenance. Also, it is optimized the network different topologies considering different reliability indices and losses.

4.1 System Data and Assumptions

To simulate the mathematical model developed and presented in Chapter 3, it is used the standard 119 bus test system from IEEE, which can be seen in Figure 4.1. The system data is shown in Annex B.1. In this figure it can also be seen the type of DG units used and in which buses of the test system they are connected. As the figure shows, two types of DG units are considered: solar power (with an installed capacity of 2MW) and wind power (with an installed capacity of 1MW). The nodes where DG units are connected and its type are shown in Annex B.2. Regarding the ESS units, their rates of charge and discharge of energy are considered equal (90%). The ESSs location and size can be found in Annex B.3. Other assumptions and system data made are:

- It is considered a 24-hour period, with an hourly reconfiguration;
- Nominal voltage value is 12.66 kV;
- Voltage deviation at each node is ±5%;
- Total active loads are 3.93MW;

- Total reactive loads are 1.62MW;
- Substation is the reference node (voltage magnitude is set to its nominal value and the angle is 0º);
- Power factor at the substation is 0.8;
- Power factor at the DG units is 0.95;
- Electricity prices follow the demand trend;
- Operation cost of ESS during charge and discharge is 5€/MWh;
- Total number of costumers is 188922;
- The failure rate of the branch with the greatest impedance is considered to be 0.4 failures/day and of the branch with the least impedance 0.1 failures/day;
- For all the other branches these values are calculated using linear interpolation;
- The average repair time for each branch is considered equal to 2 hours.

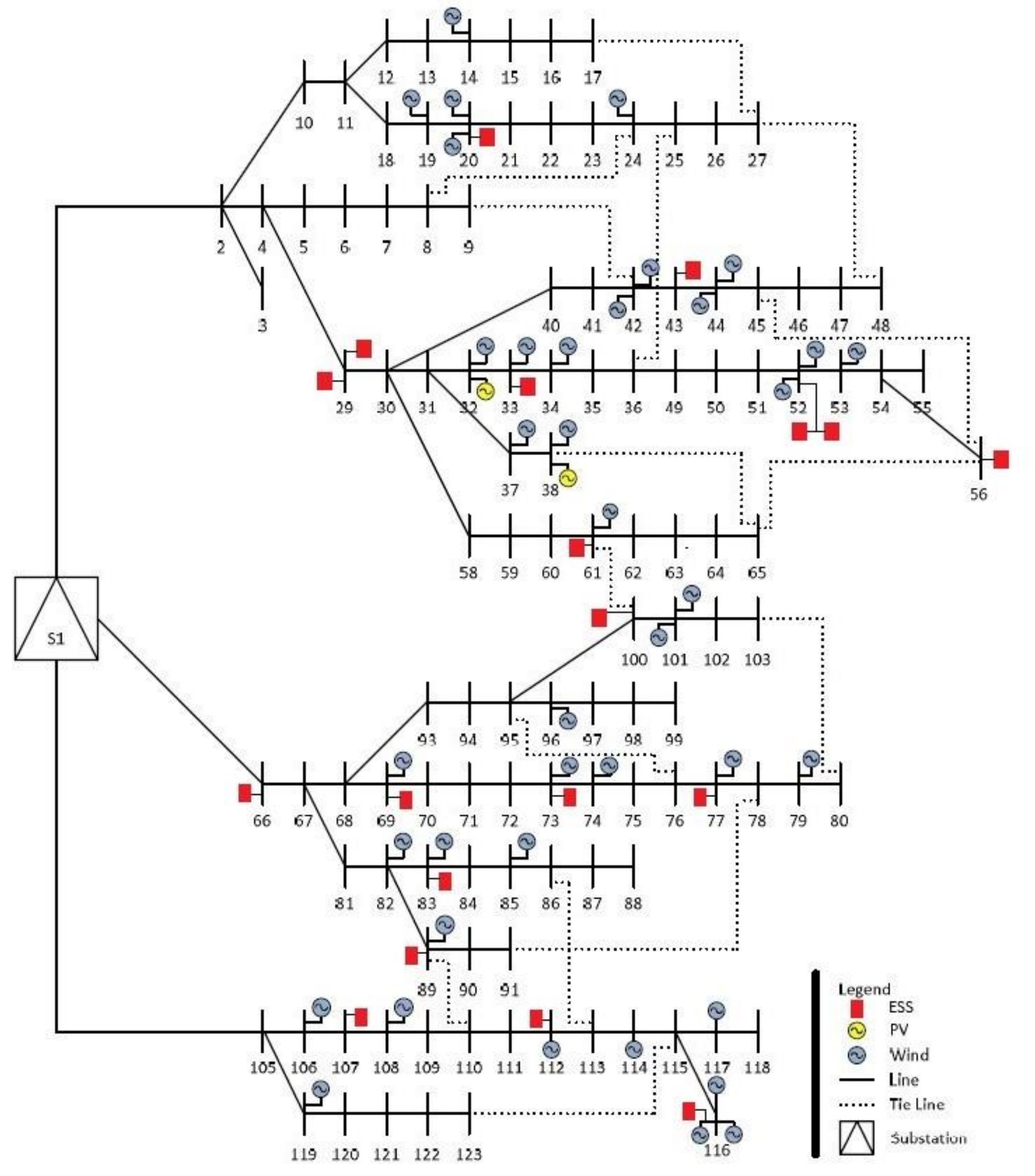

Figure 4.1- 119 Bus test system.

4.2 Scenarios Description

As mentioned in Chapter 2, RESs variability and uncertainty in production is one of the major challenges of the electric system. To consider the uncertainty of production output (wind and solar) as well as the demand, it is necessary to consider a sufficiently large set of scenarios that show a good diversity of the possible scenarios. However, the use of all these scenarios and their combinations results in a matrix of an impractical size, both in time and in computational effort, which results into an inefficient optimization.

Therefore, it is necessary to reduce the number of scenarios considered. To do this reduction, the Cluster technique known as k-means was used. This technique creates sets of scenarios- clusters- close to each other, aggregating scenarios that are more similar. In this case, it is concluded that 3 clusters are sufficient and they represent well the variability and uncertainty of the considered parameters.

4.2.1 Wind Power Scenario

The uncertainty of wind power output is analyzed considering three different scenarios, obtained through clustering. The three different scenarios are shown in Figure 4.2.

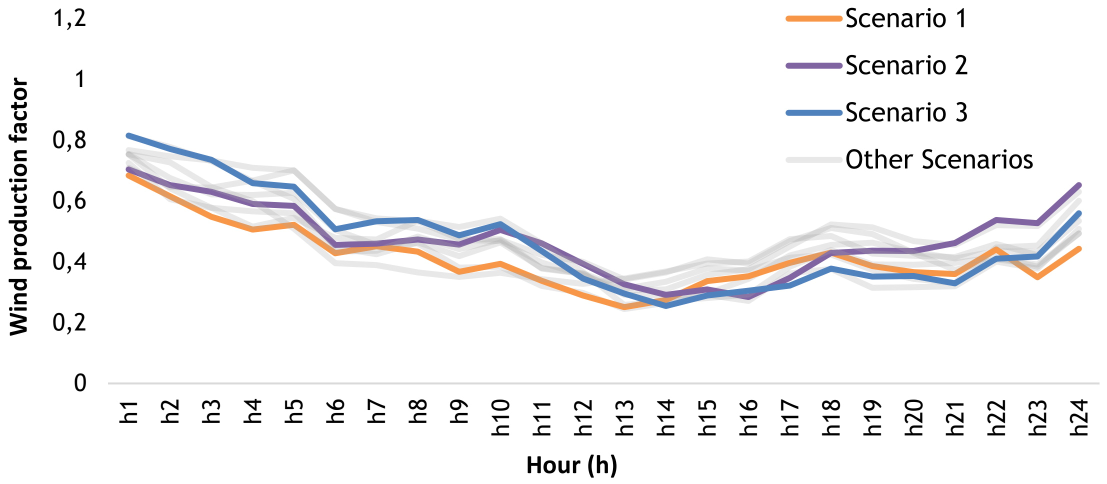

Figure 4.2- Wind power scenarios.

4.2.2 Solar Power Scenario

Likewise, the uncertainty of the solar power output is analyzed considering also three different scenarios, representative of high, medium and low production profiles. This data is also obtained through clustering. The three different scenarios are shown in Figure 4.3.

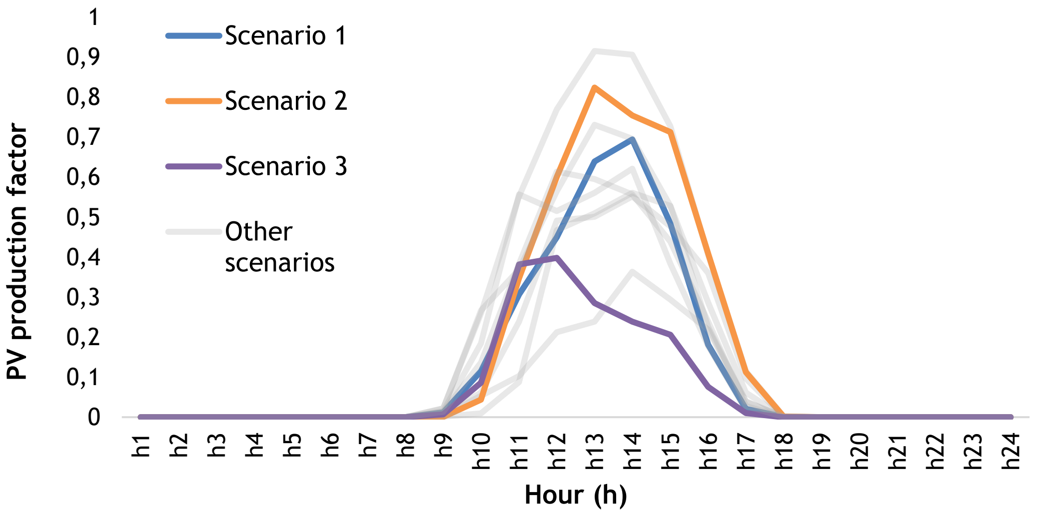

Figure 4.3- Solar power scenarios.

4.2.3 Demand Scenario

Finally, the uncertainty of energy demand is analyzed according to three different scenarios, also obtained through clustering. The three different scenarios are shown in Figure 4.4.

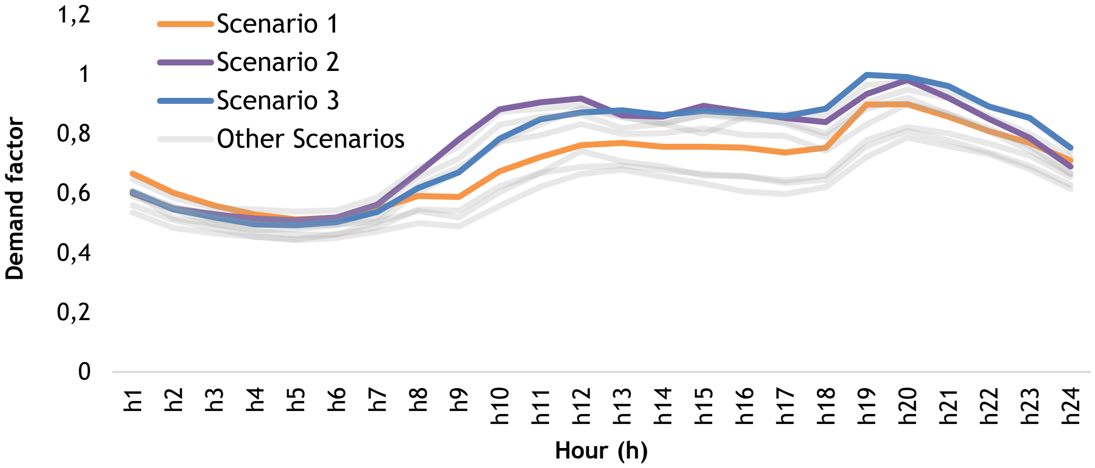

Figure 4.4- Demand scenarios.

