Faculdade de Engenharia da Universidade do Porto

Dynamic Reconfiguration of Distribution Network Systems Featuring Large-scale Intermittent Power Sources

Flávio Vieira Dantas

Dissertação realizada no âmbito do
Mestrado Integrado em Engenharia Electrotécnica e de Computadores
Major Energia

Orientador: Prof. Doutor João Paulo da Silva Catalão
Co-orientador: Doutor Sérgio Fonseca Santos

julho de 2017

Resumo

A tendência de integração de fontes de energia intermitentes no sistema eléctrico (especialmente ao nível da distribuição) está a levar a aumento da necessidade de flexibilidade em todos os níveis do trânsito de potência: quer seja no fornecimento, na rede e do lado da procura. Esta dissertação foca-se na reconfiguração dinâmica da rede como uma forma viável de fornecer flexibilidade ao sistema, através da mudança automática do estado das linhas em resposta às condições operacionais do sistema. O grande objectivo é avaliar o impacto deste tipo de flexibilidade ao nível da integração de fontes de energia variável (especialmente, fotovoltaica e eólica) no sistema de distribuição. Para realizar esta análise, neste trabalho é desenvolvido um modelo operacional de programação estocástica linear inteira-mista. O objectivo deste problema de optimização é minimizar o somatório dos termos de custos mais relevantes respeitando as várias restrições do modelo. O modelo proposto encontra dinamicamente a configuração óptima do sistema de acordo com as condições operacionais do sistema. A escala de operação no trabalho corrente é de um dia, mas há a possibilidade de reconfiguração horária. O sistema standard do IEEE 41-nós é utilizado para testar o modelo proposto e realizar a análise dos resultados. Os resultados numéricos mostram que a reconfiguração dinâmica da rede leva a uma utilização mais eficiente da geração renovável do tipo renovável no sistema, reduz os custos e as perdas, e melhora substancialmente a performance do sistema, especialmente dos perfis de tensão.

Palavras-chave – Geração distribuída; reconfiguração da rede; fontes de energia renováveis; programação estocástica linear inteira-mista;

Abstract

The growing trend of variable energy source integration in power systems (especially at a distribution level) is leading to an increased need for flexibility in all levels of the energy flows in such systems: the supply, the network and the demand sides. This thesis focuses on a viable flexibility option that can be provided by means of a dynamic network reconfiguration (DNR), an automatic changing of line statuses in response to operational conditions in the system. The ultimate aim is to assess the impacts of such flexibility on the utilization levels of variable power sources (mainly, solar and wind) integrated at a distribution level. To perform this analysis, a stochastic mixed integer linear programming (S-MILP) operational model is developed in this work. The objective of the optimization problem is to minimize the sum of the most relevant cost terms while meeting a number of model constraints. The proposed model dynamically finds an optimal configuration of an existing network system in accordance with the system's operational conditions. The operation scale in the current work is one day, but with the possibility of an hourly reconfiguration. The standard IEEE 41-bus system is employed to test the proposed model and perform the analysis. Numerical results generally show that DNR leads to a more efficient utilization of renewable type DGs integrated in the system, reduced costs and losses, and a substantially improved system performance especially the voltage profile in the system.

Keywords - Distributed generation; network reconfiguration; renewable energy sources; stochastic mixed integer linear programming;

Acknowledgments

First, I would like to thank to my parents and my brother for being the great workers of my personal formation and also for financially support all these years that I spent in the Faculty of Engineering of the University of Porto. I will never forget the efforts they have made, in a time of such difficulties, so that I could be where I am today.

It is with great gratitude that I thank to Professor João Catalão for the opportunity provided with this challenge and for having indicated an agreement with the University of Beira Interior that allowed the resolution of this thesis. To Sérgio and Desta many thanks for always being available to help and always with good advices and tips which without it, nothing of what is done would be possible. Also, the knowledge that I have been receiving, which made me a potential engineer candidate, is due to an extraordinary group of professors in FEUP that enjoy transmit their experience to their students. A big hug to all my classmates which I had the pleasure to meet, study, chat, and/or go out for some fun; and to all my friends who were always there for me in good and bad times.

Hence, many thanks to my close family members (they know who they are) for always advising me, for pointing me in the good direction, for moral supporting and for everything it can be imagined. I know that some of these persons are watching me from somewhere and they are very glad for what was achieved.

Flávio Vieira Dantas

“Let the future tell the truth, and evaluate each one according to his work and accomplishments. The present is theirs; the future, for which I have really worked, is mine.”

Nikola Tesla

Contents

List of Figures

List of Tables

Abbreviation and Symbols

List of Abbreviations

ACO	Ant Colony Optimization
ADNs	Active Distribution Networks
CBs	Capacitor Banks
DER	Distributed Energy Resources
DG	Distributed Generation
DNR	Dynamic Network Reconfiguration
DR	Demand Response
DSOs	Distribution System Operators
EIA	Energy Information Administration
EMS	Energy Management Systems
ESS	Energy Storage Systems
EU	European Union
IEA	International Energy Agency
IEO2016	International Energy Outlook 2016
MACS	Multi-Agent Control System
MICP	Mixed-Integer Conic Programming
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MIQCP	Mixed-Integer Quadratically Constrained Programming
OECD	Organisation for Economic Co-operation and Development
PEVs	Plug-in Electric Vehicles
RES	Renewable Energy Sources
RCSs	Remotely Controlled Switches

SCADA	Supervisory Control And Data Acquisition
SCB	Switchable Capacitor Bank
S-MILP	Stochastic Mixed-Integer Linear Programming
SSO	Social Spider Optimization
TLoL	Transformers Loss of Life
vRES	Variable Renewable Energy Sources

List of Symbols

Sets/Indices

c/Ω^c	Index/set of capacitor banks
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

Parameters

$d_{n,h}$	Fictitious nodal demand
$E_{es,n,s,h}^{min}$, $E_{es,n,s,h}^{max}$	Energy storage limits (MWh)
ER_g^{DG}, ER_ς^{SS}	Emission rates of DGs and energy purchased, respectively (tCO_2e/MWh)
g_l, b_l, S_l^{max}	Conductance, susceptance and flow limit of line l, respectively (Ω^{-1}, Ω^{-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
$P_{g,n}^{DG,min}$, $P_{g,n}^{DG,max}$	Power generation limits (MW)
$P_{es,n}^{ch,max}$, $P_{es,n}^{dch,max}$	Charging/discharging upper limit (MW)
$PD_{s,h}^n$, $QD_{s,h}^n$	Demand at node *n* (MW, MVAr)
$Q_{c,n,s,h}^{c,0}$	Block of capacitor bank (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)
$\eta_{es}^{ch}, \eta_{es}^{dch}$	Charging/discharging efficiency
λ^{CO_2}	Cost of emissions ($€/tCO_2e$)
λ^{es}	Variable cost of storage system ($€/MWh$)
λ_h^{ς}	Price of electricity purchased
μ_{es}	Scaling factor (%)
$\upsilon_{s,h}^{P}, \upsilon_{s,h}^{Q}$	Unserved power penalty ($€/MW, €/MVAr$)
ρ_s	Probability of scenario s

Variables

$E_{es,n,s,h}$	Reservoir level of ESS (MWh)
$f_{l,h}$	Fictitious current flows through line l
$g_{n,h}^{SS}$	Fictitious current injections at substation nodes
$I_{es,n,s,h}^{ch}$, $I_{es,n,s,h}^{dh}$	Charging/discharging binary variables
$P_{g,n,s,h}^{DG}$, $Q_{g,n,s,h}^{DG}$	DG power (MW, MVAr)
$P_{es,n,s,h}^{ch}$, $P_{es,n,s,h}^{dch}$	Charged/discharged power (MW)
$P_{\varsigma,s,h}^{SS}, Q_{\varsigma,s,h}^{SS}$	Imported power from grid (MW, MVAr)
$P_{n,s,h}^{NS}, Q_{n,s,h}^{NS}$	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)
$Q_{c,n,s,h}^{c}$	Reactive power injected by SCBs (MVAr)
$x_{c,n,h}$	Integer variable of capacitor banks
$x_{l,h}$	Binary switching variable of line l
$\Delta V_{n,s,h}, \Delta V_{n,s,h}$	Voltage deviation magnitude (kV)
$\theta_{l,s,h}$	Voltage angles between two nodes line l

Functions

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

Chapter 1

Introduction

1.1 - Background

Electrical distribution systems are designed to satisfy the consumers' demand for electricity, traditionally exhibiting uni-directional power flows with very little versatility, intelligence and autonomy. And, electricity consumers are passive elements that expect electricity to be transferred from power stations to the transmission lines and then to the distribution grid literally without any interaction such as demand response. Yet, it is important to have in mind that, with the increasing use of the new technologies, nowadays, the demand for electric energy has been increasing and is subject to high level variability during the course of a day. The limited one-way power flow makes the network response to the growing demand more difficult. This may affect the operational power flow on the distribution grid and lead to many problems including partial blackouts. To avoid those problems, it is vital to find new solutions, new technologies and new methodologies to supply the costumers in a proper and more efficiently way. Furthermore, energy security and other global concerns such as climate change are making governments and utilities aware that new policies are needed to foment a sustainable energy future.

Some solutions for reducing gas emissions go through on the approval of Renewable Energy Sources (RES) policies around the world, which are more likely to grow in the next years favouring the use and development of eco-friendly sources to generate electric energy. As it can be seen in Figure 1.1, the installed capacity of renewable energy (excluding hydro sources) reached to a new record of 53.6% in 2015 compared with 49% and 40.2% in the previous years [1]. It is understood that the increasing level of integrating such technologies leads to wide-range benefits. However, the fact that most of these resources such as wind and solar are characterized by high levels of variability and uncertainty results in enormous

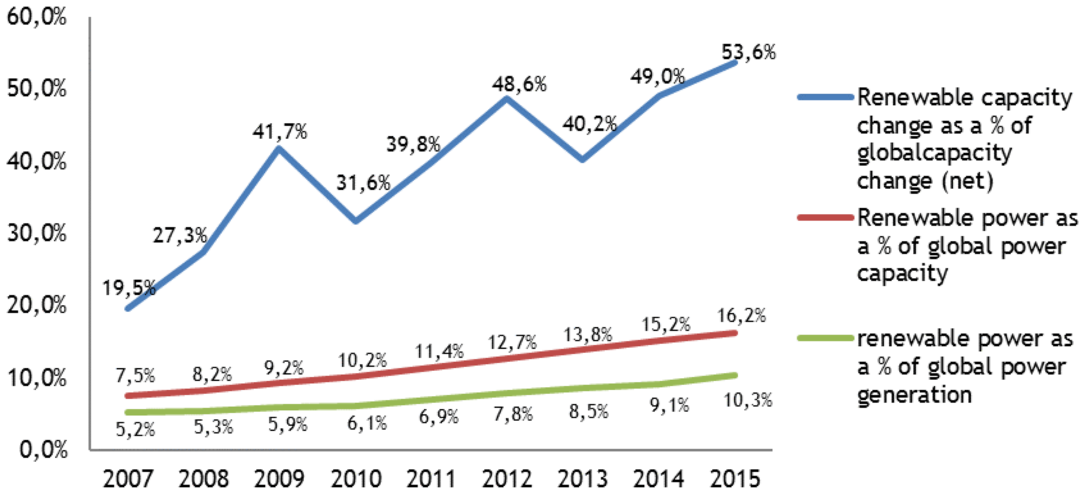

Figure 1.1 – Renewable power generation capacity as share of global power [1].

challenges especially when it comes to operating distribution grids. This is one of the biggest concerns of network operators, who need to ensure a healthy operation of their grids at all time. The traditional set up of many distribution systems does not enable large-scale integration of variable energy sources because they are not normally equipped with the right enabling mechanisms that provide adequate flexibility to cope up with the stochastic nature of such resources. For example, Distributed Generations (DGs) with reactive power support capabilities, Energy Storage Systems (ESSs) and Switchable Capacitor Banks (SCBs), if optimally deployed in the distribution network systems, can dramatically improve the flexibility in the system and contribute to achieve different policy objectives such as environmental goals. This is already leading to the evolution of distribution systems from the unidirectional passive systems to more active distribution networks allowing bidirectional power flows. Such a transition requires a paradigm shift in systems either at the design level or at the level of operation. It should be noted that both planning and operation depend on technical constraints and economic goals (minimizing investment and operational costs, energy losses, etc.). However, large-scale integration of Distributed Energy Resources (DERs) in distribution systems may bring operational problems such as the voltage fluctuation over the permissible limits. These problems need to be solved to better accommodate more power capacity to supply the increasing demand for reliable electricity.

Distribution automation is becoming increasingly important in recent years while electric utilities are seeking for more quality and reliability of customer service at low operational costs. An automation system is crucial to enabling the autonomous and intelligent operation of the system through load and generation changes, and unexpected system failures. Therefore, Distributed Network Reconfiguration (DNR) can be the key methodology to partly solve these problems and introduce more flexibility to the system and enable to accommodate large-scale of variable RES power.

1.2 - Problem Definition

The automated network reconfiguration is one of the most studied subjects in the area of automated power systems which is a promising option because it uses the already existing assets to meet important and valuable objectives. Network reconfiguration can be applied on both transmission systems and on distribution systems but the objectives and the methodology are different depending on which systems the reconfiguration is applied to. The first is a balanced and interconnected network and the second one has a radial topology. Therefore, the methodology and restrictions can obviously be different. On transmission network, the switching actions are made primarily to avoid overloads, reduce operation costs and improve reliability while in distribution systems the switching operations aim to meet different objectives such as the reduction of power losses, and improvements in voltage stability and reliability of power delivered to the end-users. In addition, network switching (also called reconfiguration) can be used as a key flexibility option to provide support for more integration and utilization of variable RESs.

The principle on the distribution network reconfiguration is to modify the topology by opening or closing the automated switches in order to optimize the system operation, isolate faults and restore power supply during interruptions. Therefore, such topology changes can introduce benefits by improving the load balance between feeders (transferring loads from heavily-loaded feeders into less-loaded ones) resulting in improved voltage levels, reducing power losses and improving reliability. In addition, it can be used to reduce the timing of annual unavailability and energy not supplied. In the recent years, the progress of automated systems and the development of the big computational capacity have been enabling the search of new reconfiguration methodologies for real-time planning and control. In other words, network systems can be reconfigured to find the best topology that minimizes power losses and improve operational performance as long as the technical limits are not violated, and the protection mechanisms remain adequately coordinated. And, the integration of energy from DGs mainly from renewable resources (particularly wind and solar) becomes easier to supply variable loads. It should be noted that reconfiguration is a short-term problem, which tries to find the optimum network configuration for a specific period of operation. Due to the high level of uncertainty regarding future network conditions, it is extremely unlikely that a single network topology will be ideal over a long period of time. Therefore, it is necessary to reconfigure the distribution network from time to time.

Many approaches have been proposed to address the reconfiguration problem, although the computational time required and computing resources still remain to be some one of the major challenges. Network reconfiguration is a complex combinatorial problem because it involves many binary variables and operational constraints.

Heuristic approaches have been reported to run faster and achieve satisfactory results, but are still not efficient enough in large-scale networks. It is known that power production using the most prominent RESs is characterized by high levels of intermittency and partial unpredictability. This, coupled with demand uncertainty, requires greater flexibility needs in distribution network systems. One of these can be provided by the network itself by means of dynamic reconfiguration. This will lead to a paradigm shift from the traditional way of operating a static and radial grid to a more active network with the possibility of a dynamically changing topology. This enables one to reconfigure the network more frequently in response to operational changes occurring in the network system, for example, due to load and RES power generation unbalances. Hence, it is highly desirable to have a highly efficient and effective approach to reconfigure the distribution system dynamically to improve the operational performance of the same system or at least maintain it at a standard level.

1.3 - Research Objectives

Network reconfiguration is one of the most studied subjects in power systems. A lot of researchers agree that it is one of the promising and emerging flexibility options because it uses the already existing assets to meet important objectives. The main objectives of this thesis are:

- To carry out a comprehensive state of the art literature review on the subject areas of system flexibility and distribution network reconfiguration, which establishes the basis for defining the problem addressed in this thesis;
- To develop a stochastic MILP operational model for the dynamic reconfiguration problem of distribution networks in the presence of large-scale variable RESs and other distributed energy resources;
- To carry out case studies and discuss the most relevant results;
- To perform an extensive analysis with regards to the economic and technical benefits of dynamic reconfiguration, as well as efficient utilization of intermittent power sources.

1.4 - Research Methodology

The work developed in this thesis focuses on a viable flexibility option that can be provided by means of a dynamic network reconfiguration, an automatic changing of line statuses in response to operational conditions in the system. In order to achieve the proposed objectives for this work, a mathematical optimization model is developed. The problem is formulated in stochastic programming environment, accounting for uncertainty and variability of RES power productions as well as that of electricity demand.

The proposed optimization model is of a mixed integer linear programming (MILP) 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

The thesis is organized as follows. Chapter 2 presents a background on the current and evolution of power systems with a particular focus on distribution networks, vRES integration, the increasing need for flexibility options, etc. Along this line, a survey of the most important developments including the challenges and opportunities of vRES integrations around the world and Europe has been made. Still, Chapter 2 covers a more detailed view of the relevant works by other researchers on the subject areas of smart grids, the growing need of flexibility and the distributed network reconfiguration which is the major point of interest of this thesis. In Chapter 3, the stochastic mathematical model developed is fully described, structured into objective function and constraints that are used in the optimization. Issues related to the case studies, including all relevant data and assumptions, results and discussions are presented in Chapter 4. Finally, Chapter 5 highlights the main findings of this thesis and points out some lines for future works.

Chapter 2

The Current and Future Power System: Background and State-of-the-Art

This chapter presents a background and the stat-of-the-art from the current and future power system, and it is divided into two major sections. In the first section it is presented a background on issues related to the conventional power systems and their recent evolutions, particularly, from the perspective of increasing deployments of distributed energy sources at distribution levels. A brief introduction to existing and emerging flexibility options is also presented. The second section of this chapter covers an extensive review of related works in the area of distribution power systems, particularly focusing on the transformation of conventional distributions systems into smarter ones. The purpose here is to present the state-of-the-art literature review on the advances of distribution network systems amid some driving factors. It is structured particularly to focus on the methodologies used to solve the growing interest of smart grids integration, flexibility and distribution network reconfiguration.

2.1 - The Current Power System (Background)

2.1.1 Conventional Power Systems and the Need for Paradigm Shift

Electric power systems are one of the largest and most complex systems ever created by mankind. The purpose of a power system is to provide electricity to its consumers in a more reliable and economical way. It is composed of generation, transmission and distribution system, where the distribution system is what links the power from electric utilities to consumers. Distribution systems generally operate in radial topology because of the simple protection and coordination schemes and reduced short circuit current, which makes that each consumer has only a single source of supply.

Traditionally, the development of electric power systems followed a hierarchical structure in which energy was produced in large power plants and then transported and distributed to all consumers as can be seen in Figure 2.1. Therefore, the energy flows were exclusively unidirectional, which presented advantages such as the efficiency of the large production plants, the ease of operation and management of the whole system and the simplicity of operation at the distribution network level. However, this system had also major disadvantages such as the increased investment needs in transmission infrastructures as a result of the often large geographic distance between producing power plants and consumers. This also leads to high system losses and probably high environmental impacts and less system reliability.

In this type of power system, demand response (DR) and interruptible loads are some of the techniques that were used to meet electrical demand preventing the building of new capacities. Utilities and energy retailers could charge customers a higher rate for the use of energy in peak hours, which in practical modes, is the same as providing incentives to consumers to reduce demand and be more conservative, or to change parts of their consumption to periods of the day with lower overall demand (load-shifting), reducing the need for peaking hours. Such programs could be cost-effective as long as the cost of such “incentives” are kept lower than the cost of building new generation capacities [3].

However, in recent years, the demand for electricity has been increasing driven by a number of factors such as economic growth, changing life styles, new forms of loads etc. According to the work in [4], global electrical energy demand is expected to experience a highly increase by 2050 with respect to the current global demand.

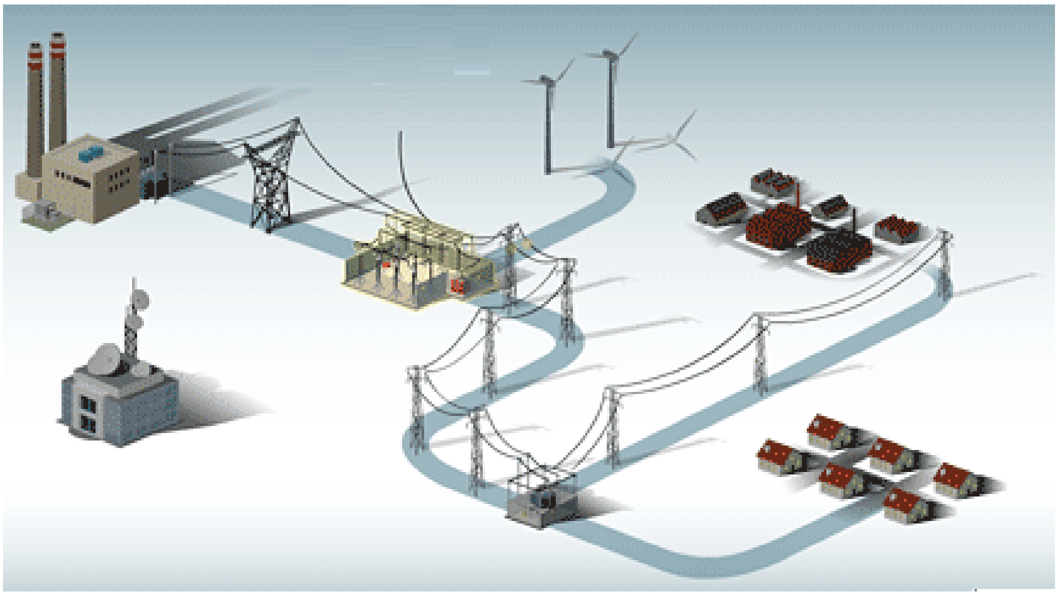

Figure 2.1 - Illustration of the current electric power systems (adapted from [2]).

Therefore, such an increase in electricity demand and inefficient production practices may result in the operation of the distribution network under heavily loaded conditions which complicates the system operation. Thus, there has been a growing interest in the distribution network upgrade, maintenance and operation with better planning and incorporating newer technologies. Some of the main objectives of such a move are:

- The reduction of greenhouse gas emissions;
- The enhancement of energy efficiency;
- The diversification of energy mix through renewable energy integration.

This paradigm shift has gained high attention from policymakers and state leaders across the world. In particular, the European Union (EU) already set forth rather ambitious targets in 2007 that is expected to result in large-scale investments in the energy sector, and meet the following goals by 2020 [5]:

- Reduce greenhouse gases by 20% (from 1990 levels);
- Increase energy efficiency by 20%;
- Promote the use of renewable energy sources in such a way that their share in the final energy mix reaches 20%.

In addition, there is already new energy and climate goals put in place for 2030 [6], which EU countries agreed on covering at least 27% of the overall energy consumption in EU by renewable energy, and a 40% reduction in greenhouse gas emissions compared to the levels in 1990.