4.3 Dynamic Reconfiguration Results and Energy Mix

4.3.1 Hourly Dynamic Reconfiguration Results

In this work the automation of switches was considered, based on the network dynamic reconfiguration considering the presence of renewable (wind and solar generation), as well as ESSs. This reconfiguration was obtained from the perspective of optimizing the system operation, considering the economic requirements and technical restrictions of the system.

Thus, in Table 5.1 it can be seen the total operation cost of the system together with the cost terms that make up the objective function. From this table it can be highlight the cost of power not served, 0MW, due to the integration of smart grid enabling technologies. In this case, the presence of DGs combined with ESSs allows a better balance of generation and demand, leading to all the energy being used while the reliability of the system is maintained. Also, the dynamic reconfiguration together with the DGs and ESSs presents lower losses than without these technologies being present, compared with the literature values [13].

Therefore, in the first phase of this work, system dynamic reconfiguration was done based on the mathematical formulation presented in Chapter 3, where a different configuration for each hour was obtained. The reconfiguration results are presented in Tables 5.2 and 5.3, where the closed lines set and open lines set constitute the network topology. The reconfiguration made assumes that all lines have the ability to reconfigure in this first stage.

Table 4.1- Costs and losses optimization results.

Total Cost [€]	29912,27
Reconfiguration Cost [€]	1010
Energy Cost [€]	27901,72
Emission Cost [€]	1000,55
Power not Served Cost [€]	0
P Losses [MW]	10,00
Q Losses [MVAr]	6,60

Table 4.2- Reconfiguration results.

Hour	Closed Lines	Open Lines
1	1-22, 24, 25, 27-33, 35-60, 62-81, 83-89, 91-94, 96-116, 118, 120, 123, 125, 126, 129, 131, 132	23, 26, 34, 61, 82, 90, 95, 117, 119, 121, 122, 124, 127, 128, 130
2	1-22, 24, 25, 27-33, 35-41, 43-60, 62-75, 77-81, 83, 84, 86-89, 91-94, 96-118, 120, 121, 123, 125, 126, 128-130, 132	23, 26, 34, 42, 61, 76, 82, 85, 90, 95, 119, 122, 124, 127, 131
3	1-22, 24, 25, 27-33, 35-60, 62-73, 75, 77-81, 83, 84, 86-89, 91-94, 96-118, 120, 123, 125-130, 132	23, 26, 34, 61, 74, 76, 82, 85, 90, 95, 119, 121, 122, 124, 131
4	1-22, 24, 25, 27-33, 35-52, 54-60, 62-73, 75, 77-81, 83, 84, 86-89, 91-94, 96-117, 119, 120, 122, 123, 125-130, 132	23, 26, 34, 53, 61, 74, 76, 82, 85, 90, 95, 118, 121, 124, 131
5	1-22, 24, 25, 27-33, 35-41, 43-52, 54-60, 62-73, 75, 77-81, 83-89, 91-94, 96-117, 119-123, 125-129, 132	23, 26, 34, 42, 53, 61, 74, 76, 82, 90, 95, 118, 124, 130, 131
6	1-22, 24, 25, 27-33, 35-52, 54-60, 62-73, 75, 77-81, 83-89, 91-94, 96-117, 119, 120,122, 123, 125-129, 132	23, 26, 34, 53, 61, 74, 76, 82, 90, 95, 118, 121, 124, 130, 131
7	1-22, 24, 25, 27-33, 35-41, 43-60, 62-73, 75, 77-89, 91-94, 96-118, 120, 121, 123, 125-128, 132	23, 26, 34, 42, 61, 74, 76, 90, 95, 119, 122, 124, 129-131
8	1-22, 24, 25, 27-33, 35-52, 54-60, 62-81, 83, 84, 86-89, 91-94, 96-118, 120 122, 123, 125, 126, 129, 130, 132	23, 26, 34, 53, 61, 82, 85, 90, 95, 119, 121, 124, 127, 128, 131
9	1-22, 24, 25, 27-33, 35-60, 62-81, 83, 84, 86-89, 91-94, 96-118, 120, 123, 125, 129, 130, 132	23, 26, 34, 61, 82, 85, 90, 95, 119, 121, 122, 124, 126-128, 131
10	1-22, 24, 25, 27-33, 35-38, 40-52, 54-60, 62-89, 91-94, 96-118, 120, 122, 123-126, 132	23, 26, 34, 39, 53, 61, 90, 95, 119, 121, 127-130, 131
11	1-22, 24, 25, 27-33, 35-38, 40-52, 54-60, 62-73, 75-117, 119, 120, 122-124, 126, 127, 132	23, 26, 34, 39, 53, 61, 74, 118, 121, 125, 128-130, 131
12	1-22, 24, 25, 27-33, 35-38, 40-60, 62-84, 86-89, 91-118, 120, 123, 124, 130, 132	23, 26, 34, 39, 61, 85, 90, 119, 121, 122, 125, 116-129, 131

Table 4.3- Reconfiguration results (continuation).

Hour	Closed Lines	Open Lines
13	1-22, 24, 25, 27-33, 35-52, 54-60, 62-89, 91-94, 96-118, 120, 122, 123, 125, 126, 132	23, 26, 34, 53, 61, 90, 95, 119, 121, 124, 127, 128-130, 131
14	1-22, 24, 25, 27-33, 35-60, 62-73, 75-81, 83,84, 86-117, 120, 123, 127, 129, 130, 132	23, 34, 61, 74, 82, 85, 118, 119, 121, 122, 124-126, 131
15	1-22, 24, 25, 27-33, 35-60, 62-73, 75-81, 83, 84, 86-116, 120, 123, 127, 129-132	23, 34, 61, 74, 82, 85, 117-119, 124-126, 128
16	1-22, 24, 25, 27-33, 35-38, 40-52, 54-60, 62-84, 86-117, 120, 122-124, 130, 132	23, 34, 39, 53, 61, 85, 118, 119, 121, 125-129, 131
17	1-22, 24, 25, 27-33, 35-52, 54-60, 62-73, 75-89, 91-94, 96-116, 119, 120, 122, 123, 125-127, 131, 132	23, 26, 34, 53, 61, 74, 90, 95, 117, 118, 121, 124, 128-130
18	1-22, 24, 25, 27-33, 35-52, 54-60, 62-73, 74-89, 91-94, 96-118, 120, 122, 123, 125, 126, 132	23, 26, 34, 53, 61, 90, 95, 119, 121, 124, 127-131
19	1-25, 27-33, 35-38, 40-52, 62-84, 86-117, 119, 122, 123, 124, 130, 132	26, 34, 39, 53, 61, 85, 118, 120, 121, 125, 126-128, 129, 131
20	1-25, 27-33, 35-38, 40-60, 62-73, 75-118, 123, 124, 127, 132	26, 34, 39, 61, 74, 119-122, 125, 126, 128-130,131
21	1-25, 27-38, 40-60, 62-73, 75-84, 86-117, 86-117, 119, 123, 124, 127, 130	26, 39, 61, 74, 85, 118, 120-122, 125, 126, 128, 129, 131, 132
22	1-22, 24-33, 35-38, 40-52, 54-60, 62-75, 77-81, 83, 84, 86-117, 120, 122-124, 128-130, 132	23, 34, 39, 53, 61, 76, 82, 85, 118, 119, 121, 125-127, 131
23	1-22, 24, 25, 27-33, 35-52, 54-60, 62-73, 75-81, 83, 84, 86-118, 120, 122, 123, 127, 129, 130, 132	23, 26, 34, 53, 61, 74, 82, 85, 119, 121, 124-126, 131
24	1-22, 24, 25, 27-33, 35-41, 43-52, 54-73, 75-81, 83, 84, 86-89, 91-94, 96-116, 118, 120-122, 125-127, 129-132	23, 26, 34, 42, 53, 74, 82, 85, 90, 95, 117, 119, 123, 124, 128

4.3.2 Production and Consumption Profiles

In this dissertation the influence of the ESSs, DGs units and substation in meeting energy demand are analyzed based on the production and consumption profile of the system. In Figure 4.5 is presented the power produced and consumed per hour.

As expected, most part of the energy produced comes from the substation, and from the 23rd to the 7th hours the production of the wind turbine DGs units is null. The influence of wind power production is notorious mainly at hours 10, 11, 12 and 18, where the large production of energy from the wind allowed, with the help of the ESS discharges, to reduce production at the substation and, consequently, reduce the operation costs. Regarding ESSs, it can be seen that from hour 23 to hour 8 these charge energy, discharging it for the rest of the day when necessary. The influence of the ESSs is very important, since it is balancing the production of the DGs with the discharge of the ESSs that the demand is guaranteed with the possibility of resorting as little as possible to the energy of the substation.

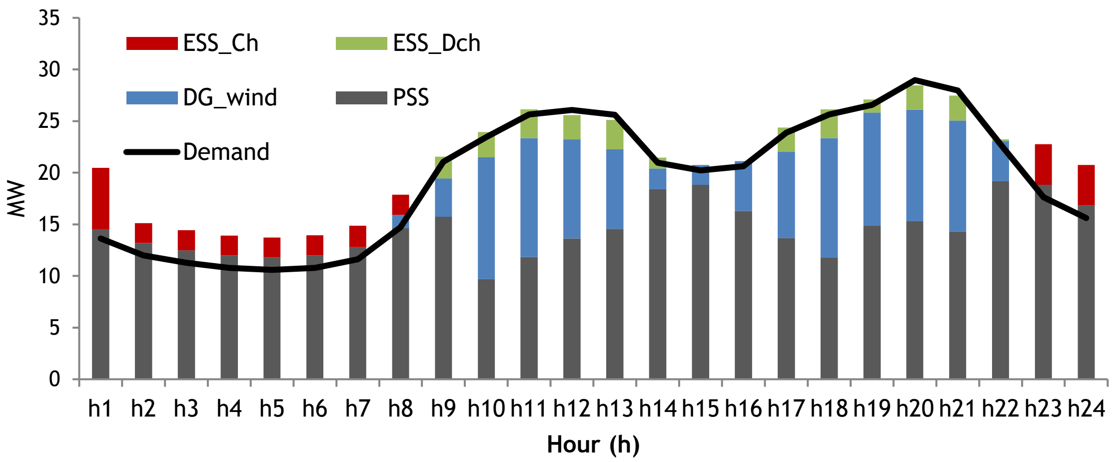

Figure 4.5- Production and consumption per hour.

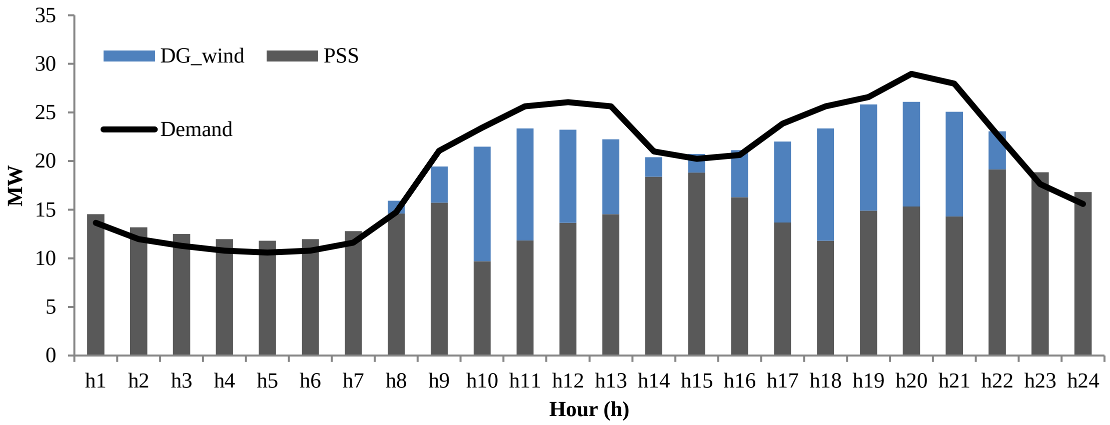

Figure 4.6- Production and consumption profile without ESS's.

Hypothetically, if the influence of the ESSs is removed, for the same wind power and substation values, the supply of demand would not be assured, as can be seen in Figure 4.6. However, in reality, the supply of demand would be assured only by the energy from conventional generation through the substation.

4.4 Automation Update

In a second phase of the present work, a sensitivity analysis was carried out in order to analyze which switches should be updated from manuals to automatic ones, if some new switches should be placed in places where no switch exist, and which ones need more attention with regard to physical maintenance actions.

In Tables 4.2 and 4.3 are presented the reconfiguration results based on the lines on and off. From these tables it can be established that there are lines that never actively participate in the reconfiguration, which means that the switches of the respective lines never work. Therefore, these lines do not need to be automated, in the perspective of minimizing costs. As such, it can be determined from the table analysis that only 22% of lines participate in reconfiguration, which means that 78% of lines do not need to be automated.

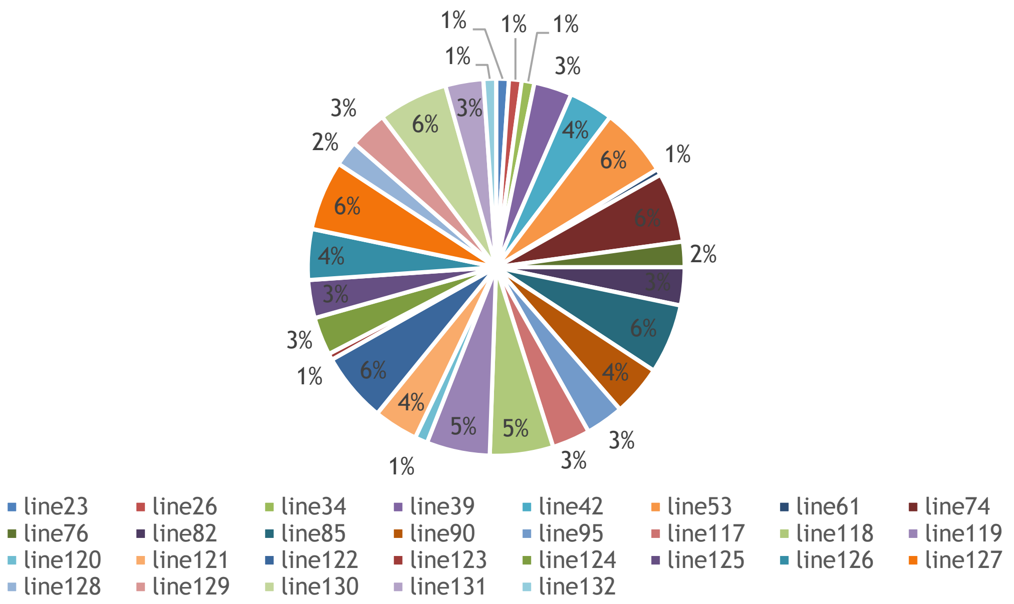

Figure 4.7- Lines that actively participate in reconfiguration.

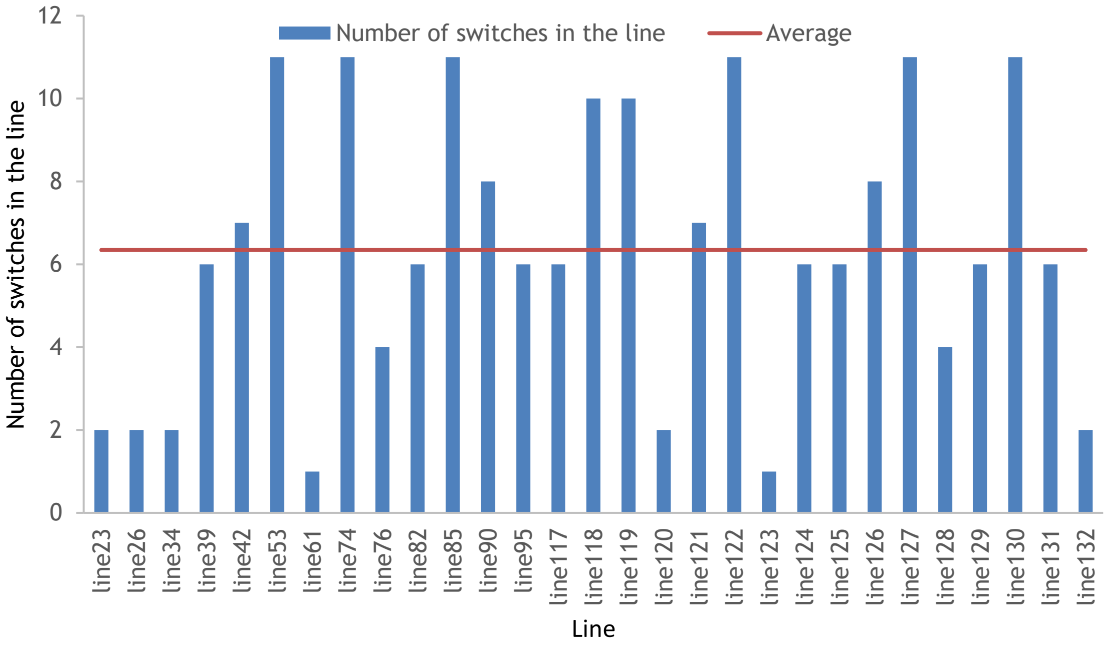

Figure 4.8- Switches actions per line.

The graph in Figure 4.7 shows all the lines that actively participate in the network reconfiguration, and the percentage of commutations occurring in the respective line over the operation period, relative to the total number of commutations.

Nonetheless, from these 22% not all lines will be automated due to the cost, being necessary to choose which lines will be automated. In this perspective, it is necessary to identify using one or several criteria which set of switches are essential to automate. As a result, the criterion of the average value was used, where for the lines that have a number of switches above the average are the possible candidates to constitute the set of switches to be automated. Figure 4.8 represents the number of switches per line, as well as the average number of switches per line.

As previously mentioned, the choice of the lines to be automated depends on whether the number of line switches exceeds or not the average number of switches per line. Therefore, Table 4.4 demonstrates the lines to be automated. From the analysis of this set it is possible to verify the existence of two subsets, the set of lines where there are no manual switches and should be installed - {line42, line53, line74, line85, line90} - as well as a second set, where manual switches are already present and should be automated - {line118, line119, line121, line122, line126, line127 and line130}.

Another aspect considered in this analysis was the maintenance of the switches. Since not all switches operate at the same frequency (as it may have been concluded earlier), their maintenance will also vary depending on how often they act to change the network topology. Thus, logically, it will be paid more attention to those switches that act more frequently in the reconfiguration of the system. The graph in Figure 4.9 shows the percentage of switching of each one of the lines to be automated, so that it is possible to verify which switches require more maintenance work.

Table 4.4- Lines to automate.

Set of Lines to Automate
$\begin{Bmatrix} line42, line53, line74, line85, line90, line118, \\ line119, line121, line122, line126, line127, line130 \end{Bmatrix}$

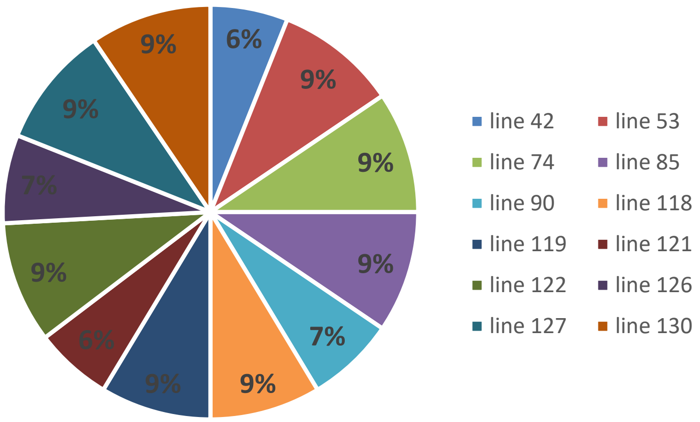

Figure 4.9- Lines with more switches actions than the average.

4.5 Reliability Analysis

In the first part of this work it was made a sensitivity analysis of switches automation based on active reconfiguration. The second part of the work concerns about the operation of the system considering that this one has already been automated, based on previous results.

However, despite the system already has the ability to dynamically reconfigure, it is not practical to make a reconfiguration every hour because of technical and economic factors. Therefore, according to the literature and the demand response models, an optimization of 3 different topologies (one per load period) was chosen, following a set of criteria. To optimize the system operation, two reliability indices- SAIFI and SAIDI- are used, together with system losses. In here, a TOPSIS decision support tool is subsequently used to identify the best configuration for the considered periods (set of hours), where different case studies are analyzed.

4.5.1 SAIFI

Using the expression (3.32), the SAIFI (the total number of consumer interruption duration by the total number of consumers) is calculated as a weighted mean of the duration of the interruptions assuming the number of customers as weights.

Figures 4.10 and 4.11 show the SAIFI hourly values obtained and its average value. The values shown in those charts for each hour of the day correspond to the sum of the SAIFI value obtained on each one of the lines in the respective hour and the evolution of this index is verifiable in both charts. Figure 4.10 allows to quickly identify the hours during which there are more interruptions, namely at hours 4, 8, 11, 16, 19, 22 and 24.

Also, in Figure 4.11 is possible to see the SAIFI average value of 0.165. The value for the frequency of the interruptions varies between 0.162 and 0.17, which is considered low, as expected.

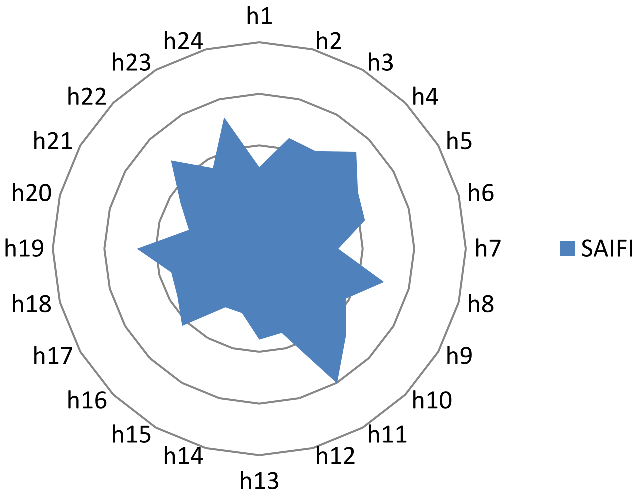

Figure 4.10- SAIFI hourly values.

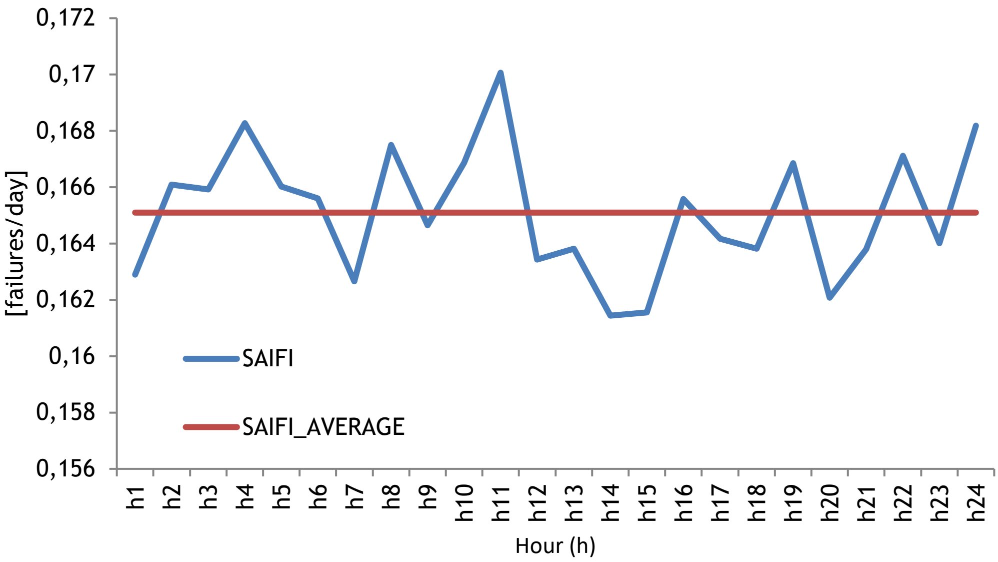

Figure 4.11- SAIFI: hourly and average values.

4.5.2 SAIDI

Using the expression (3.33) the SAIDI (the total number of consumer interruption duration by the total number of consumers) is calculated as a weighted mean of the duration of the interruptions assuming the number of customers as weights.