2.1.2 - The Evolution of Power Systems

As said before, distribution networks have been operated on unidirectional power flows and designed to accept upstream power from the transmission network to lead it to the consumers. But in the past decades, power systems have faced numerous changes worldwide due the continuous growth of demand. The International Energy Outlook 2016 (IEO2016) project a significant growth of electric demand in worldwide until 2040 [7]. As it can be seen in Figure 2.2, the total world consumption of electrical energy is expected to increase from 549 quadrillion Btu in 2012 to 629 quadrillion Btu in 2020, and 815 quadrillion Btu in 2040, resulting in a 48% increase from 2012 to 2040.

Environmental concerns are also strong drivers for a more cleaner energy production. Hence, the use of local energy resources with less CO_2 emissions have become particularly interesting. Generally, the electric industry needs to meet multiple objectives simultaneously: achieve targets related to CO_2 reductions, increase renewable generation and comply to the requirement of a non-discriminatory energy market [8].

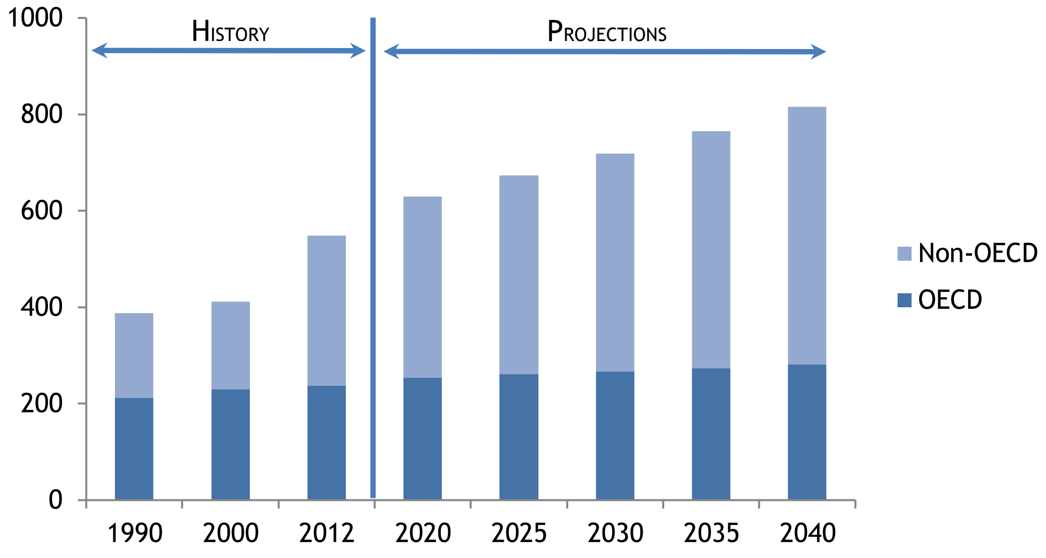

Figure 2.2 – World energy consumption in quadrillion Btu, 1990 – 2040 (adapted from [7]).

Supported by favorable energy policies, the integration of renewable energy sources is largely increasing which, as result, is changing the traditional paradigm. Penetration of renewable sources has had significant interest to help industry policies to reach the global decarbonisation effort. Moreover, certain technologies such as storage systems and demand response programs, also collectively known as distributed energy resources (DERs), are playing significant roles in taking power systems to another level. As a result, such technologies also bring new barriers for distribution system operators (DSOs) related to increased peaks and undesirable voltage excursions and grid reliability in the event of high renewable production levels [9]. It should be noted that system operators and utilities must meet an extensive set of regulations to maintain a reliable network; the most important ones are shown in Figure 2.3.

Consequently, new planning ideas are required to incorporate new technologies for power operation, local generation and DR. It follows that significant network reinforcements or replacements on the traditional grid may be required over the next decades to integrate those new components and meet those regulations more efficiently. However, the big uncertainty around magnitude, location and timing of renewable sources introduces a very significant challenge to realize this transition, preventing network planners from making fully informed and difficult to accurately determine in advance where network violation may occur. Therefore, one big step to the evolution of power systems was the liberalization of the energy markets, allowing users to generate and inject power into the grid. With this measure, the traditional power system scheme will change by promoting the growing interest of generation units' connection on the medium and low voltage grid that is near the consumption, resulting in the exchange of energy between different voltage levels in both directions.

Most Important Regulations to Maintain a Reliable Network

- Power generation and transmission capacity must be sufficient to meet peak demand for electricity;
- Power systems must have enough flexibility to control variability and uncertainty in demand and generation;
- Power systems must be able to maintain a stable frequency;
- Power systems must be able to regulate voltage within its limits.

Figure 2.3 – Most important regulations points to maintain a reliable network.

As well, in the transmission and distribution systems, the need of replacement to leave behind the centralized based topology of such components is arising.

In general, for the network planners, the ability of the network to accommodate DG is determined by its voltage which may go beyond acceptable limits at valley hours and thermal limits which relates to moments where there is high output of DG units resulting in high current flows beyond the transfer limits of lines and transformers.

Nowadays, new technologies like DER and smart grids are enabling new options for meeting demand and providing reliable service. Many of these options are relatively inexpensive and fast to be deployed when comparing to constructing traditional generation. While DR has been part of the network operation for decades, the rise of smart grids technologies enables even greater opportunities for managing the load supply in difficult hours. Smart grid technologies include new components like smart meters and information devices that will allow a more cost-effective balance of power demand and supply. It has reduced the metering costs and can now provide consumers and utilities with information that better reflects the true costs of electricity consumption to the user. Similarly, there are incentives to consumers to save energy or for shifting they loads into periods of low demand resulting in a cheaper bill for them.

Besides, it is one of the most talked about topics in the electrical systems area; yet, it is still difficult to define a smart grid in words that could be universally accepted. In simple terms, we can say that a smart grid needs to be intelligent, operating in automation. Beyond the smart distribution of the electrical power, it should be able to communicate and make decisions on its own [10]. For that reason, it is necessary to transform the traditional/current grid in to a better one, a grid that can fulfill all future energy needs, a smart grid. This grids will bring the capability of making the grid more efficient, according to [11]:

- Ensure more reliability;
- Fully accommodate renewable and traditional energy sources;
- Reduce carbon footprints;
- Reinforce global competitiveness;
- Maintain its affordability.

Nevertheless, before any revolutionary change, countless evolutionary steps are needed and will take some time due to the upgrades that are necessary to have its full implementation. However, the evolutionary studies needed about which areas will be the most affected by the change are already being made by many organizations. In [12], it states that in 2003, the biggest organizations in the American power system agreed that the United States electrical infrastructure was in many cases inefficient and unsafe. For these reasons, the solutions they reach to have a better electrical system were, among others, the same objectives that a smart grid should get. Despite the focus of that meeting was to the high voltage power grid, the same results could be reached for the low voltage grid. Actually, the high voltage grid is already good enough compared to the distribution grid, due to the supervisory control data acquisition (SCADA), and energy management systems (EMS).

2.1.3 - Flexibility Featuring Smart Grids

2.1.3.1 - Definition of Flexibility

Flexibility has gaining particular interest for the twenty-first century power systems under scenarios with variable renewable energy generation growth like wind and solar sources and changes in demand profiles. In this work, flexibility is considered as the power system ability to respond to changes in load and/or supply sides in order to match the demand more efficiently and operate properly. It is one element to improve reliability focusing on frequency and voltage stability, reducing consumer emissions and creating better investment conditions [13]. DR capacity levels of dispatchable power production, energy storage systems like pumped-hydro storage, automatic network reconfiguration and interconnection to neighbouring systems are some examples that can provide flexibility in power systems.

2.1.3.2 - The Need for Flexibility

Flexibility is not a new aspect in power systems. In fact, the classical grid had also to deal with some variability and uncertainty due to load changes over time and sometimes in unpredictable ways. Typically, electricity demand is higher during the day and during hot summer months and winter colder months. Yet, demand varies over short periods of time.

Therefore, all power systems have some level of flexibility to match the variable demand particularly the delivery of energy during peak demand periods; otherwise, there will be partial black-outs [3].

However, the increasing integration of RESs is complicating the balancing process of demand and generation in a real-time. Given such a circumstance, the need for flexibility options is increasing. Figure 2.4 shows how variable RES (wind, in this case) can increase the need for flexibility. In this figure, the yellow area represents the demand, the green area shows wind energy and the orange features the difference between demand and wind power generation which must be supplied by the remaining conventional generators. As it can be seen, the output level of the remaining generators must change quickly to supply short peaks and steeper ramps of demand which is a difficult task to get this done without major problems, power losses and power curtailment.

A more flexible power system means a more efficient system, decreasing the risk of curtailment and reducing overall system costs and consumer prices. Flexibility may also improve environmental impacts by increasing the optimization of DR, more efficient use of transmission and distribution of power and reduced curtailment of renewable generation [14]. Authors in [13], consider inflexibility in Table 2.1 to present flexibility in an easier way.

Table 2.1 - Signs of inflexibility in power systems [13].

Sometimes examples of inflexibility are easier to document than flexibility. Signs of inflexibility include:	And in wholesale markets:
▪ **Difficulty balancing demand and supply**, resulting in frequency excursions or dropped load. ▪ **Significant renewable energy curtailments**, occurring when generation is not needed routinely or long periods (e.g., nights, seasonally), most commonly due to excess supply and transmission constraints. ▪ **Area balance violations**, which are deviations from the schedule of the area power balance. Such deviations can indicate how frequency a system cannot meet its electricity balancing responsibility.	▪ **Negative market prices**, which signal several types of inflexibility, including conventional plants that cannot reduce output, load that cannot absorb excess supply, surplus, of renewable energy, and limited transmission capacity to balance supply and demand across broader geographic areas. Negative prices can occur in systems without renewable energy but may be exacerbated as renewable penetration increases. ▪ **Price volatility**, swings between low and high prices, which can reflect limited transmission capacity, limited availability of ramping, fast response, and peaking supplies, and limited ability for load to reduce demand.

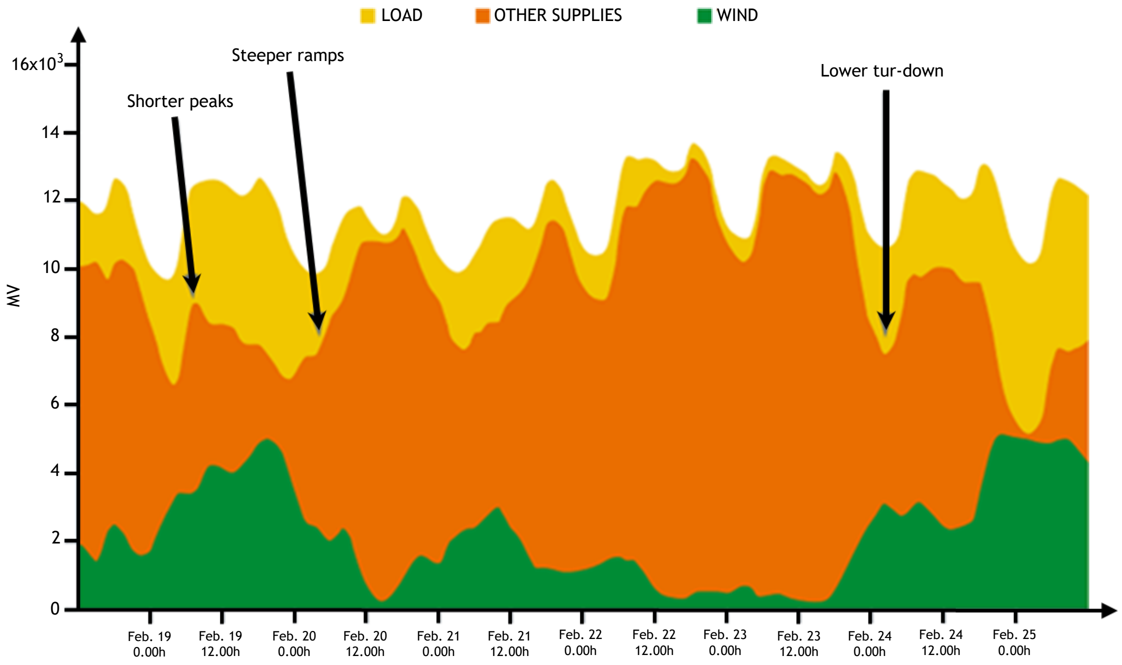

Figure 2.4 - The higher need for flexibility (adapted from [13]).