Figures 4.12 and 4.13 present the SAIDI values, in a similar way to the graphs presented for the SAIFI analysis. The values shown in these charts for each hour of the day correspond to the sum of the SAIDI value obtained on each of the lines in their respective hour and the evolution of this index is verifiable in both charts. Figure 4.12 is also useful to identify the hours during which longer interruptions occur, namely at 4, 8, 11, 16, 19, 22 and 24. As can be seen by comparing with the graph of Figure 4.13, the hours during which more interruptions occur, also coincide with the hours where interruptions last longer.

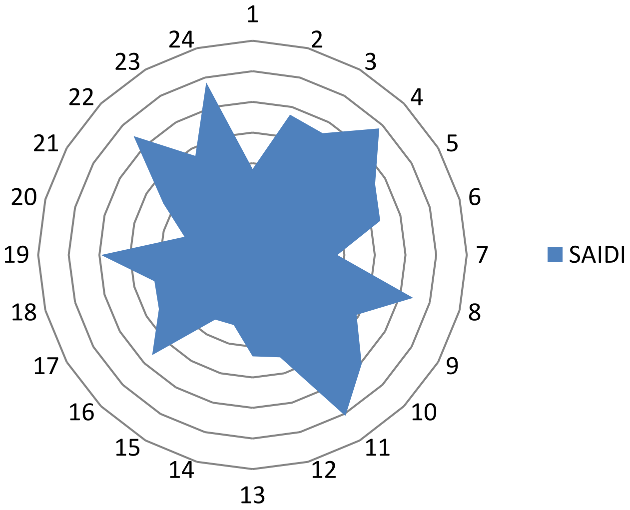

Figure 4.12- SAIDI hourly values.

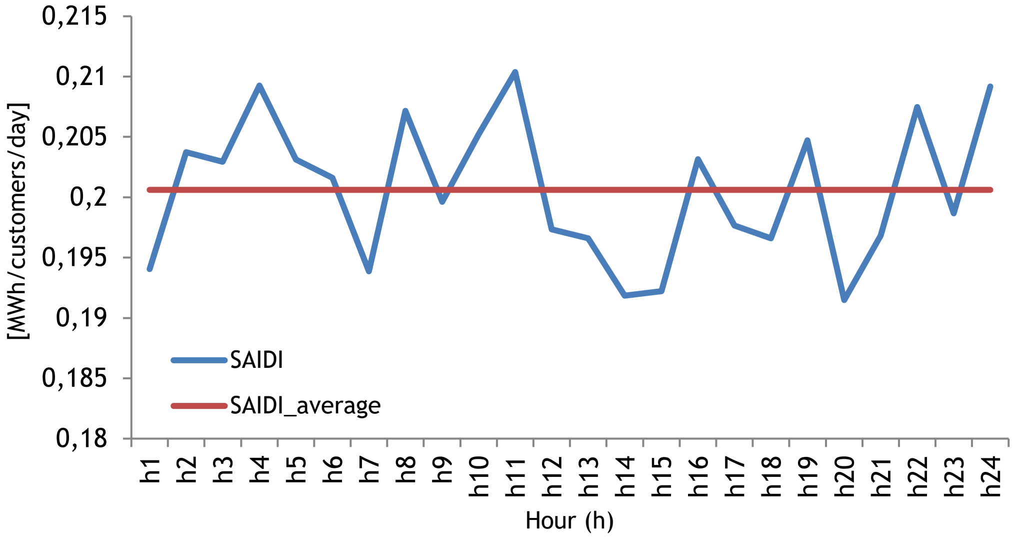

Figure 4.13- SAIDI: hourly and average values.

Analyzing the graph of Figure 4.13, it can be seen that the SAIDI has an average value of approximately 0.201 and the value for the duration of the interruptions ranges from about 0.192 to 0.211.

4.5.3 Active Power Losses

In this work it was also taken into account the power losses. Figures 4.14 and 4.15 present graphs where it can be seen the losses registered at each hour and even its average value. The value of the power losses per hour was also obtained by the sum of the losses value registered in each one of the lines in the respective hour. Looking at the graph in Figure 4.14, it can be seen the hour where more power losses were obtained, particularly in hours 8, 9, 14, 15, 16, 22, 23 and 24. Figure 4.15 shows the range of the power losses value, which is between about 0,29 and 0,6. The average value for the power losses per hour can also be seen: approximately 0,41.

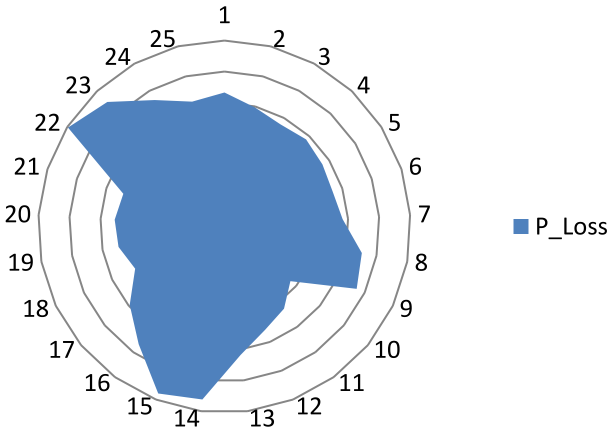

Figure 4.14- Active power losses per hour.

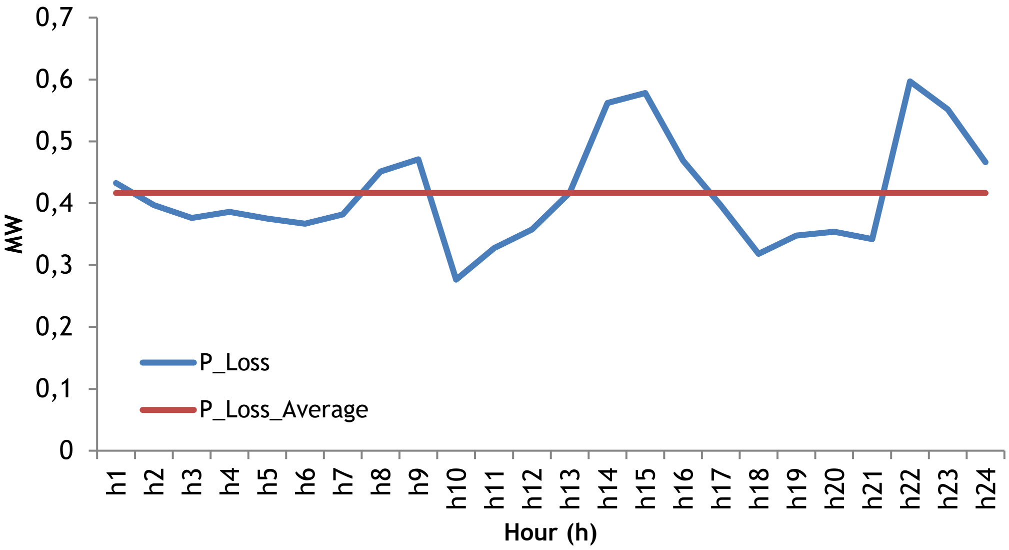

Figure 4.15- Active power losses: hourly values vs average value.

4.5.3 Multi-Objective Optimization

In the first phase of the work, it was assumed the possibility of changing the topology of the network every hour during a day. However, given the efforts required of the network and its components, such switching frequency is impractical and unrealistic. Thus, three reconfiguration moments were chosen, characterized by the type of energy demand of three periods:

- Off-peak period- hour 1 until hour 7;
- Peak period- hour 11 until hour 13 and hour 20 until hour 22
- Shoulder period- hour 8 until hour 10, hour 14 until hour 19, hour 23 and hour 24;

Therefore, it will be necessary to choose a different topology of the network for each of these periods, which means that 3 reconfigurations per day will occur. The choice of the best topology by period is done based on the optimization of the reliability indices and losses mentioned in the previous subsections. However, it is technically impossible to optimize the three indices at the same time, since by optimizing one of them we are making the others worse. Consequently, it is necessary to find the optimum balance of all indices and power losses. For this purpose, the TOPSIS method (already presented in Chapter 3) was used.

Through multi-objective optimization, we can achieve a classification of all topologies, sorted by hour and ordered from the hour with the best topology until the hour with the worst topology, always based on the optimization of the reliability indices and losses. It is following this classification that the topology to be assumed is chosen for each one of the above periods. However, in an optimization process, objectives do not always have the same weight, sometimes there is a main objective and other secondary objectives. In this perspective, 5 cases were created, characterized by the different weight given to each index in the multi-objective optimization that is described in Table 4.5.

The values attributed to the weights in each case allow us to study the trend between the objectives. With these cases, it is intended that the results show which hours the topology should be adopted in the period in question. These results are presented in Table 4.6.

In case 1, the same weight was attributed to the three indices under study, in an attempt to perceive the one that will have the greatest influence on the final result. In case 2, it was given greater weight to the power losses index, thus giving greater "value" to the losses as an objective to be optimized. As it can be seen, if greater weight is given to energy losses, the ideal topology per period changes completely. In case of study 3, the SAIFI index was given greater weight, thus giving a higher "value" to the frequency of interruptions as an objective to be optimized. In here, if SAIFI is given greater weight, the ideal topologies for the off-peak and peak periods return to those that resulted in case 1. On the other hand, in the shoulder period, the ideal topology will change again. In case 4, the SAIDI index was given greater weight, thus giving greater importance to the duration of the interruptions. Therefore, if the SAIDI is given a greater weight, the ideal topology for each period is exactly the same as the ones obtained from case 3. In case 5, the two SAIFI and SAIDI indices were given a higher weight and the results obtained are exactly the same as case 3 and 4. As previously mentioned, for all cases, the TOPSIS method is applied in order to verify the best topology to give to the network in the different periods of the day. From this analysis, no clear tendency stood out from the different cases, consequentially the ideal solution will depend only on the importance of each weight assigned to each objective in the optimization process.

Table 4.5- Cases for analysis and optimization of reliability indices.

Case	Weight		
	SAIFI	SAIDI	P_Loss
1	0,1	0,1	0,1
2	0,1	0,1	0,5
3	0,5	0,1	0,1
4	0,1	0,5	0,1
5	0,5	0,5	0,1

Table 4.6- Multi-objective optimization results.

Period	Off-peak	Shoulder	Peak
Case 1	Hour 1	Hour 18	Hour 20
Case 2	Hour 6	Hour 10	Hour 21
Case 3	Hour 1	Hour 14	Hour 20
Case 4	Hour 1	Hour 14	Hour 20
Case 5	Hour 1	Hour 14	Hour 20

4.6 Chapter Summary

Initially, this chapter has described all the system data considered, the assumptions made and the different scenarios that allow considering the uncertainty and variability. Then, the model was tested, where a sensitivity analysis on different issues is made. It was present an improve a SMILP operation model that aims to identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration and if the automatic switches will be installed only were manual switches already exist or also in places where there are no switches at all. The results show the existence of a feasible set of switches to automate in economic terms considering the technical constraints, in which it was possible to identify two sub sets, one of manual switches (to be automated) and another sub set of lines where there are no switches. The automation of these lines can bring several benefits to the system operation in different levels.

This work also studied the optimization of the system under different topologies for certain periods of operation throughout the day, taking into account different reliability indices and losses. The support decision technique TOPSIS was also applied to select the best topologies to use in the three different optimization periods of the day. From the results analysis it can be seen that because of the objectives being so distinct it was not possible to identify a trend that is maintained when different weights are selected, since when one objective is optimized another is under optimized.

Chapter 5

Conclusion and Future Works

In this chapter, it is described the main conclusions of this dissertation, as well as some future works that could be done in order to extend the study on dynamic reconfiguration of the distribution system. Finally, the contributions of this work are highlighted by presenting the publication, a result of this dissertation work.