2.1.3.3 -The Flexibility Growth

The concept of flexibility is growing when policymakers ask to system planners how much wind and solar sources can be reliable to install in the system. The answer should be on how flexible the system is. Therefore, the planning process and investments in new generators and new lines are the first critical activities to ensure the sufficient flexibility of the new power systems. Without this, the system may not have sufficient flexibility options to operate efficiently and economically.

The urgent need to reduce greenhouse gas emissions involves integrating non-conventional energy supply sources such as RES (mainly, wind and solar) [15]. The growth of RES share has been accelerating in recent years and as predictions show that this will continue to increase by 30% to 80% until 2100 [16]. However, the integration of such technologies in the distribution systems might be a major challenge to system operators and planners due to the high uncertainty and variability that characterize such energy resources.

According to the U.S. Energy Information Administration (EIA), in the last years, the electrical demand has reduced but projections from 2015 to 2050 are pointing to a 28% increase in consumption. Also, projections show that in 2050 the coal fired source for generation will be reduced by 15%, giving room for the introduction of RES and natural gas to fill the gap [4].

2.1.4 - Technologies for Increasing System Flexibility

2.1.4.1 - Distributed Generation Integration

The concept of distributed generation is to produce electricity at smaller scales (contrary to the centralized big power generation paradigms common in conventional power systems). The capacity of a distributed generation often falls in the range of 1 kW to a few MW nameplates [17]. Hence, DGs are connected to distribution network systems and near the end consumers. Nowadays, they are becoming economically reliable and efficient ways of producing power and meet the increasing demand for electricity. A distributed generation can be of a conventional or non-conventional type. The non-conventional DGs are based on harnessing renewable power such as photovoltaic, wind, hydro, geothermal, biofuel, etc., and the conventional type DGs are based on fossil fuels such as a diesel generator [18]. According to the International Energy Agency (IEA) [19], there are five points of interest on the growing installation of distributed generation in the distribution grid such as the constant development of DG technologies, the limitations on the construction of new lines, the increasing need and more reliable electricity demand for the consumers, the electricity market liberalization and the concerns about the environment and climate change.

Some advantages of considering the integration of DG units on the distribution network are related to voltage profile and power quality improvements, allocation of generation closer to the load which can be translated in a shorter power flow path (meaning reduced losses and costs), reduction of emissions CO_2 and other gases, and deferring investments in network infrastructures. In addition, in case of contingencies in the upstream network, the integration of DGs can also enhance the possibility operating the grid in an island mode,, resulting in more secure and reliable power for consumers [17], [20]. Besides all the advantages, as the electric grid is not designed with this technology in mind, and the power flow happens only in one direction from higher to lower voltage levels. As a result, DGs may have adverse effects, especially if not properly planned and operated. Those are associated with overvoltages, congestion in the network branches and substations, more difficulty in frequency control, impacts on harmonics introduced by the intermittent nature of renewable sources which use power electronic converters, reactive power management issues due to DG units that are not capable of providing it, impacts on protections, and even more occurrences of flicker effects [17]. It also makes it more difficult to manage the network operation. For that reason, there are certain barriers that are slowing the process towards the change of the traditional grid into a smarter one.

2.1.4.2 - Energy Storage Systems

Storage technologies can be classified based on the form of storage or the lifetime. From the first perspective, energy storage systems can be mechanical, chemical or electrical, and from the lifetime perspective, it can be short, medium or long term storage. All types of ESSs have their own application and technical characteristics. The most usual form of storage is pumped hydro storage, but other technologies are becoming largely competitive such as compressed air, flywheels and new battery technologies.

ESSs are generally becoming crucial components of future electricity grids because of economic and technical reasons. For example, ESSs are able to store energy when RES power production is higher than the demand (mainly during the early mornings), and they inject the stored energy back to the system in periods where available power generation is short of meeting the demand. Like this, the system can meet the demand in a more effective way without the need of an oversized production during the course of a day. In other words, this will reduce the need for constructing extra power production facilities.

One interesting way to control the intermittence and the unpredictable output power from the RES units (particularly wind and solar) is by deploying ESSs in the appropriate locations of the grid. In other words, the problems arising from the intermittency of such resources can be partly managed by ESSs. This in turn helps to meet policy targets and reduce emissions. ESSs can also contribute to the voltage and frequency control strategies, which are vital for a healthy operation of the grid in general. For instance, it can store extra power to be used at a desirable time. This can contribute to voltage and frequency control, eliminate power curtailment and oversized power capacities [21]. Moreover, in some cases, ESSs has been used to fix the production capacity to avoid undesirable shutdowns, introducing more reliability to the system [22].

Another area which is positively affected by the introduction of ESSs is the transmission and the distribution network. ESSs can reduce the network contingencies and decrease the problems resulting from overloaded networks, achieving a reduction of management cost and improving reliability [23]. ESSs can ease the integration of RESs in microgrids, resulting in higher energy security and lower emissions. And , this is an essential solution for achieving sustainable energy in smart grids [24].

From another perspective, deregulated electricity markets can introduce a competitive environment from producers, increasing the cost of energy for meeting peak demands. Therefore, ESSs may balance markets and show benefits on the wasteful power production and high prices in peak hours resulting in a more efficient market, more attractive for both producers and consumers [21]. The European Commission has recognized energy storage as one of the strategic energy technologies to accomplish the EU energy targets by 2020 and 2050. Likewise, the US Department of Energy has also identified ESS as a solution for grid flexibility and stability [21].

2.1.4.3 - Distributed Network Reconfiguration

Network reconfiguration can be understood as a method to modify the topology of the distribution grid by changing the status of normally closed sectionalising switches and normally open tie switches in order to meet some objectives [25]. Network reconfiguration is another technique which can improve system wide flexibility and network reliability. At the same time, it can reduce energy losses in the system. Reconfiguration techniques can be implemented by any power company where automatic tie and sectionalising switches can be installed together with remote monitoring facilities available by software integration [25].

2.2 – Next-gen Distribution Grids: State-of-the-Art

2.3.1 - Smart Grids

Nowadays, smart grid is one of the most talked about topics in the electrical systems area. The idea of a high-tech, intelligent and futuristic electric power system - Smart Grid, is the most consensual name. Functionally, smart grids should be able to provide new abilities (e.g. self-healing, high reliability, energy management and real time pricing), and from a design perspective, they should enable distributed energy options with the possibility of engaging costumers in producing and consuming energy (the so-called prosumers). This requires a two-way communication. Therefore, smart grids should have automated information and communication systems put in place to make such a two-way communication possible [26].

There are various driving factors for the need to transform distribution assets into smart grids such as the increasing penetration of distributed energy resources. For example, electrical distribution systems need to cope up with the growing challenges induced by the increasing vRES penetration at distribution levels amid global concerns on environmental change and energy security among others. All this is driving the evolution of existing distribution network systems into smarter ones. At this point, Smart Grid is not a dream of energy management anymore. In fact, the new electrical grid is already a model [27]. Pagani *et al.* have taken an important step regarding to a topologic methodology to transform the traditional passive-only grid into a newer smart grid model. This methodology consists of upgrading the distribution grid, considering that medium and low voltage grid levels which are more interesting due to the increased needs of accommodating renewable power sources [28].

There are a couple of approaches to determine the allowed DG penetration level on the distribution grid. One w ay can lead to passive distribution systems, and the other way can lead to active distributed systems which is an important step towards smart grid implementation. Authors in [29] focused their work on many strategies and methods that have been developed in recent years to accommodate DG integration and planning leading to the evolution of the traditional distribution systems.

Many strategies are based on the principle that DGs are integrated only if they do not lead to operational constraint violations, such as voltage and thermal limits. However, these strategies are too conservative. On the other hand, there are other methods where control schemes, communication systems and measuring devices allow effective management to DG outputs, but this also means significant investment needs. Konstantelos *et al.* [30] report optimal planning of distribution networks to enable cost effective integration of DGs under uncertainty and demonstrate how the planner can take advantage of the strategic flexibility embedded in such technologies. In order to integrate DGs and remove thermal overload and voltage constraints, authors in [31] propose ways to reduce the amount of curtailed generation of DG units by using remotely controlled switches (RCSs).

One important aspect in smart grids is self-healing; suppose when a particular feeder is congested. Under this circumstance, the system will be able to automatically perform reconfiguration and ideally find the best topology without adversely violating any constraint. A new decentralized multi-agent control system is proposed on [32] under a variety of contingency conditions. This method has been able to eliminate congestions in the feeder, globally correct voltages violations, coordinate the operation of reactive power control devices, and avoid active power curtailment from DG units. In addition, authors show interesting results on the prevention of overstress on the substation voltage regulator, and maintain bus voltages and line flows within the allowable limits. Unfortunately, many distribution systems are not fully automated. Furthermore, in their transition towards active distribution systems and smart grids, it is expected that distribution systems will be equipped with strategically located and remotely controlled switches that will improve reliability and power quality. Many authors propose approaches for determining the best set of remote control switches and their optimal placements following system operators and demand in order to reduce the losses in the radial system [33], [34], and new algorithms to build a “dynamic data matrix” that will allow to reorganize the feeder topology [35]. Many strategies of feeder reconfiguration will be featured further in this chapter.

Therefore, experimental simulations of real time smart grids with a significant number of distributed energy sources and loads are still usually not economically feasible and quite limited [36].

Smart grid implementation improves the power quality of a system and may help to comply with the uncertainty of RES integration using automated controls, modern communications, and energy management techniques that optimize demand, energy and network accessibility [37]. A methodology for energy resource scheduling in smart grids, considering DG penetration and load curtailment enabled by demand response programs is proposed in [38].

2.3.2 - Flexibility

Smart network systems are expected to be equipped with advanced technologies such as emerging flexibility options that can support the integration and effective utilization of non-conventional energy sources such as wind and solar. Such energy resources are particularly gaining interest globally, and their share in the final energy delivery is growing dramatically [39], [40]. This development will be further accelerated following the favorable agreement of states to curb global warming and mitigate climate change. Many policy makers across the globe are now embarking on ambitious sustainable energy production targets [41], [42].

Renewable energy sources can become the major energy supply. However, increased level of vRESs such as wind and solar comes with certain conceptual issues [43] and challenges [44] mainly due to their intermittent nature. This increases uncertainty and variability in the system, leading to technical problems and enormous difficulty in the critically important minute-by-minute balancing requirement of supply and demand. Particularly, at distribution levels, there is little room for any compromise on the stability and integrity of the system as well as the reliability and quality of power delivered to the end-users. Generally, the intermittent nature of such resources vRESs substantially increases the need of flexibility in the system. Traditionally, this has been mostly handled by the supply side i.e. any variation in demand has been instantly balanced by generators designed for this purpose. However, this convention is nowadays changing, where flexibility options that can be provided by the supply, demand, network and/or other means are largely sought.

Energy storage systems are being applied in distribution systems to manage the problems like the intermittent output of RES [45], improve power system stability [46], and to turn it more economically efficient [47]. Authors in [48] see in the combination of renewable energy and energy storage an opportunity to better exploit the intermittency and uncertainty of the local generation in distribution systems, under the specific case of islanding. Finn *et al.* in [49] present demand side management as an alternative of flexibility. Authors analyze the impacts in the wholesale price of electricity by load shifting their demand towards hours of lower prices in order to increase their wind generation. Power system control and grid expansion are other measures that will ensure a more efficient power flow through the grid [50].