5.1 Conclusions

In this work two complementary studies were made. The first study carried out an analysis on the dynamic reconfiguration used in conjunction with DGs and ESS as a way to operate the system with more reliability and integrate higher levels of RESs. To perform this analysis an improved stochastic MILP was used to obtain numerical results of operating the 119 bus test system assessing the impact on systems operation with the integration of DSR, DGs and ESS. The analysis of the case study showed that:

- From the dynamic reconfiguration analysis, it was possible to identify jointly with one or several criteria which is the minimum set of switches that must be automated, so as not to lose the benefits of dynamic reconfiguration and increase the system reliability through faster system restoration due to automated switches.
- It was also possible to determine that the automated switch ideal positioning is not always in the place where the manual switch is located, being possible through this analysis to identify the locations where it is more beneficial to install them. Moreover, it was possible to identify the set of switches which will require more maintenance.

With this approach to automate the system it is possible to perform 68% of the dynamic reconfigurations obtained.

In the second study was made an analysis on the optimization of system operation after the implementation of the results from the first study, taking into account the fact that it is not practical for the system operators to carry out an hourly reconfiguration. However, it is feasible to perform some reconfigurations throughout the day. As such, and going towards what is mentioned in the literature, three reconfigurations were considered throughout the day, corresponding to the three loading periods. The configurations to be used were selected based on the individual calculation of two reliability indices, SAIFI and SAIDI together with the power losses. To obtain the best reconfigurations to each period, the TOPSIS support decision tool was used to minimize these functions. The analysis showed that:

- It was possible to identify a set of network configurations for the three periods considered, and these configurations correspond to the best configuration from the perspective of system reliability and losses. The set of configurations changes according with the weight assigned to each function, according to the preferences of the decision maker.
- The results of changing different weights showed that the one that most influences the configuration is the power losses, although this conclusion can be case sensitive.

In general, the electrical system has undergone a great change since the introduction of system automation concept. With this work, it was possible to show the advantages of making the system increasingly automatic, both in terms of reliability and in the perspective of reducing operating costs.

5.2 Future Works

Possible future works to be done, considering the same subject are:

- To extend the reconfiguration period from 24h to 1 moth or even 1 year;
- To use a more complex method on the selection of switches to replace, instead the average criterion, in order to meet a more refined model;
- To add to sensibility analysis the priority consumers concept.

5.3 Works Resulting from this Dissertation

This thesis has resulted in one IEEE conference paper that has already been presented at the 18th IEEE International Conference on Environment and Electrical Engineering — EEEIC 2018 (technically co-sponsored by IEEE), Palermo, 12-15 June 2018. This paper can be found in Appendix C.

C. Santos, S.F. Santos, D.Z. Fitiwi, M.R.M. Cruz, J.P.S. Catalão, "*Sensitivity analysis in switches automation based on active reconfiguration to improve system reliability considering renewables and storage*", in: Proceedings of the IEEE 18th International Conference on Environment and Electrical Engineering — EEEIC 2018, Palermo, Italy, 12-15 June 2018.

Appendices

Appendix A

Appendix A.1 - Line Losses Linearization

According with [15], the active and reactive power losses in line l can be approximated as follows. “The customary AC power flow equations, given by (A.1) and (A.2), are highly non-linear and non-convex. Understandably, using these flow expressions in power system planning applications is increasingly difficult. Because of this, Eqs. (A.1) and (A.2) are often linearized by considering two practical assumptions. The first assumption is concerning the bus voltage magnitudes, which in distribution systems are expected to be close to the nominal value V_{nom}. The second assumption is in relation to the voltage angle difference θ_k across a line which is practically small, leading to the trigonometric approximations $\sin\theta_k \approx \theta_l$ and $\cos\theta_l \approx 1$. Note that this assumption is valid in distribution systems, where the active power flow dominates the total apparent power in lines. Furthermore, the voltage magnitude at bus i can be expressed as the sum of the nominal voltage and a small deviation ΔV_n, as in (A.3).

$$P_l = V_n^2 g_l - V_n V_m (g_l \cos\theta_l + b_k \sin\theta_l) \tag{A.1}$$

$$Q_l = -V_i^2 b_l + V_n V_m (b_l \cos\theta_l - g_l \sin\theta_l) \tag{A.2}$$

$$V_i = V_{nom} + \Delta V_n, \qquad where\ \Delta V^{min} \leq \Delta V_n \leq \Delta V^{max} \tag{A.3}$$

Note that the voltage deviations at each node ΔV_n are expected to be very small. Substituting (A.1) in (A.2) and (A.3) and neglecting higher order terms, we get:

$$P_l \approx (V_{nom}^2 + 2V_{nom}\Delta V_n) g_l - (V_{nom}^2 + V_{nom}\Delta V_n + V_{nom}\Delta V_m)(g_l + b_l\theta_l) \tag{A.4}$$

$$Q_l \approx -(V_{nom}^2 + 2V_{nom}\Delta V_n) b_l + (V_{nom}^2 + V_{nom}\Delta V_n + V_{nom}\Delta V_m)(b_l - g_l\theta_l) \tag{A.5}$$

Note that Eqs. (A.4) and (A.5) still contain nonlinearities because of the products of two continuous variables—voltage deviations and angle differences. However, since these variables (ΔV_n, ΔV_m and θ_l) are very small, their products can be neglected. Hence, the above flow equations become:

$$P_l \approx V_{nom}(\Delta V_n - \Delta V_m)g_l - V_{nom}^2 b_l \theta_l \qquad \text{(A.6)}$$

$$Q_l \approx -V_{nom}(\Delta V_n - \Delta V_m)b_l - V_{nom}^2 g_l \theta_l \qquad \text{(A.7)}$$

Eqs. (A.6) and (A.7) must be multiplied by the corresponding binary variables as in (A.8) — (A.11). This is to make sure the flow through an existing/a new feeder is zero when its switching/investment variable is zero; otherwise, the flow in that feeder should obey the Kirchhoff's law.

$$P_l \approx u_{l,k}\{V_{nom}(\Delta V_l - \Delta V_m)g_l - V_{nom}^2 b_l \theta_l\} \qquad \text{(A.8)}$$

$$Q_l \approx x_{l,h}\{-V_{nom}(\Delta V_l - \Delta V_m)b_l - V_{nom}^2 g_l \theta_l\} \qquad \text{(A.9)}$$

$$P_l \approx x_{l,h}\{V_{nom}(\Delta V_l - \Delta V_m)g_l - V_{nom}^2 b_l \theta_l\} \qquad \text{(A.10)}$$

$$Q_l \approx x_{l,h}\{-V_{nom}(\Delta V_l - \Delta V_m)b_l - V_{nom}^2 g_l \theta_l\} \qquad \text{(A.11)}$$

The bilinear products, involving binary with voltage deviation and angle difference variables, introduces undesirable nonlinearity to the problem. This nonlinearity can be avoided using the big-M formulation i.e. by reformulating the above equations into their respective disjunctive equivalents as in (A.12)—(A.15). As a rule-of-thumb, the big-M parameter is often set to the maximum transfer capacity in the system."

$$\left|P_{l,s,h} - \{V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)g_k - V_{nom}^2 b_l \theta_{l,s,h}\ )\}\right| \le MP_l\left(1 - u_{l,h}\right) \qquad \text{(A.12)}$$

$$\left|Q_{l,s,h} - \{-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)b_k - V_{nom}^2 g_l \theta_{l,s,h}\}\ \right| \le MQ_k\left(1 - u_{l,h}\right) \qquad \text{(A.13)}$$

$$\left|P_{l,s,h} - \{V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)g_k - V_{nom}^2 b_l \theta_{l,s,h}\}\right| \le MP_k\left(1 - x_{l,h}\right) \qquad \text{(A.14)}$$

$$\left|Q_{l,s,h} - \{-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)b_k - V_{nom}^2 g_l \theta_{l,s,h}\}\right| \le MQ_k\left(1 - x_{l,h}\right) \qquad \text{(A.15)}$$

Appendix B

Appendix B.1- System Data

Table B.1 – IEEE 116 Distribution System Data

Line	From	To	R [Ω]	X [Ω]	Capacity lim
line1	1	2	0,036	0,01296	13,2
line2	2	3	0,033	0,01188	4,4
line3	2	4	0,045	0,0162	13,2
line4	4	5	0,015	0,054	8,8
line5	5	6	0,015	0,054	8,8
line6	6	7	0,015	0,0125	8,8
line7	7	8	0,018	0,014	4,4
line8	8	9	0,021	0,063	4,4
line9	2	10	0,166	0,1344	4,4
line10	10	11	0,112	0,07889	4,4
line11	11	12	0,187	0,313	4,4
line12	12	13	0,142	0,1512	4,4
line13	13	14	0,18	0,118	4,4
line14	14	15	0,15	0,045	4,4
line15	15	16	0,16	0,18	4,4
line16	16	17	0,157	0,171	4,4
line17	11	18	0,218	0,285	4,4
line18	18	19	0,118	0,185	4,4
line19	19	20	0,16	0,196	4,4
line20	20	21	0,12	0,189	4,4
line21	21	22	0,12	0,0789	4,4

(Continuation of the previous table)

Line	From	To	R [Ω]	X [Ω]	Capacity lim
line22	22	23	1,41	0,723	4,4
line23	23	24	0,293	0,1348	4,4
line24	24	25	0,133	0,104	4,4
line25	25	26	0,178	0,134	4,4
line26	26	27	0,178	0,134	4,4
line27	4	29	0,015	0,0296	8,8
line28	29	30	0,012	0,0276	8,8
line29	30	31	0,12	0,2766	8,8
line30	31	32	0,21	0,243	4,4
line31	32	33	0,12	0,054	4,4
line32	33	34	0,178	0,234	4,4
line33	34	35	0,178	0,234	4,4
line34	35	36	0,154	0,162	4,4
line35	31	37	0,187	0,261	4,4
line36	37	38	0,133	0,099	4,4
line37	30	40	0,33	0,194	4,4
line38	40	41	0,31	0,194	4,4
line39	41	42	0,13	0,194	4,4
line40	42	43	0,28	0,15	4,4
line41	43	44	1,18	0,85	4,4
line42	44	45	0,42	0,2436	4,4
line43	45	46	0,27	0,0972	4,4
line44	46	47	0,339	0,1221	4,4
line45	47	48	0,27	0,1779	4,4
line46	36	49	0,21	0,1383	4,4
line47	49	50	0,12	0,0789	4,4
line48	50	51	0,15	0,0987	4,4
line49	51	52	0,15	0,0987	4,4
line50	52	53	0,24	0,1581	4,4
line51	53	54	0,12	0,0789	4,4
line52	54	55	0,405	0,1458	4,4
line53	54	56	0,405	0,1458	4,4
line54	30	58	0,391	0,141	4,4
line55	58	59	0,406	0,1461	4,4

(Continuation of the previous table)

Line	**From**	**To**	**R** **[Ω]**	**X** **[Ω]**	**Capacity lim**
line56	59	60	0,406	0,1461	4,4
line57	60	61	0,706	0,5461	4,4
line58	61	62	0,338	0,1218	4,4
line59	62	63	0,338	0,1218	4,4
line60	63	64	0,207	0,0747	4,4
line61	64	65	0,247	0,8922	4,4
line62	1	66	0,028	0,0418	13,2
line63	66	67	0,117	0,2016	13,2
line64	67	68	0,255	0,0918	8,8
line65	68	69	0,21	0,0759	4,4
line66	69	70	0,383	0,138	4,4
line67	70	71	0,504	0,3303	4,4
line68	71	72	0,406	0,1641	4,4
line69	72	73	0,962	0,761	4,4
line70	73	74	0,165	0,06	4,4
line71	74	75	0,303	0,1092	4,4
line72	75	76	0,303	0,1092	4,4
line73	76	77	0,206	0,144	4,4
line74	77	78	0,233	0,084	4,4
line75	78	79	0,591	0,1773	4,4
line76	79	80	0,126	0,0453	4,4
line77	67	81	0,559	0,3687	8,8
line78	81	82	0,186	0,1227	8,8
line79	82	83	0,186	0,1227	4,4
line80	83	84	0,26	0,139	4,4
line81	84	85	0,154	0,148	4,4
line82	85	86	0,23	0,128	4,4
line83	86	87	0,252	0,106	4,4
line84	87	88	0,18	0,148	4,4
line85	82	89	0,16	0,182	4,4
line86	89	90	0,2	0,23	4,4
line87	90	91	0,16	0,393	4,4
line88	68	93	0,669	0,2412	4,4
line89	93	94	0,266	0,1227	4,4

(Continuation of the previous table)

Line	From	To	R [Ω]	X [Ω]	Capacity lim
line90	94	95	0,266	0,1227	4,4
line91	95	96	0,266	0,1227	4,4
line92	96	97	0,266	0,1227	4,4
line93	97	98	0,233	0,115	4,4
line94	98	99	0,496	0,138	4,4
line95	95	100	0,196	0,18	4,4
line96	100	101	0,196	0,18	4,4
line97	101	102	0,1866	0,122	4,4
line98	102	103	0,0746	0,318	4,4
line99	1	105	0,0625	0,0265	8,8
line100	105	106	0,1501	0,234	8,8
line101	106	107	0,1347	0,0888	8,8
line102	107	108	0,2307	0,1203	4,4
line103	108	109	0,447	0,1608	4,4
line104	109	110	0,1632	0,0588	4,4
line105	110	111	0,33	0,099	4,4
line106	111	112	0,156	0,0561	4,4
line107	112	113	0,3819	0,1374	4,4
line108	113	114	0,1626	0,0585	4,4
line109	114	115	0,3819	0,1374	4,4
line110	115	116	0,2445	0,0879	4,4
line111	115	117	0,2088	0,0753	4,4
line112	117	118	0,2301	0,0828	4,4
line113	105	119	0,6102	0,2196	4,4
line114	119	120	0,1866	0,127	4,4
line115	120	121	0,3732	0,246	4,4
line116	121	122	0,405	0,367	4,4
line117	122	123	0,489	0,489	4,4
line118	48	27	1	0,5	4,4
line119	17	27	1	0,5	4,4
line120	8	24	1	0,5	4,4
line121	56	45	1	0,5	4,4
line122	65	56	1	0,5	4,4
line123	38	65	1	0,5	4,4

(Continuation of the previous table)

Line	From	To	R [Ω]	X [Ω]	Capacity lim
line124	9	42	1	0,5	4,4
line125	61	100	1	0,5	4,4
line126	76	95	1	0,5	4,4
line127	91	78	1	0,5	4,4
line128	103	80	1	0,5	4,4
line129	113	86	1	0,5	4,4
line130	110	89	1	0,5	4,4
line131	115	123	1	0,5	4,4
line132	25	36	1	0,5	4,4

Appendix B.2- Distributed Generation Nodes

Table B.2 – Distributed Generation Nodes

Node	DG units quantity		Node	DG units quantity	
	Photovoltaic	Wind		Photovoltaic	Wind
14	-	1	74	-	1
19	-	1	77	-	1
20	-	2	79	-	1
24	-	1	82	-	1
32	1	1	83	-	1
33	-	1	85	-	1
34	-	1	89	-	1
37	-	1	96	-	1
38	1	1	101	-	2
42	-	2	106	-	1
44	-	2	108	-	1
52	-	2	112	-	1
53	-	1	114	-	1
56	-	1	116	-	3
61	-	1	117	-	1
69	-	1	119	-	1
73	-	1			

Appendix B.3- Energy Storage System Nodes

Table B.3 –Energy Storage System Nodes

Node	ESS Quantity
n20	1
n29	2
n33	1
n43	1
n52	2
n56	1
n61	1
n66	1
n69	1
n73	1
n77	1
n83	1
n89	1
n100	1
n107	1
n112	1

Appendix C

Publication

C. Santos, S.F. Santos, D.Z. Fitiwi, M.R.M. Cruz, J.P.S. Catalão, “Sensitivity analysis in switches automation based on active reconfiguration to improve system reliability considering renewables and storage”, in: Proceedings of the IEEE 18th International Conference on Environment and Electrical Engineering — EEEIC 2018, Palermo, Italy, 12-15 June, 2018.

Sensitivity Analysis in Switches Automation Based on Active Reconfiguration to Improve System Reliability Considering Renewables and Storage

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***Abstract*—Distributed Smart Systems (DSS) should operate and restore discontinued service to consumers. In order to the system gain theses ability it is necessary to replace the manual switches for remotely controlled switches, improving the system restoration capability having in view the Smart Grids implementation. This paper aims to develop a new model, determining the minimal set of switches to replace in order to automate the system, along with a senility analysis on the position of the new switches, whether it should be placed in the same place as the manual switch or in a new location. The optimization of the system is made considering the renewable energy sources (RES) integration in the grid and energy storage systems (ESS), simultaneously, in order to improve the system reliability. The computational tool is tested using the IEEE 119 Bus test system, where different types of loads are considered, residential, commercial and industrial.**

***Keywords*—Distribution Automation, Distributed Smart Systems, Reliability, Self-healing, Smart Grid, Service Restauration.**

I. NOMENCLATURE

A. Sets/Indices

es/Ω^{es}	Index/set of energy storage
g/Ω^{g}	Index/set of generators
h/Ω^{h}	Index/set of hours
l/Ω^{l}	Index/set of lines
$n,m/\Omega^{n}$	Index/set of buses
s/Ω^{s}	Index/set of scenarios
ss/Ω^{ss}	Index/set of energy purchased
$\varsigma/\Omega^{\varsigma}$	Index/set of substations
Ω^{1}/Ω^{0}	Set of normally closed/opened lines
Ω^{D}	Set of demand buses

B. Parameters

$d_{n,h}$	Fictitious nodal demand
$E^{min}_{es,n,s,h}, E^{max}_{es,n,s,h}$	Energy storage limits (MWh)
$ER^{DG}_{g}, ER^{ss}_{\varsigma}$	Emission rates of DGs and energy purchased, respectively (tCO_2e/MWh)
$d_{l}, b_{l}, S^{max}_{l}$	Conductance, susceptance and flow limit of line l, respectively $(\Omega^{-1}, \Omega^{-1}, MVA)$
n_{DG}	Number of candidate nodes for installation of distributed generation
OC_{g}	Cost of unit energy production $(€/MWh)$
pf_{g}, pf_{ss}	Power factor of DGs and substation
$p^{DG,min}_{g,n}, p^{DG,max}_{g,n}$	Power generation limits (MW)
$p^{ch,max}_{es,n}, p^{dch,,max}_{es,n}$	Charging/discharging upper limit (MW)
$PD^{n}_{s,h}, QD^{n}_{s,n}$	Demand at node n $(MW, MVAr)$
R_{l}, X_{l}	Resistance and reactance of line l (Ω, Ω)
SW_{l}	Cost of line switching $(€/switch)$
V_{nom}	Nominal voltage (kV)
$\eta^{ch}_{es}, \eta^{dch}_{es}$	Charging/discharging efficiency
λ^{CO_2}	Cost of emissions (tCO_2e)
λ^{es}	Variable cost of storage system $(€/MWh)$
μ_{es}	Scaling factor (%)
$v^{p}_{s,h}, v^{Q}_{s,h}$	Unserved power penalty $(€/MWh)$ $(€/MVAr)$
ρ_{es}	Probability of scenarios

C. Variables

$E_{es,n,s,h}$	Reservoir level of ESS (MWh)
$f_{l,h}$	Fictitious current flows through line *l*
$g^{SS}_{n,h}$	Fictitious current injections at substation nodes
$I^{ch}_{es,n,s,h}, I^{dch}_{es,n,s,h}$	Charging/discharging binary variables
$P^{DG}_{g,n,s,h}, Q^{DG}_{g,n,s,h}$	DG power $(MW, MVAr)$
$P^{ch}_{es,n,s,h}, P^{dch}_{es,n,s,h}$	Charged/discharged power (MW)

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$P^{SS}_{\varsigma,s,h}, Q^{SS}_{\varsigma,s,h}$	Imported power from grid $(MW, MVAr)$
$P^{NS}_{n,s,h}, Q^{NS}_{n,s,h}$	Unserved power $(MW, MVAr)$
$P_{l,s,h}, Q_{l,s,h}$	Power flow through a line l $(MW, MVAr)$
$PL_{l,s,h}, QL_{l,s,h}$	Power losses in each feeder $(MW, MVAr)$
$X_{l,h}$	Binary switching variable of line l
$\Delta V_{n,s,h}, \Delta V_{m,s,h}$	Voltage deviation magnitude (kV)
$\theta_{l,s,h}$	Voltage angles between two nodes line l

A. Functions

$EC^{DG}, EC^{ES}, EC^{SS}$	Expected cost of energy produced by DGs, supplied by the ESS and imported (€)
$EmiC^{DG}, EmiC^{SS}$	Expected emission costs of power produced by DGs and imported from the grid (€)
$ENCS$	Expected cost for unserved energy (€)
SWC	Cost of line switching (€)

II. INTRODUCTION

B. Motivation, Aims, and Background

In today's power systems ensuring the continuity of service is one of the major concerns because of the main changes that are expected in the near future of these networks. The interruption in power grids is unavoidable due to a wide variety of reasons, such as system components maintenance, grid expansion, improving protection devices, therefore maintaining continued service provision is a major concern [1]. Also, the regulations on continuity of service have evolved to improve customer satisfaction and to improve the energy quality available for residential, commercial and industrial activities. In this sense, it is necessary to proceed with the development of technological solutions in order to improve the service and system restoration. One of the ways is through the optimal positioning of automated switches in distribution lines (Fig. 1), developing technological resources in order to improve the network operation and restoration conditions. Remote control of switches is one of the possible approaches to achieving network improvement and responding to the problem in remote parts of the network.

Therefore, the future of the electrical system is one of the topics on the agenda where the great majority of roads indicate that the future of the electric grid is the smartification of the grid in order to make it "intelligent" giving rise to smart grids. Smart grids will have the ability to perform operations in an automated manner, operating with great reliability and with low operating and maintenance costs. In [2] can be found some projects and research in the area of the smart grid. Within the smart grid there is the concept of system automation, where distribution system automation o plays an important role in the operations and system restoration, achieved through the implementation of remotely controlled switches and new communication technologies [3].

The vast majority of works in the literature focus only on the distribution system reconfiguration, mainly with the aim of minimizing the energy losses or helping to integrate more RES into the system [4]–[6].

In [4] Tahboub *et al.* present a new formulation for the distribution system reconfiguration with the aim of reducing energy losses in one year considering several distributed generation profiles. Haghighat and Zeng present in [5] an operation strategy using distribution system reconfiguration considering the uncertainty of the load and renewable generation with the objective of minimizing losses. In [6] Capitanescu et al. present a work that assesses the potential of network reconfiguration to improve the integration capacity of DGs in an active network management scheme.

Also, there is a set that through the system reconfiguration aims to improve the system reliability [7], [8]. Chen et al. in [7] present a method to evaluate the reliability index's, the total distribution system delivery capacity considering the reconfiguration of the network and daily load curves. In [8] it is presented a work on reconfiguration of the system in operation formulated as a multi-objective problem, where it is intended to minimize the losses and several reliability indexes.

Therefore, there is a very limited set of works focuses on the automation of switches. In this works the great majority focuses on the total automation of the switches which is unthinkable for the distribution system operation (DSO) due the cost of updating the switches from manual to automated, being few works that make this distinction or account for this fact [9]–[11].

Chen *et al.* present in [9] an algorithm to perform the placement of switches on the system lines with the goal to automate the distribution system. In [10] it is made also the placement of remotely controlled switches to improve the restoration capacity of the distribution system. In [11] it is presented a new methodology to carry out distribution system reconfiguration (DSR) in an automated way incorporating DGs in the system operation. Only automated switches are considered in the analysis of this work.

In this work is presented a different approach from the previous works, since this work has two objectives, perform dynamic reconfiguration in the system operation and improve the system restore capacity after a failure. Therefore, the system is dynamically reconfigured considering that all switches are automated in the first phase.

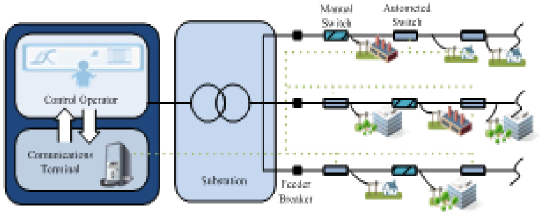

Fig. 1. Switch automation framework.

In a second phase, a sensitivity analysis is made based on the hourly reconfiguration topologies, in order to identify the minimum set of switches that must be upgraded from manuals to automatic, in order to improve system operation performance and restore capability after a failure. The sensitivity matrix will also allow identifying which switches will need the most maintenance.