An important evolutionary step towards the smart grid flexibility is the concept of active distribution networks (ADNs) [51]. In ADNs, loads, generators, and storage devices can be controllable to reduce the distributed energy resources impact on distribution systems. With this concept, the operation of the system is divided between both DSOs and costumers according to the regulatory environment. With this, it will be expected to improve reliability, increase assets utilization and network stability by reinforcement. Pilo *et al.* in [52], show the coordination of flexible network topology with the continuous active management of energy resources that allows to improve the efficiency of the delivered power.

2.3.3 - Smart Grid, Flexibility and Reconfiguration

This work focuses on a viable flexibility option that can be provided by means of a dynamic network reconfiguration. DNR deals with a continuous and automated change of line statuses depending on the operational conditions in the distribution system. This should generally lead to a more efficient operation of the system by maximizing the utilization level of variable energy resources (mainly, wind and solar), and minimizing their side effects such as voltage rise issues.

References [25], [53] present a detailed review of the most relevant works in the subject area of distribution network reconfiguration by mainly focusing on the methods employed to handle the resulting optimization problem, and the main objectives of carrying out such an optimization. Generally, the purpose of reconfiguration in existing studies has been mainly to minimize network losses [54]–[57]. However, a properly (optimally) executed network reconfiguration can simultaneously meet a number of additional objectives such as improving the voltage profile and reliability in the system [58]–[61], or minimize both network losses and operational costs [62], or improve a set of reliability indices while system losses are minimized [63]. In addition, a more frequent reconfiguration (which is alternatively called as an intelligent reconfiguration) can substantially enhance the flexibility of existing systems, paving the way to an increased penetration and use levels of vRESs. Authors in [64] demonstrate that reconfiguration allows to reduce operational losses as well as increase the renewable generation hosting capacity. Authors in [65] investigate the impact of network reconfiguration to plan the growing integration of DGs under thermal and voltage constraints. Munoz-Delgado *et al.* in [66] propose a joint optimization model for simultaneously planning DGs and expanding the distribution network systems, embedding a reconfiguration algorithm However, the reconfiguration task involves a yearly switching operation of distribution feeders i.e. a more frequent switching of feeders is not considered. The work in [67] also uses a static network reconfiguration for the purpose of “mitigating voltage sags and drops” in the presence of DERs. Another interesting objective of reconfiguration is for service restoration in distribution systems. Elmitwally *et al.* [68], use a multi-agent control system (MACS) to detect and locate faults to reconfigure the network topology in order to restore it and redirect power to unserved loads.

Many of these approaches diverge on the mathematical programming (e.g. forward-backward sweep method [69], mixed-integer linear programming [70], [71] , mixed-integer nonlinear programming (MINLP) [72], mixed-integer conic programming (MICP) [73], [74], mixed-integer quadratically constrained programming (MIQCP) [75]–[77], linear programming [52], dynamic programming [78]) or heuristic techniques (e.g. branch exchange [79] and others [80]). Reference [81] develops a stochastic mixed-integer linear programming (S-MILP) optimization model, incorporating a static network reconfiguration in the presence of wind and energy storage, with the specific aim of reducing the impacts of outages and losses. In [82], network reconfiguration is used MINLP to achieve three objectives: minimizing DG curtailments, congestion and voltage rise issues. In a similar line, authors in [83] use a self-adaptive evolutionary swarm algorithm based on social spider optimization (SSO) to develop a reconfiguration model for increasing the penetration level of plug-in electric vehicles (PEVs) and reducing system costs. Ameli *et al.* in [84] are using an Ant Colony Optimization (ACO) technique for dynamic scheduling of network reconfiguration and capacitor banks (CBs) switching in presence of DG units in order to minimize the operational cost and transformers loss of life (TLoL) costs.

As mentioned earlier, the vast literature in the network reconfiguration focuses on a static switching of lines, and mainly for the purpose of minimizing network losses and/or improving reliability by balancing load and restoring supply in the event of contingencies. The DNR problem is not adequately addressed from the smart-grids perspective and under high penetration level of variable energy sources. The technological advances make it possible to carry out hourly (or generally more frequent) reconfiguration. This provides a key flexibility option that can partly help to counterbalance the fluctuations in vRESs, and increase their efficient utilization. Reference [85] is proposing a dynamic model for reconfiguration of distribution systems considering the scheduling of day-ahead DG controllable outputs in order to minimize costs. Authors in [86], are presenting a dynamic programming model for different snapshots and time stages which are enabling the coordination of network reconfiguration and the optimal arrangement of DGs and ESSs minimizing a weighted sum of costs (investment costs, maintenance costs, cost of energy in the system, costs of unserved power and CO_2 emissions costs). Reference [87], also presents dynamic programming model for hourly reconfiguration over a period of 24 hours considering only wind generation in order to minimize costs and analyze the voltages impacts throughout the distribution system.

2.3 - Chapter Summary

This chapter has presented, in the first part, a background on issues related to the conventional power systems and their recent evolutions, particularly, from the perspective of increasing deployments of distributed energy sources at distribution levels. Therefore, a brief introduction to existing and emerging flexibility options has been included in part one.

Also, in the second part, this chapter has presented a detailed review of relevant works in the subject areas of smart grid integration, flexibility and distribution network reconfiguration considering the use of large-scale intermittent power sources. Furthermore, this literature review is structured by the types of technology used and organized from the simpler to the most complex methodology in order to solve the aforementioned problems.

Environmental and other socio-economic concerns are pushing the integration of renewable energy sources. Such resources are becoming the most interesting technologies to meet the worldwide growing demand for electric energy. However, the integration of such technologies comes with ample challenges as they introduce operating problems affecting system stability and power quality due to their variable and uncertain nature. The solution for these challenges is the main concern of this thesis, particularly, focusing on the dynamic reconfiguration of distribution networks. The motivation of doing this is to enhance system flexibility, and thereby further enable efficient utilization of DG technologies, mainly renewables.

The integration of DG technologies is an area which has been extensively studied by other researchers. However, the integration and effective management of RES type distributed generations, energy storage systems, switchable capacitors in tandem with distribution network reconfiguration has not been adequately studied. The present work aims to address this same issue and achieve multiple objectives such as improving system flexibility, increasing RES penetration, reducing losses as well as enhancing system stability, reliability and power quality.

Chapter 3

Mathematical Formulation

This chapter presents the algebraic formulation of a new operational model with dynamic reconfiguration of distribution systems, featuring large-scale distributed energy resources, mainly variable renewable energy sources. The problem is formulated as stochastic mixed integer linear programming to account for the stochastic nature of renewable power outputs and other traditional sources of variability and uncertainty such as demand. The formulation also incorporates energy storage systems and switchable capacitor banks, all aiming to maximize the utilization level of RESs.

3.1 - Objective Function

The objective of the formulated DNR problem is to minimize the sum of relevant cost terms, namely, switching costs SWC, expected costs of operation TEC, emissions $TEmiC$ and unserved power $TENSC$ in the system as:

$$Minimize\, TC = SWC + TEC + TENSC + TEmiC \tag{3.1}$$

where TC refers to the total cost.

A switching cost is incurred when the status of a given line changes from 0 (open) to 1 (closed) or 1 (closed) to 0 (open). Thus, the first term in (3.1), SWC can be expressed as a function of the sum of new auxiliary variables as:

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

where

$$x_{l,h} - x_{l,h-1} = y^+_{l,h} - y^-_{l,h};\ y^+_{l,h} \geq 0;\ y^-_{l,h} \geq 0 \tag{3.3}$$

$$x_{l,0} = 1;\ \forall l \in \Omega^1\ and\ x_{l,0} = 0;\ \forall l \in \Omega^0 \tag{3.4}$$

The switching action leads to the absolute value of difference in successive switching variables. In order to linearly represent such a module, two non-negative auxiliary variables $y^+_{l,h}$ and $y^-_{l,h}$, not negative are introduced in (3.2). The binary variable $x_{l,0}$ in (3.4) represents the states that the line can assume, 0 and 1, to open and closed, respectively.

As stated earlier, *TEC* is given by the sum of the cost of power produced by DGs, discharged from energy storage systems and imported from upstream as in (3.5).

$$TEC = EC^{DG} + EC^{ES} + EC^{SS} \tag{3.5}$$

where each in (3.5) is calculated as:

$$EC^{DG} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h}\sum_{g\in\Omega^g} OC_g P^{DG}_{g,n,s,h} \tag{3.6}$$

$$EC^{ES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h}\sum_{es\in\Omega^{es}} \lambda^{es} P^{dch}_{es,n,s,h} \tag{3.7}$$

$$EC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h}\sum_{\varsigma\in\Omega^\varsigma} \lambda^{\varsigma}_h P^{SS}_{\varsigma,s,h} \tag{3.8}$$

The equation in (3.6) represents the expected cost of the energy produced by the DGs, given by the sum of the scenarios probability product (ρ_s), with the sum of the energy cost produced (OC_g), bounded by the generation limits $(P^{DG}_{g,n,s,h})$. Equation (3.7) refers to the cost of energy supplied by the ESSs, given by the sum of the scenarios probability (ρ_s), with the energy storage cost (λ^{es}), limited by the discharge limit of the energy storage system $(P^{dch}_{es,n,s,h})$. Finally, equation (3.8) models the cost of energy imported from the upstream network, given by the sum of the scenarios probability (ρ_s), with the electricity price purchased (λ^{ς}_h) by the energy imported from the network $(P^{SS}_{\varsigma,s,h})$.

The cost of load shedding *TENSC* is determined as given in equation (3.9):

$$TENSC = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h}\sum_{n\in\Omega^n} \left(\upsilon^P_{s,h} P^{NS}_{n,s,h} + \upsilon^Q_{s,h} Q^{NS}_{n,s,h}\right) \tag{3.9}$$

where $\upsilon^{P}_{s,h}$ and $\upsilon^{Q}_{s,h}$ 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.

Equation (3.10) represents the total cost of emissions as a result of power production using DGs and imported power.

$$TEmiC = EmiC^{DG} + EmiC^{SS} \tag{3.10}$$

where each of the terms in (3.10) are determined by equations (3.11) and (3.12):

$$EmiC^{DG} = \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{g \in \Omega^{g}} \sum_{n \in \Omega^{n}} \lambda^{CO_2} ER^{DG}_{g} P^{DG}_{g,n,s,h} \tag{3.11}$$

$$EmiC^{SS} = \sum_{s \in \Omega^{s}} \rho_s \sum_{h \in \Omega^{h}} \sum_{\varsigma \in \Omega^{\varsigma}} \sum_{n \in \Omega^{n}} \lambda^{CO_2} ER^{SS}_{\varsigma} P^{SS}_{\varsigma,s,h} \tag{3.12}$$

The equation (3.11) represents the expected emission costs of power produced by DGs, given by the sum of the scenarios probability product (ρ_s), with the sum of the emissions cost λ^{CO_2}, emissions rate of DGs (ER^{DG}_{g}) and DGs power $(P^{DG}_{g,n,s,h})$. Equation (3.12) models the expected emission costs of power imported from the grid, given by the sum of the scenarios probability product (ρ_s), with the sum of the emissions cost λ^{CO_2}, emission rate of energy purchased (ER^{SS}_{ς}) and energy imported from grid $(P^{DG}_{g,n,s,h})$.