C. Contributions

The main contributions of this paper are the following:

- Develop an improved stochastic mixed integer linear programing (SMILP) operation model considering de presence of DGs-based renewables, ESS and dynamic reconfiguration;
- Create a methodology on the system sensitivity analysis to identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration.
- Identify whether the automate switches will be placed, if only in places were manual switches exist or also in places.
- Identify switches that require more maintenance due to dynamic reconfiguration.

III. MATHEMATICAL FORMULATION

A. Objective Function

The objective of the current work is to minimize the sum of the most relevant cost terms (1); namely, the costs related to network reconfiguration (switching), operation, emissions and load shed.

$$MinTC = SWC + TEC + TENSC + TEmiC \tag{1}$$

The switching cost term (2) is incurred when a change of status in a given line occurs, that is, when it goes from 0 (open) to 1 (closed) or vice versa.

$$SWC = \sum_{\iota \in \Omega^{l}} \sum_{h \in \Omega^{h}} SW_{\iota} * (y_{\iota,h}^{+} + y_{\iota,h}^{-}) \tag{2}$$

The emission cost (3) is given by the sum of costs of power produced by DGs, discharged from ESS and imported from upstream grid.

$$\begin{aligned} TEC = & \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{g \in \Omega^{g}} OC_g P_{g,n,s,h}^{DG} \\ & + \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{es \in \Omega^{es}} \lambda^{es} P_{es,n,s,h}^{dch} \\ & + \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{\varsigma \in \Omega^{\varsigma}} \lambda_h^{\varsigma} P_{\varsigma,n,s,h}^{SS} \end{aligned} \tag{3}$$

The cost of load shedding, given by *TENSC*, is formulated as follows:

$$TENSC = \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} (v_{s,h}^{P} P_{n,s,h}^{NS} + v_{s,h}^{Q} Q_{n,s,h}^{NS}) \tag{4}$$

Finally, equation (5) refers to the total cost of emissions as a result of power either supplied by DGs or imported from upstream.

$$\begin{aligned} TEmiC = & \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{g \in \Omega^{g}} \sum_{n \in \Omega^{n}} \lambda^{CO_2} ER_g^{DG} P_{g,n,s,h}^{DG} \\ & + \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{\varsigma \in \Omega^{\varsigma}} \sum_{n \in \Omega^{n}} \lambda^{CO_2} ER_{\varsigma}^{SS} P_{\varsigma,s,h}^{SS} \end{aligned} \tag{5}$$

A. Constraints

The sum of all incoming flows to a node should be equal to the sum of all outgoing flows, which is given by the *Kirchhoff's Law*. This is applied to both active (6) and reactive (7) power flows, and must be respected at all times:

$$\begin{aligned} & \sum_{g \in \Omega^{g}} P_{g,n,s,h}^{DG} + \sum_{es \in \Omega^{es}} \left(P_{es,n,s,h}^{dch} - P_{es,n,s,h}^{ch}\right) + P_{\varsigma,s,h}^{SS} \\ & + P_{n,s,h}^{NS} + \sum_{in,\iota \in \Omega^{l}} P_{\iota,s,h} - \sum_{out,\iota \in \Omega^{l}} P_{\iota,s,h} = PD_{s,h}^{n} \\ & + \sum_{in,\iota \in \Omega^{l}} \frac{1}{2} PL_{\iota,s,h} + \sum_{out,\iota \in \Omega^{l}} \frac{1}{2} PL_{\iota,s,h}; \ \forall \varsigma \in i \end{aligned} \tag{6}$$

$$\begin{aligned} & \sum_{g \in \Omega^{g}} Q_{g,n,s,h}^{DG} + Q_{c,n,s,h}^{c} + Q_{\varsigma,s,h}^{SS} + Q_{n,s,h}^{NS} \\ & + \sum_{in,\iota \in \Omega^{l}} Q_{\iota,s,h} - \sum_{out,\iota \in \Omega^{l}} Q_{\iota,s,h} = QD_{s,h}^{n} \\ & + \sum_{in,\iota \in \Omega^{l}} \frac{1}{2} QL_{\iota,s,h} + \sum_{out,\iota \in \Omega^{l}} \frac{1}{2} QL_{\iota,s,h} \ \forall \varsigma \in i \end{aligned} \tag{7}$$

Equations (8) and (9) present the linearized AC power flows through each feeder, which are governed by the *Kirchhoff's Voltage Law*. Note that $\theta_{\iota,s,h}$ refers to the angle difference $\theta_{n,s,h} - \theta_{m,s,h}$ where n and m are bus indices corresponding to the same line l.

$$\begin{aligned} & \left|P_{\iota,s,h} - (V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right) g_k \right. \\ & \left. - V_{nom}^{2} b_k \theta_{\iota,s,h}\right| \leq MP_{\iota}(1 - \chi_{\iota,h}) \end{aligned} \tag{8}$$

$$\begin{aligned} & \left|Q_{\iota,s,h} - (-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right) b_k \right. \\ & \left. - V_{nom}^{2} g_k \theta_{\iota,s,h}\right| \leq MQ_{\iota}(1 - \chi_{\iota,h}) \end{aligned} \tag{9}$$

The maximum amount of flow that can pass through a line is given by inequality (10). Equations (11) and (12) represent active and reactive power losses in a given line.

$$P_{\iota,s,h}^{2} + Q_{\iota,s,h}^{2} \leq \chi_{\iota,h} (S_{\iota}^{max})^{2} \tag{10}$$

$$PL_{\iota,s,h} = R_{\iota}\left(P_{\iota,s,h}^{2} + Q_{\iota,s,h}^{2}\right) / V_{nom}^{2} \tag{11}$$

$$QL_{\iota,s,h} = X_{\iota}\left(P_{\iota,s,h}^{2} + Q_{\iota,s,h}^{2}\right) / V_{nom}^{2} \tag{12}$$

ESS is modeled by the expressions (13)--(18).

$$0 \leq P_{es,n,s,h}^{ch} \leq I_{es,n,s,h}^{ch} P_{es,n,h}^{ch,max} \tag{13}$$

$$0 \leq P_{es,n,s,h}^{dch} \leq I_{es,n,s,h}^{dch} P_{es,n,h}^{ch,max} \tag{14}$$

$$I_{es,n,s,h}^{ch} + I_{es,n,s,h}^{ch} \leq 1 \tag{15}$$

$$E_{es,n,s,h} = E_{es,n,s,h-1} + \eta_{es}^{ch} P_{es,n,s,h}^{cg} - \frac{P_{es,n,s,h}^{dch}}{\eta_{es}^{dch}} \tag{16}$$

$$E_{es,n}^{min} \leq E_{es,n,s,h} \leq E_{es,n}^{max} \tag{17}$$

$$E_{es,n,s,h0} = \mu_{es} E_{es,n}^{max};\ E_{es,n,s,h24} = \mu_{es} E_{es,n}^{max} \tag{18}$$

The limits on the amount of power charged and discharged are given by (13) and (14), respectively, while (15) guarantees that charging and discharging processes do not simultaneously happen at any given time.

The state of charge is modelled as presented in (16). Inequality (17) ensures that the storage level is always within a permissible range. Finally, (18) sets the initial storage level, and ensures the storage is left with the same amount at the end of the operational period.

The active and reactive power limits of DGs are given by (19) and (20), respectively. Inequality (21) limits the DGs ability to inject or consume reactive power.

$$P_{g,n,s,h}^{DG,min} \leq P_{g,n,s,h}^{DG} \leq P_{g,n,s,h}^{DG,max} \tag{19}$$

$$Q_{g,n,s,h}^{DG,min} \leq Q_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG,max} \tag{20}$$

$$\begin{aligned} -\tan\left(\cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} &\leq Q_{g,n,s,h}^{DG} \\ &\leq \tan\left(\cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \end{aligned} \tag{21}$$

The active and reactive power limits at the substations are given by (22) and (23), due to stability reasons.

$$P_{\varsigma,s,h}^{SS,min} \leq P_{\varsigma,s,h}^{SS} \leq P_{\varsigma,s,h}^{SS,max} \tag{22}$$

$$Q_{\varsigma,s,h}^{SS,min} \leq Q_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS,max} \tag{23}$$

The reactive power that is withdrawn from the substation is subject to the bounds presented in inequality (24).

$$\begin{aligned} -\tan(\cos^{-1}(pf_{ss}))P_{\varsigma,s,h}^{SS} &\leq Q_{\varsigma,s,h}^{SS} \\ &\leq \tan(\cos^{-1}(pf_{ss}))P_{\varsigma,s,h}^{SS} \end{aligned} \tag{24}$$

The radial operation of the considered system is guaranteed by including the constraints in (25) through (31). Constraints (27)—(31) ensure radiality in the presence of DGs, and simultaneously avoid islanding.

$$\sum_{l\in\Omega^l} \chi_{l,h} = 1, \forall m \in \Omega^D; l \in n \tag{25}$$

$$\sum_{in,l\in\Omega^l} \chi_{l,h} - \sum_{out,l\in\Omega^l} \chi_{l,h} \leq 1, \forall m \notin \Omega^D; l \in n \tag{26}$$

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = g_{n,h}^{SS} - d_{n,h}, \forall n \in \Omega^\varsigma; l \in n \tag{27}$$

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = -1, \forall n \in \Omega^g; \forall n \in \Omega^D \tag{28}$$

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = \ 0, \forall n \notin \Omega^g; \forall n \notin \Omega^D \forall n \notin \Omega^\varsigma \tag{29}$$

$$0 \leq \sum_{in,l\in\Omega^l} f_{l,h} + \sum_{out,l\in\Omega^l} f_{l,h} \leq n_{DG}; l \in n \tag{30}$$

$$0 \leq g_{n,h}^{SS} \leq n_{DG}, \forall n \in \Omega^\varsigma; l \in n \tag{31}$$

IV. NUMERICAL RESULTS

The 119 bus test system from IEEE is used to test the proposed optimization model, Fig. 2, where can be seen the position and type of DGs in the system. Detailed data about this test system can be found in [12].

In this system, there are two types of DGs, solar and wind which have an installed capacity of 2 MW and 1 MW, respectively. The ESS have as installed capacity of 1 MW with both charging and discharging efficiencies assumed to be 90%. The total active and reactive loads of the system are 3.93 MW and 1.62 MVar, respectively. The operational period is assumed to 24 hours long. A possible hourly reconfiguration is considered. The voltage of the system is 10 kV, and the maximum voltage deviation allowed at each node is ± 5% of the nominal voltage value. The substation is considered as the reference node, where the voltage magnitude is set to the nominal voltage and the angle as 0. In addition, the power factor at the substation 0.95 is considered to be constant. Electricity prices follow the demand trend, ranging from 42 to 107 €/MWh. The lowest electricity price happens during the valley periods and the highest ones during peak consumption periods. The operation cost of ESS during charging and discharging is considered to be 5 €/MWh. The rate of emissions at the substation is assumed to be 0.4 tCO2e/MWh, and a carbon price of 7 €/tCO2 is considered in all simulations.

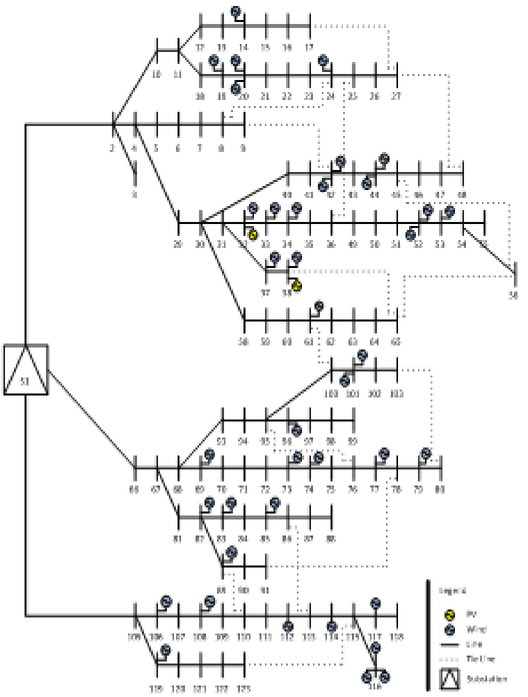

Fig. 2. 119 Bus test system.

A tariff of 40 €/MWh and 20 €/MWh are considered for remunerating the power productions from solar PV and wind farms. The cost of switching any line is considered to be 5 €/switching.

In this work the automation of switches was considered, based on the network dynamic reconfiguration considering the presence of renewable (wind and solar generation), as well as ESS. This reconfiguration was obtained from the perspective of optimizing the system operation, considering the economic requirements and technical restrictions of the system.

Thus, in Table I can see the total cost of system operating together with the cost terms that make up the objective function. From this table can be highlight the cost of power not served, 0MW, as shown in Fig. 2, due to the integration of smart grid enabling technologies. In this case, the presence of DGs combined with ESS, which allows a better balance of generation and demand, leading to all the energy being used while the reliability of the system is maintained.

Also in Table I is presented the total value of the energy losses, and in Fig. 3 its profile can be analyzed over the period of operation, which due to the dynamic reconfiguration together with the DGs and ESS, presents lower losses than the without these technologies being present, compared with the literature values [13].

Therefore, in the first phase of this work, system dynamic reconfiguration was done based on the mathematical formulation presented, where different reconfiguration for each hour was obtained. The reconfiguration results are presented in Table II, where the closed lines set and open lines set constituting the network topology.

In a second phase, a sensitivity analysis was performed to the dynamic reconfiguration of the system. Based on the analysis of Table II, the number of switches per line was analyzed. This analysis can be realized in Fig. 4, where it can be seen that not all lines undergo reconfiguration. From the totality of all lines, only 22% of them perform reconfiguration at least once in the time period considered, which means that 78% of lines do not need to be automated. However, the 22% of the lines still represent a major investment effort to automate the system. In this perspective, it is necessary to identify using one or several criteria which set of switches are essential to automate. As a result, the criterion of the average value was used, where for the lines that have a number of switches above the average are the possible candidates to constitute the set of switches to be automated. For the majority of cases, the set of lines belonging to the set of values above the average represent more than 50% of the total system switches. In this case, as shown in Fig. 5, this set of values represents 62% of the total switches.

Also, in the realization of this study it was considered that all lines can perform reconfiguration to evaluate if the automation of the switches would be in the same place where the manual switches are, or in other places of the network are positioned (since the manual switches are only present in the tie lines). Since the tie lines correspond to the lines belonging to the set of lines 118 to 132 it is possible to verify that there is a set of lines $\{ine23, line26, line34, line39, line42, line53, line61, line74, line76, line82, line85, line95\}$, that it is beneficial to put an automated switch. From this set the lines, {line42,line53, line74, line 85 e, line90} are part of the priority set to be automated.

TABLE I – SYSTEM COSTS

Total Cost [€]	29912,27
Reconfiguration Cost [€]	1010
Energy Cost [€]	27901,72
Emission Cost [€]	1000,55
Power nor served [€]	0
P Losses [MW]	10,00
Q Losses [MVAr]	6,60

TABLE II – NETWORK RECONFIGURATION FOR EACH HOUR (WITHIN A 24 HOURS PERIOD)

Hour	Closed Lines	Open Lines
1	1-22; 24; 25; 27-33; 35-60; 62-81; 83-89; 91-94; 96-116; 118; 120; 123; 125; 126; 129; 131; 132;	23; 26; 34; 61; 82; 90; 95; 117; 119; 121; 122; 124; 127; 128; 130;
2	1-22; 24; 25; 27-33; 35-41; 43-60; 62-75; 77-81; 83; 84; 86-89; 91-94; 96-118; 120; 121; 123; 125; 126; 128-130; 132;	23; 26; 34; 42; 61; 76; 82; 85; 90; 95; 119; 122; 124; 127; 131;
3	1-22; 24; 25; 27-33; 35-60; 62-73; 75; 77-81; 83; 84; 86-89; 91-94; 96-118; 120; 123; 125-130; 132;	23; 26; 34; 61; 74; 76; 82; 85; 90; 95; 119; 121; 122; 124; 131;
4	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75; 77-81; 83; 84; 86-89; 91-94; 96-117; 119; 120; 122; 123; 125-130; 132;	23; 26; 34; 53; 61; 74; 76; 82; 85; 90; 95; 118; 121; 124; 131;
5	1-22; 24; 25; 27-33; 35-41; 43-52; 54-60; 62-73; 75; 77-81; 83-89; 91-94; 96-117; 119-123; 125-129; 132;	23; 26; 34; 42; 53; 61; 74; 76; 82; 90; 95; 118; 124; 130; 131;
6	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75; 77-81; 83-89; 91-94; 96-117; 119; 120; 122; 123; 125-129; 132;	23; 26; 34; 53; 61; 74; 76; 82; 90; 95; 118; 121; 124; 130; 131;
7	1-22; 24; 25; 27-33; 35-41; 43-60; 62-73; 75; 77-89; 91-94; 96-118; 120; 121; 123; 125-128; 132;	23; 26; 34; 42; 61; 74; 76; 90; 95; 119; 122; 124; 129-131;
8	1-22; 24; 25; 27-33; 35-52; 54-60; 62-81; 83; 84; 86-89; 91-94; 96-118; 120; 122; 123; 125; 126; 129; 130; 132;	23; 26; 34; 53; 61; 82; 85; 90; 95; 119; 121; 124; 127; 128; 131;
9	1-22; 24; 25; 27-33; 35-60; 62-81; 83; 84; 86-89; 91-94; 96-118; 120; 123; 125; 129; 130; 132;	23; 26; 34; 61; 82; 85; 90; 95; 119; 121; 122; 124; 126-128; 131;
10	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-89; 91-94; 96-118; 120; 122; 123-126; 132;	23; 26; 34; 39; 53; 61; 90; 95; 119; 121; 127-130; 131;
11	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-73; 75-117; 119; 120; 122-124; 126; 127; 132;	23; 26; 34; 39; 53; 61; 74; 118; 121; 125; 128-130; 131;
12	1-22; 24; 25; 27-33; 35-38; 40-60; 62-84; 86-89; 91-118; 120; 123; 124; 130; 132;	23; 26; 34; 39; 61; 85; 90; 119; 121; 122; 125; 116-129; 131;
13	1-22; 24; 25; 27-33; 35-52; 54-60; 62-89; 91-94; 96-118; 120; 122; 123; 125; 126; 132;	23; 26; 34; 53; 61; 90; 95; 119; 121; 124; 127; 128-130; 131;
14	1-22; 24; 25; 27-33; 35-60; 62-73; 75-81; 83;84; 86-117; 120; 123; 127; 129; 130; 132;	23; 34; 61; 74; 82; 85; 118; 119; 121; 122; 124-126; 131;
15	1-22; 24; 25; 27-33; 35-60; 62-73; 75-81; 83; 84; 86-116; 120; 123; 127; 129-132;	23; 34; 61; 74; 82; 85; 117-119; 124-126; 128;
16	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-84; 86-117; 120; 122-124; 130; 132;	23; 34; 39; 53; 61; 85; 118; 119; 121; 125-129; 131;
17	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75-89; 91-94; 96-116; 119; 120; 122; 123; 125-127; 131; 132;	23; 26; 34; 53; 61; 74; 90; 95; 117; 118; 121; 124; 128-130;
18	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 74-89; 91-94; 96-118; 120; 122; 123; 125; 126; 132;	23; 26; 34; 53; 61; 90; 95; 119; 121; 124; 127-131;
19	1-25; 27-33; 35-38; 40-52; 62-84; 86-117; 119; 122; 123; 124; 130; 132;	26; 34; 39; 53; 61; 85; 118; 120; 121; 125; 126-128; 129; 131;
20	1-25; 27-33; 35-38; 40-60; 62-73; 75-118; 123; 124; 127; 132;	26; 34; 39; 61; 74; 119-122; 125; 126; 128-130;131;
21	1-25; 27-38; 40-60; 62-73; 75-84; 86-117; 86-117; 119; 123; 124; 127; 130;	26; 39; 61; 74; 85; 118; 120-122; 125; 126; 128; 129; 131; 132;
22	1-22; 24-33; 35-38; 40-52; 54-60; 62-75; 77-81; 83; 84; 86-117; 120; 122-124; 128-130; 132;	23; 34; 39; 53; 61; 76; 82; 85; 118; 119; 121; 125-127; 131;
23	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75-81; 83; 84; 86-118; 120; 122; 123; 127; 129; 130; 132;	23; 26; 34; 53; 61; 74; 82; 85; 119; 121; 124-126; 131;
24	1-22; 24; 25; 27-33; 35-41; 43-52; 54-73; 75-81; 83; 84; 86-89; 91-94; 96-116; 118; 120-122; 125-127; 129-132;	23; 26; 34; 42; 53; 74; 82; 85; 90; 95; 117; 119; 123; 124; 128;

Thus, the set of lines to be automated is presented in Table III and corresponds to 62% of the total of switches, as mentioned, allowing that from the hourly reconfigurations presented in Table II it is possible to realize 68% of the configurations, with the automation of these lines. Since the minimum set of switches to be updated corresponds to the most used switches, these will consequently be also the set of lines that will require higher maintenance.

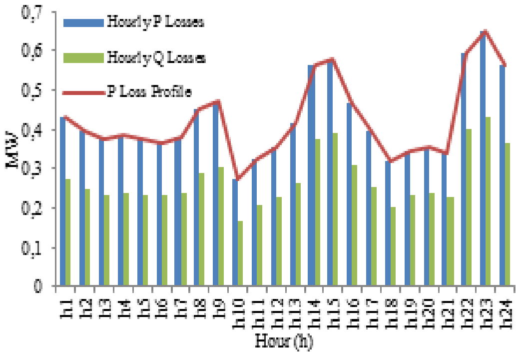

Fig. 3. Active and reactive hourly losses for the different time settings.

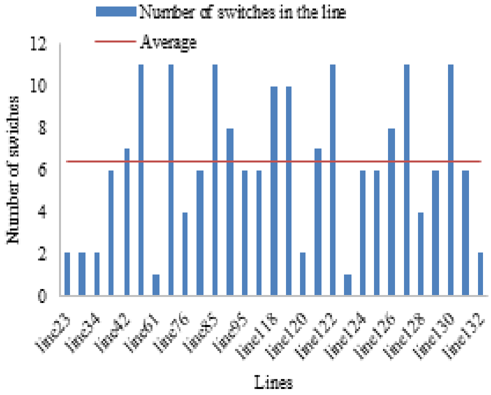

Fig. 4. Number of switches per line.

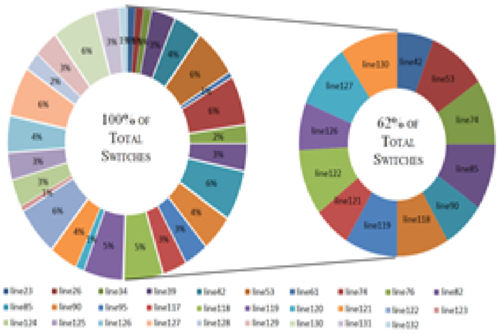

Fig. 5. Percentage of number of switches per line.

TABLE III – SET OF LINES TO AUTOMATE

Set of Lines to Automate
$\left\{\begin{matrix} line42, line53, line74, line85, line90, line118, line119, \\ line121, line122, line126, line127, line130 \end{matrix}\right\}$

V. CONCLUSIONS

In this study, an analysis on the dynamic reconfiguration used in conjunction with DGs and ESS as a way to operate the system with more reliability and integrate higher levels of RES was presented. To perform this analysis an improved stochastic MILP was used to obtain numerical results of operating the 119 bust test system assessing the impact on systems operation with the integration of DSR, DGs and ESS. The analysis of the case study showed that:

- From the dynamic reconfiguration analysis it was possible to identify jointly with one or several criteria which is the minimum set of switches that must be automated, so as not to lose the benefits of dynamic reconfiguration and increase the system reliability through faster system restoration due to automated switches.
- It was also possible to determine that the automated switch positioning is not always in the place where the manual switch is located, being possible through this analysis to identify the locations where it is beneficial to place them. Moreover, it was possible to identify the set of switches which will require more maintenance.

With this approach to automate the system it is possible to perform 68% of the dynamic reconfigurations obtained.

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