3.2 - Constraints

3.2.1 - Kirchhoff's Current Law

According to Kirchhoff's law, the sum of all incoming flows to a node should be equal to the sum of all outgoing flows. This constraint applies to both active (3.13) and reactive (3.14) power flows, and should be respected all the time:

$$\begin{aligned} \sum_{g \in \Omega^{g}} P^{DG}_{g,n,s,h} + \sum_{es \in \Omega^{es}} \left(P^{dch}_{es,n,s,h} - P^{ch}_{es,n,s,h} \right) + P^{SS}_{\varsigma,s,h} + P^{NS}_{n,s,h} + \sum_{in,l \in \Omega^{l}} P_{l,s,h} - \sum_{out,l \in \Omega^{l}} P_{l,s,h} = PD^{n}_{s,h} \\ + \sum_{in,l \in \Omega^{l}} \frac{1}{2} PL_{l,s,h} + \sum_{out,l \in \Omega^{l}} \frac{1}{2} PL_{l,s,h} \ ; \forall \varsigma \epsilon \Omega^{\varsigma};\ \forall\ \varsigma \in n;\ l \in n \end{aligned} \tag{3.13}$$

$$\sum_{g\in\Omega^g} Q^{DG}_{g,n,s,h} + Q^{c}_{c,n,s,h} + Q^{SS}_{\varsigma,s,h} + Q^{NS}_{n,s,h} + \sum_{in,l\in\Omega^l} Q_{l,s,h} - \sum_{out,l\in\Omega^l} Q_{l,s,h} = QD^{n}_{s,h} + \sum_{in,l\in\Omega^l} \frac{1}{2} QL_{l,s,h} + \sum_{out,l\in\Omega^l} \frac{1}{2} QL_{l,s,h} \ ; \forall \varsigma \epsilon \Omega^{\varsigma};\ \forall\, \varsigma\ \epsilon\ n; l\ \epsilon\ n \tag{3.14}$$

3.2.2 - Kirchhoff’s Voltage Law

The well-known AC power flow equations (which are naturally complex nonlinear and non-convex functions of voltage magnitude and angles) are presented (3.15) and (3.16).

$$P_{l,s,h} = V^2_{n,s,h}\, g_k - V_{n,s,h} V_{m,s,h} (g_k cos\theta_{l,s,h} + b_k sin\theta_{l,s,h}) \tag{3.15}$$

$$Q_{l,s,h} = -V^2_{n,s,h}\, b_k + V_{n,s,h} V_{m,s,h} (b_k cos\theta_{l,s,h} - g_k sin\theta_{l,s,h}) \tag{3.16}$$

Because of this non-linearity, those equations are linearized according to [88] by making a couple of assumptions. The linearized active and reactive flows in a line are given by the disjunctive inequalities in (3.17) and (3.18), respectively.

$$\left|P_{l,s,h} - \left(V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right) g_k - V^2_{nom} b_k \theta_{l,s,h}\right)\right| \le MP_l (1 - x_{l,h}) \tag{3.17}$$

$$\left|Q_{l,s,h} - \left(- V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right) b_k - V^2_{nom} g_k \theta_{l,s,h}\right)\right| \le MQ_l (1 - x_{l,h}) \tag{3.18}$$

It is important to note that, due to the reconfiguration problem, equations (3.17) and (3.18), 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. Furthermore, it should be noted that, in inequalities (3.15), (3.16), (3.17) and (3.18), the angle difference $\theta_{l,s,h}$ is defined as $\theta_{l,s,h} = \theta_{n,s,h} - \theta_{m,s,h}$ where *n* and *m* indices correspond to the same line *l*.

3.2.3 - Power Flow Limits and Losses

Power flows in each line should not exceed the maximum transfer capacity, which is enforced by (3.19):

$$P^2_{l,s,h} + Q^2_{l,s,h} \le x_{l,h} (S^{max}_l)^2 \tag{3.19}$$

The following constraints are related to the active (3.20) and reactive (3.21) power losses in a line l.

$$PL_{l,s,h} \; = \; R_l \left(P_{l,s,h}^2 \; + \; Q_{l,s,h}^2\right) / \, V_{nom}^2 \tag{3.20}$$

$$QL_{l,s,h} \; = \; X_l \left(P_{l,s,h}^2 \; + \; Q_{l,s,h}^2\right) / \, V_{nom}^2 \tag{3.21}$$

Note that the quadratic flows in (3.19)—(3.21) are linearized using an SOS2 approach, presented in [89] (also see in Appendix A).

3.2.4 - Energy Storage Model

Constraints (3.22)—(3.27) represent the energy storage model employed in this work. The amount of power charged and discharged are limited as in (3.22) and (3.23). Constraint (3.24) ensures charging and discharging operations do not happen at the same time. The state of charge constraint is given by (3.25). The storage level should always be within the permissible range (3.26). Equation (3.27) sets the initial storage level, and makes sure the storage level at the end of the time span is equal to the initial level. For sake of simplicity, both η_{es}^{dch} and η_{es}^{ch} are often set equal and their efficiencies are expressed in percentage of energy at the nodes where ESS are connected to.

$$0 \; \leq \; P_{es,n,s,h}^{ch} \; \leq \; I_{es,n,s,h}^{ch} P_{es,nh}^{ch,max} \tag{3.22}$$

$$0 \; \leq \; P_{es,n,s,h}^{dch} \; \leq \; I_{es,n,s,h}^{dch} P_{es,n}^{ch,max} \tag{3.23}$$

$$I_{es,n,s,h}^{ch} + \; I_{es,n,s,h}^{dch} \; \leq 1 \tag{3.24}$$

$$E_{es,n,s,h} = E_{es,n,s,h-1} + \eta_{es}^{ch} P_{es,n,s,h}^{ch} - \; P_{es,n,s,h}^{dch} / \eta_{es}^{dch} \tag{3.25}$$

$$E_{es,n}^{min} \; \leq \; E_{es,n,s,h} \; \leq \; E_{es,n}^{max} \tag{3.26}$$

$$E_{es,n,s,h0} \; = \mu_{es} E_{es,n}^{max}; \; E_{es,n,s,h24} \; = \mu_{es} E_{es,n}^{max} \tag{3.27}$$

3.2.5 - Active and Reactive Power Limits of DGs

Equations (3.28) and (3.29) impose the active and reactive power limits of DGs, respectively, at the nodes where DGs are connected to. The upper bound of eq. (3.28) should be equal to the actual production level of the specific unit and the lower bound should be always zero.

$$P_{g,n,s,h}^{DG,min} \le P_{g,n,s,h}^{DG} \le P_{g,n,s,h}^{DG,max} \tag{3.28}$$

$$Q_{g,n,s,h}^{DG,min} \le Q_{g,n,s,h}^{DG} \le Q_{g,n,s,h}^{DG,max} \tag{3.29}$$

It is important to note that equation (3.29) can be used only for DGs which do not have reactive power support capabilities. For DGs which do not have such capability, new modifications should be done due to their operation modes.

$$-\tan\left(cos^{-1}\left(pf_g\right)\right) P_{g,n,s,h}^{DG} \le Q_{g,n,s,h}^{DG} \le \tan\left(cos^{-1}\left(pf_g\right)\right) P_{g,n,s,h}^{DG} \tag{3.30}$$

Inequality (3.30) considers both upper and lower limits in order to present an expression that should be able to feature, for instance, double fed induction generators or voltage source inverters based PV, that are capable to inject or consume reactive power.

3.2.6 - Reactive Power Limits of Capacitor Banks and Substations

The reactive power supplied by switchable capacitor banks (SCBs) is limited by inequality (3.31):

$$0 \le Q_{c,n,s,h}^{c} \le Q_{c,n,s,h}^{c,0} x_{c,n,h} \tag{3.31}$$

For stability reasons, the power from the substation could have bounding limits, such as inequalities (3.32) and (3.33):

$$P_{\varsigma,s,h}^{SS,min} \le P_{\varsigma,s,h}^{SS} \le P_{\varsigma,s,h}^{SS,max} \tag{3.32}$$

$$Q_{\varsigma,s,h}^{SS,min} \le Q_{\varsigma,s,h}^{SS} \le Q_{\varsigma,s,h}^{SS,max} \tag{3.33}$$

And, the reactive power from the transmission grid is subject to bounds as in inequality (3.34):

$$-\tan\left(cos^{-1}\left(pf_{ss}\right)\right) P_{\varsigma,s,h}^{SS} \le Q_{\varsigma,s,h}^{SS} \le \tan\left(cos^{-1}\left(pf_{ss}\right)\right) P_{\varsigma,s,h}^{SS}. \tag{3.34}$$

where, pf_{ss} is the power factor at the substation and is assumed to be 0.9 through the whole work.

3.2.7 - Radiality Constraints

Distribution networks are normally operated in a radial configuration. Hence, in addition to the aforementioned ones, the radiality constraints in [66] are adapted to this case study:

$$\sum_{l\in\Omega^l} x_{l,h} = 1, \qquad \forall m \in \Omega^D;\ l\epsilon n \tag{3.35}$$

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

Equation (3.35) imposes that nodes with demand at hour *h* are mandatory to be connected and have a single input flow through line *l*. The inequality shown in (3.36) set a maximum of one input flow for the terminal nodes. In this work, DGs are considered, the previous equations are not sufficient to prevent cases where particular nodes could be supplied by DGs and not connected to the rest of the network. For that reason, the following constraints (3.37)-(3.41) are added to avoid isolated generators by modeling a fictitious system with fictitious loads. Such fictitious loads can only be supplied by fictitious energy through the actual feeders.

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = g_{n,h}^{SS} - d_{n,h}, \qquad \forall n \in \Omega^\varsigma;\ l\epsilon n \tag{3.37}$$

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = -1, \qquad \forall n \in \Omega^g;\ \forall n \in \Omega^D \tag{3.38}$$

$$\sum_{in,l\in\Omega^l} f_{l,h} - \sum_{out,l\in\Omega^l} f_{l,h} = 0, \qquad \forall n \notin \Omega^g;\ \forall n \notin \Omega^D;\ \forall n \notin \Omega^\varsigma \tag{3.39}$$

$$0 \leq \sum_{in,l\in\Omega^l} f_{l,h} + \sum_{out,l\in\Omega^l} f_{l,h} \leq n_{DG};\ l\epsilon n \tag{3.40}$$

$$0 \leq g_{n,h}^{SS} \leq n_{DG}, \qquad \forall n\epsilon\Omega^\varsigma;\ l\epsilon n \tag{3.41}$$

Constrain (3.37) represents the nodal fictitious current balance equation while constraints (3.38) and (3.39) impose limits of fictitious flows through the feeders. Inequality (3.40) limits the fictitious flow in a line to the number of nodes which could have fictitious generation. The last constraint (3.41) models the limits for the fictitious currents injected by fictitious substations.

3.3 - Chapter Summary

This chapter has presented the operational model developed in this thesis along with detailed descriptions of the objective function and constraints involved. The model is developed to carry out operational analysis of distribution network systems featuring large-scale DERs along with a dynamic reconfiguration of the distribution systems.

This problem is handled via a stochastic mixed integer linear programming optimization. The developed mathematical model simultaneously minimizes switching costs, expected costs of operation, emissions and the energy not provided while meeting a set of technical constraints. In the following chapter, this model is tested on an IEEE 41-bus distribution network system where an economic and technical analysis of the system is made.

Chapter 4

Case Study, Results and Discussion

A case study is presented in this chapter to test the mathematical formulation described in the Chapter 3. Moreover, the numerical results are extensively discussed in terms of voltage deviation profiles, costs, losses, energy mix and network reconfiguration outcomes.

4.1 System Data and Assumptions

A standard IEEE 41-bus test system, shown in Figure 4.1, is employed to test the proposed operational model, and perform the technical and economic analysis of DNR. This system is selected for our case of study because it is more sensitive to changes in load and generation. The total active and reactive loads of the system are 4.635 MW and 3.25 MVar, respectively. The authors of [90] have optimally placed distributed energy resources such as wind and solar type DGs, ESSs and SCBs (which their installed capacities can be found in the Appendix B). In this work, it is therefore assumed that all these resources are present and that they are the optimal ones for this system. In Figure 4.1 can be seen the locations of the DGs and ESSs. Other data and assumptions made throughout this work are as follows:

- A 24-hour period is considered, with the possibility of an hourly configuration.
- The range of permissible voltage deviation at each node is ±5% of the nominal value (which, in this case, is 12.66 kV).
- The substation is the reference node, whose voltage magnitude and angle are set equal to the nominal value and 0, respectively.
- Both charging and discharging efficiency of ESSs is 90%.

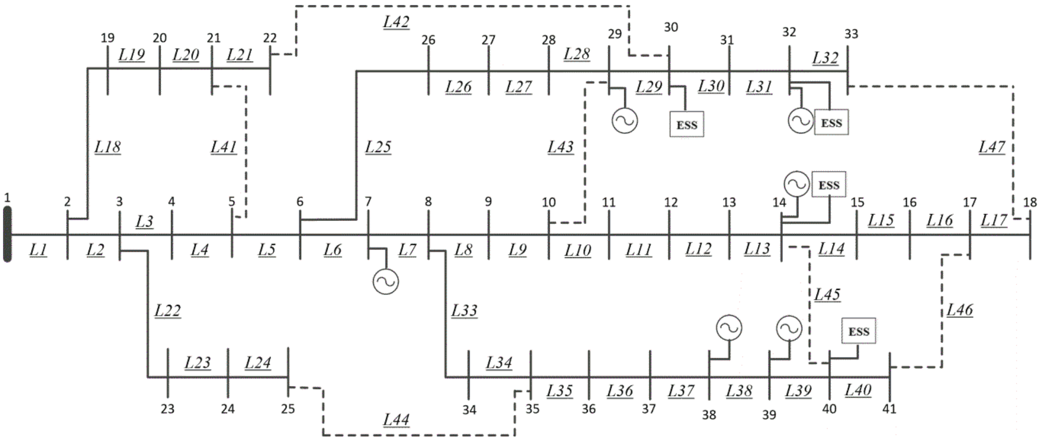

Figure 4.1 – IEEE 41-bus distribution system with new tie-lines.

- The power factor of the substation is set constant at 0.8 while the power factor of all DG types is considered to be 0.95.
- Electricity prices are assumed to follow the same trend as demand, varying between 108 €/MWh during peak and 30 €/MWh during shallow hours.
- The emission rate at the substation is assumed to be 0.4 tCO_2e/MWh, and the emission rates of solar and wind type DGs are set to 0.0584 and 0.0276 tCO_2e/MWh, respectively.
- The price of emissions is considered to be 7 $€/tCO_2e$.
- The tariffs of solar and wind power generation are set equal to 40 and 20 €/MWh, respectively.
- The variable cost of ESSs is considered as 5 €/MWh.
- The switching cost of each line is considered to be 0 €/switch
- The penalty for unserved power (active and reactive alike) is 3000 €/MW.

4.2 Scenario Description

There are various sources of uncertainty and variability pertaining to the problem addressed in this thesis. However, modelling all sources of variability and uncertainty may be computationally excessive and inefficient. But accounting for the variability and uncertainty of RES power outputs (mainly wind and solar) and demand is an important step that cannot be overlooked. Reference [91] proposes a methodology that effectively handle these problems. This method considers a large number of operational states which are then drastically reduced using a clustering technique. Then, based on certain criteria, a representative operational state of each group is selected to be assigned to a weight proportional to the number of operational situations in its group. As such, a similar technique presented in [91] is used in this work to model the uncertainty and variability of RES power outputs (wind and solar) and demand.

The uncertainty of demand, wind and solar power outputs are accounted for by considering three different scenarios for each individual uncertain parameter. It should be noted that each scenario represents the realization of the uncertain parameter under consideration in an hourly basis.

In this work, the data of São Miguel Island in the Azores for wind speed and solar radiation are used. The data are retrieved from public available databases of wind speed [92] and solar radiation [93] at different locations in the island. Therefore, this wind speeds and solar radiation will be converted to power production series by using their corresponding appropriate power curve expressions.

In this work, three uncertain parameters are considered such as electricity demand growth, wind power output and solar power output. Given three different scenarios for each individual uncertain parameters and assuming they are all independent, 27 different combinations are obtained to form the new set of scenarios used. These combinations of the individual scenarios form the set of scenarios finally considered in the analysis.

4.2.1 Demand Scenarios

As shown in Figure 4.2, demand uncertainty is represented by three scenarios, which are themselves obtained by clustering 30 different demand profiles. Such a reduction in the number of scenarios is required to ensure problem tractability.

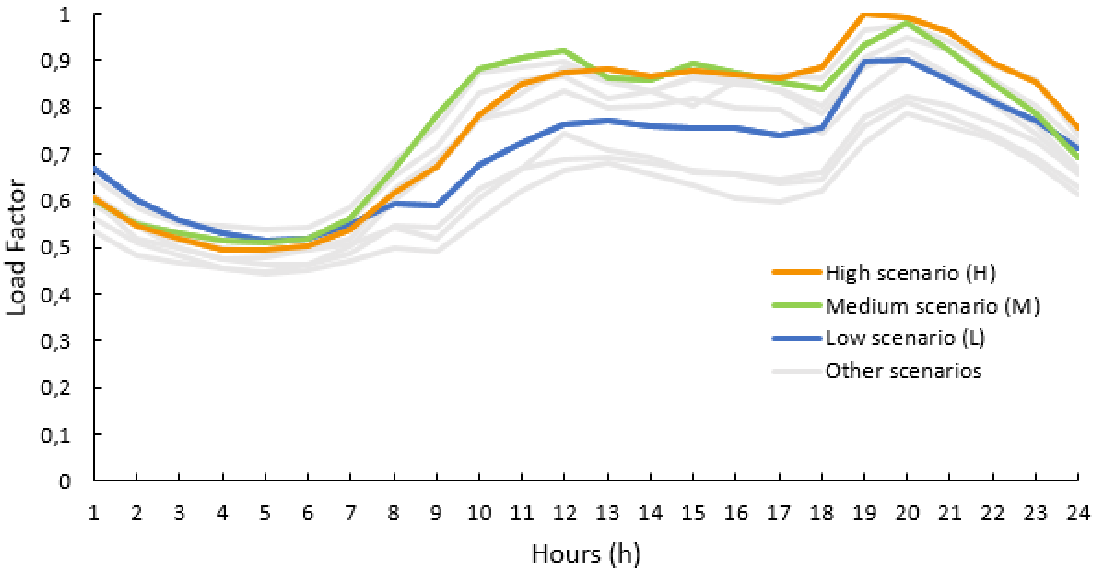

Figure 4.2 - Demand scenarios.

4.2.2 Wind Power Scenarios

Likewise, the wind power output uncertainty is accounted for by considering three representative scenarios, obtained by means of clustering originally 30 different wind power output profiles. This is illustrated in Figure 4.3.

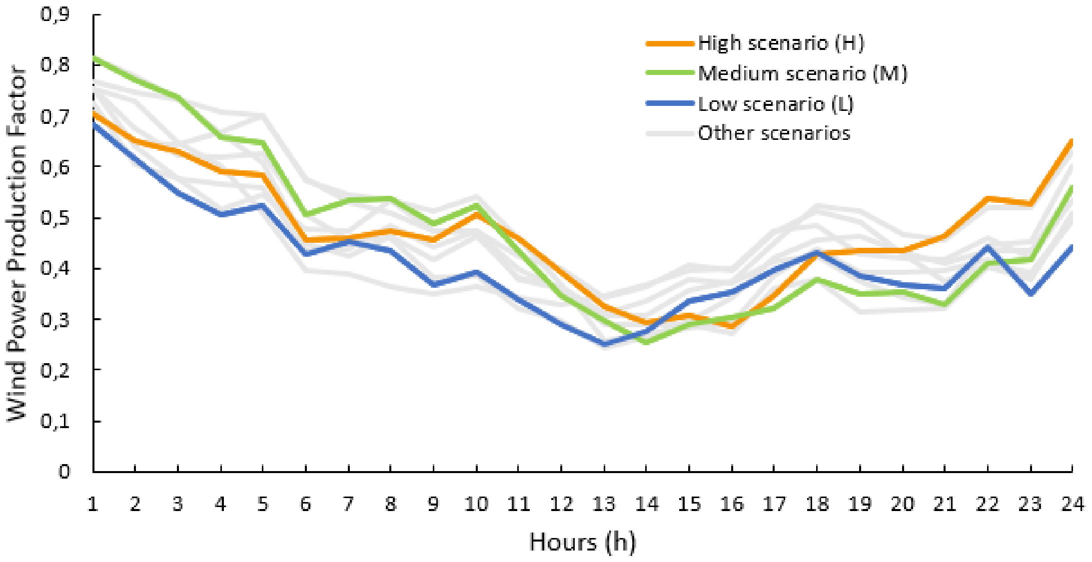

Figure 4.3 – Considered wind power output scenarios.

4.2.3 Solar Power Scenarios

Similar to the demand and wind scenarios, three solar power outputs scenarios are considered corresponding to high, medium and low power production profiles, as shown in Figure 4.4. Note that these are also defined based on clustering 30 different power output profiles.

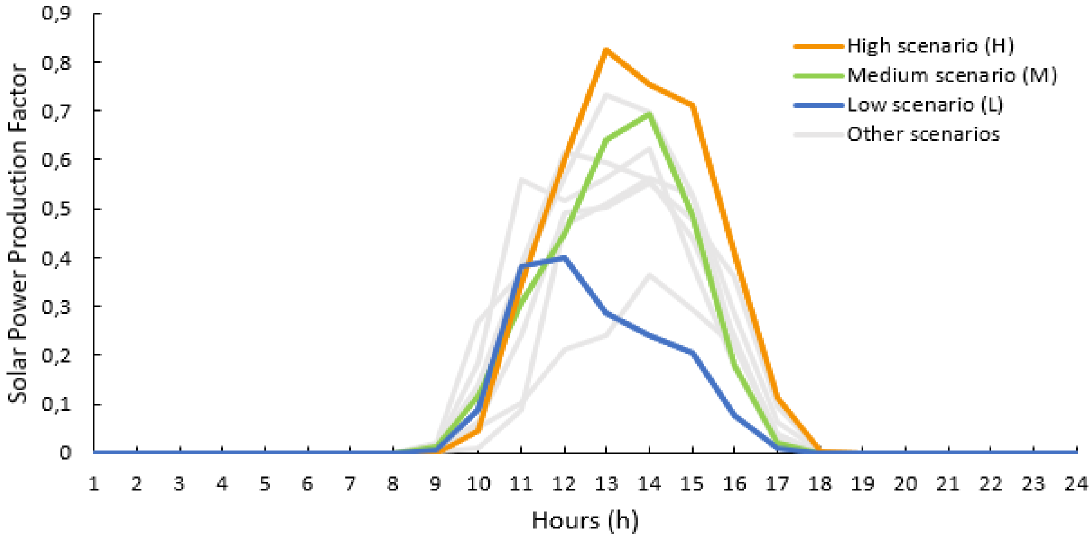

Figure 4.4 – Considered solar power output scenarios.

4.3 Results and Discussions

Four different cases (designated as Case A to D) form part and parcel of the extensive analysis carried out in this work. A summary of the different cases considered in the analysis is shown in Table 4.1. In this table, the control parameters clearly distinguish each case. Case A represents the base case, where there is no reconfiguration, without any DER connected to the system. For this case, the voltage lower bound is relaxed to avoid unrealistically high unserved power (reactive power, in particular). In Case B, all DERs (DGs, SCBs and ESSs) are connected, but dynamic reconfiguration is not considered. To further investigate the impacts of DNR on the system's performance, Case C is formed. This case is similar to Case B, but excluding ESSs and introducing dynamic reconfiguration. Case D is similar to Case B, but now it is considered DNR to better evaluate vRES integration level.

In addition, starting from Case D as basis, three more cases are formed which are called "sensitivity cases". In these cases, only a certain parameter (Table 4.2) is changed for each case to observe the impacts of such alteration in the system. The only change in Sensitivity Case D.1 is on the variable cost of energy injected into the system by ESS which is decreased to 3 $€/MWh$ from the base case value of 5 $€/MWh$. In Sensitivity Case D.2, only the efficiency of the storage system is changed to 70% from 90% in Case D. Finally, in Sensitivity Case D.3 considers alterations on the price of emissions from 7 to 15 $€/tCO_2e$.

Table 4.1 – Details of the considered cases.

Cases	Reconfiguration	DGs	SCBs	ESSs
A	No	No	No	No
B	No	Yes	Yes	Yes
C	Yes	Yes	Yes	No
D	Yes	Yes	Yes	Yes

Table 4.2 – Details of the considered sensitivity cases.

Sensitivity Cases	Standard Value	New Value
D.1	λ^{es} = 5 $€/MWh$	λ^{es} = 3 $€/MWh$
D.2	η_{es}^{dch} = 90%	η_{es}^{dch} = 70%
D.3	λ^{CO_2} = 7 $€/tCO_2e$	λ^{CO_2} = 15 $€/tCO_2e$

4.3.1 Case A - Base Case

Case A represents the base case, where there is no reconfiguration and without any DER connected to the system, typically simulating the traditional grid. For this case, it was not considered the lower bound of voltage because that will lead to the infeasibility of the simulation/operation. Figure 4.5 plots the average voltage profiles in the system for Case A. Note that this figure displays only the hours which have more voltage deviations, the hour with less voltage deviations and the average values for all hours. It should be noted that all downstream buses have negative voltage deviations, as power flows from upstream to downstream. Since the only source of active and reactive power is the substation (no SCBs at this case), there are no voltage control mechanisms, therefore, the voltage in most of the nodes exceed the technically permissible limit (5%). At peak hours i.e. at hour 20, the high demand will make the voltage levels move far away from the nominal value. Hence, the voltage deviation will be as large as the nodes are more distant from the substation, thus nodes 18, 33 and 41 are the most problematic. In some operational situations, the voltage deviation in node 41 can be as high as 12%. Also, at valley hours where the voltage should be more stable, the permissible limit is also exceeded in nodes from 15 to 18 and from 36 to 41. This indicates that the system is highly lossy and poorly compensated.

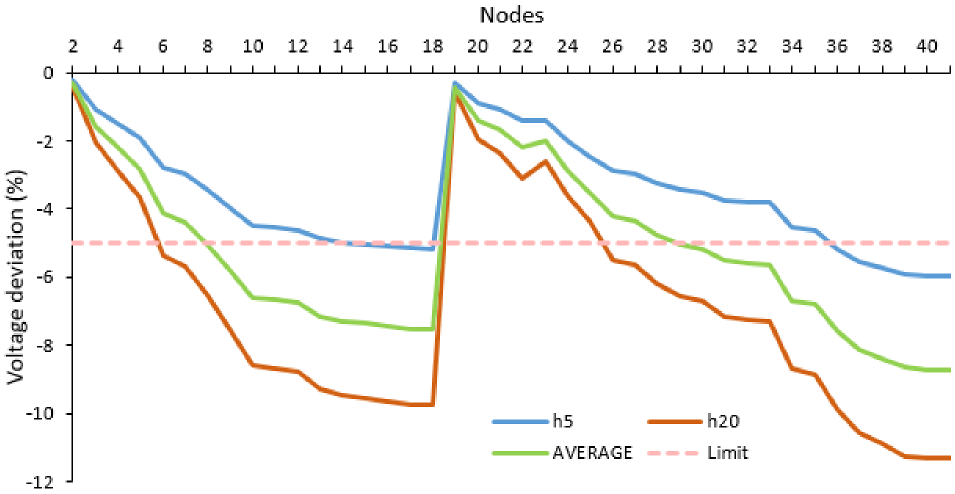

Figure 4.5 - Voltage deviation profile in the system for Case A.

4.3.2 Case B – Considering Distributed Energy Resources (DGs, SCBs and ESSs)

Case B represents a more evolved system where all DERs are connected to the system but without reconfiguration. Figure 4.6 shows the average values of the voltage deviations in the system with respect to Cases A and B. This figure analysis reveal the voltage profile improved to reasonable limits, mainly because of the reactive power injected by SCBs and DGs into the system. Therefore, node voltages can be locally controlled. Also, the positive values of voltage deviations can be due to the power supplied by distribution generations.

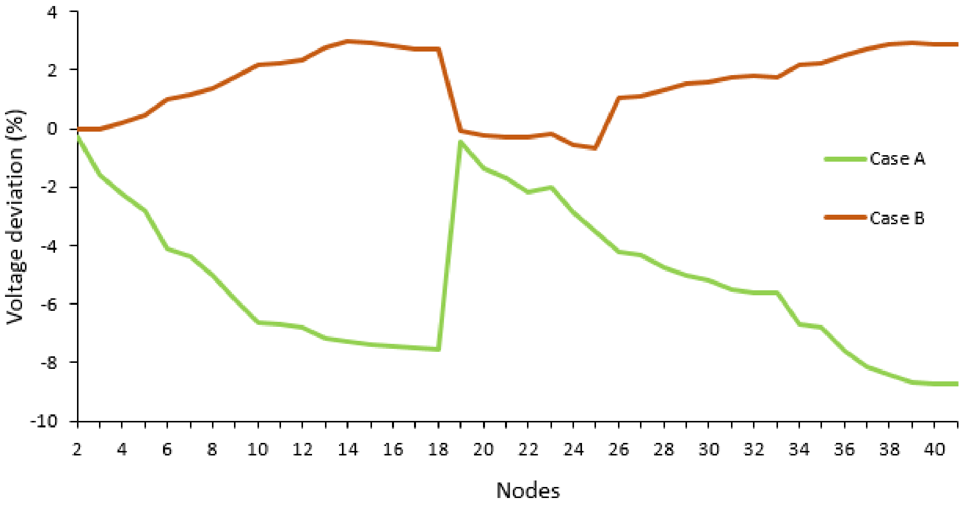

Figure 4.6 - Comparison of voltage deviation profiles in the system for Case A and Case B.

As DGs are included, power flows can now occur from downstream to upstream, making that consumers are not only supplied by the substation, as it occurs in case A. It can be seen that the nodes which are now with DGs particularly, nodes 38, and 39 present an overall voltage deviation, less than 3% comparing with 8% in the Case A. Also, it is important to note that the inclusion of DGs in node 14 can supply its further nodes, which can be a way to control their voltage (nodes 14 to 18), since they present lower deviations in Case B instead of what happened in Case A. The voltage profiles for peak and valley hours are not shown in this figure, but results show that even for the more demanding hours, the system continues to operate within the permissible limits, being that the highest voltage deviation registered is around 4,9% at node 14.

Figure 4.7 displays the energy mix corresponding to Case B. In this figure, it is possible to observe that more than 90% of the electricity demand in the system is met by energy that comes from RES, particularly wind and solar type DGs. A small quantity of electricity is imported only during valley hours to take advantage of the low electricity prices, mainly to charge the ESSs in the system. This way, the ESS systems can discharge during peak hours to meet the portion of demand that could not be locally met. Despite being more expensive than ESSs power, solar production must be used since further in the day there will not be any and import power will be more expensive. Therefore, the system uses the solar production until it is available, leaving the major part of ESS power for meet the demand in peak hours, when there is no solar production, avoiding importing energy at higher prices. Consequently, ESSs charges during valley hours (with power bought from the upstream grid at lower prices) and uses that power in peak hours (where the electricity prices are higher) to meet the demand and providing lower costs to the users. Furthermore, energy losses are also represented in Figure 4.7 when the production slightly exceeds the demand.

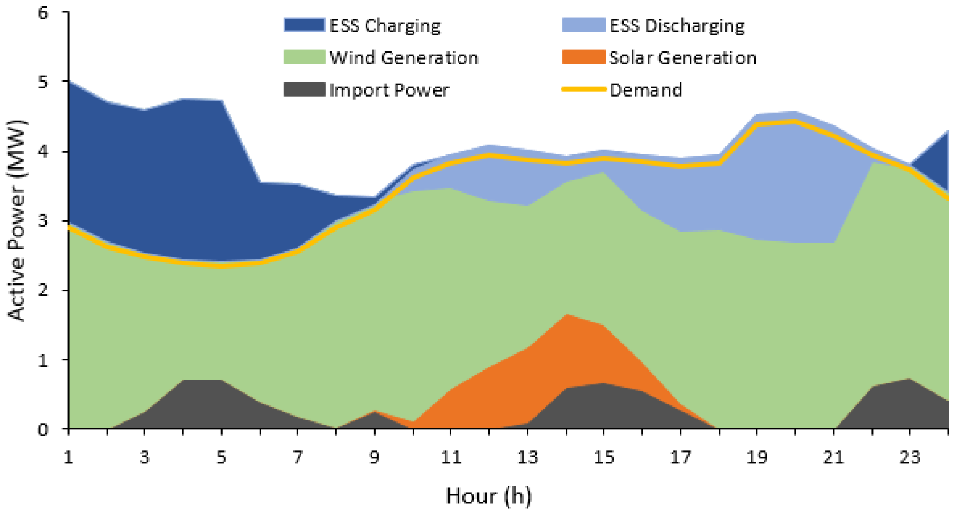

Figure 4.7 - Energy mix in Case B.

4.3.3 Case C - Considering Distribution Network Reconfiguration and Distributed Energy Resources without Considering Energy Storage Systems

Case C features an even more evolved system. Here, the impacts resulting of dynamic reconfiguration but without ESSs are analysed. The results of hourly switching operations corresponding to Case C are summarized in Table 4.3. In Table 4.3, it can be observed that, all other lines not shown in the table do not experience switching operations i.e. the statuses of those lines remain 1 throughout the day.

Table 4.3 – Dynamic reconfiguration outcome of a typical day, in Case C.

Lines	Hours with $x_{l,h} = 0$
Line 20	8-10, 13-15, 17-18, 22-24
Line 28	1, 3-4
Line 29	1-8, 10-16, 24
Line 32	2
Line 34	All day long off
Line 39	8-10, 18, 22-24
Line 40	20-21
Line 41	1-7, 11-12, 16, 19-21
Line 42	9, 17-23
Line 43	2, 5-24
Line 45	1-7, 11-17, 19-21
Line 46	1-19, 22-24
Line 47	1, 3-24

The purpose of reconfiguration is to efficiently adapt to the continuously changing operational situations, with the aim of routing the actual generation to the nodes, where it is being consumed in real-time. In this case, since the system does not have energy storage, the network system will feature more switching operations in order to offer more flexibility, to meet the demand. For example, from hour 1 to 7, lines 20 and 42 are connected and 29 and 41 are disconnected, revealing that power produced by wind DGs in node 32 is enough to supply until node 20. Also, only during hour 2, the same production in node 32 was able to supply node 18 via line 47. On the other hand, in peak hours, from hour 17 to 23, since lines 42, 43 and 47 are disconnected, the production in node 32 was only able to supply the closer neighbours and join the production on node 29. On the other side of the grid, line 44 seems always on, substituting line 34, to interconnect the demand nodes with the large amount of RES production in nodes 38 and 39.

Figure 4.8 presents the average values of the voltage deviation in the system for Case C and also for the previous cases. The analysis reveals a very stable system regarding to voltage profile throughout a typical day. Besides the benefits of the introduction of DGs in this system, the positive contribution of DNR in improving voltage profile can be observed. This improvement is evident in Figure 4.8 by comparing the profiles corresponding to Cases C and Case B (where a static topology is considered). Case C, besides to operating within the permissible limits, also leads to a largely smoother voltage profile and the voltage in every node is closer to the nominal value. The average voltage deviation is never higher than 0.6%. In fact, even in the peak hours (hour 20), the higher value of voltage deviation registered is -1.48% at node 35. In this hour, the load is partly supplied by importing power through the substation (indicated by negative voltage deviation). It should be noted that, at this hour, line 40 is open and thus, power generated at nodes 38 and 39 flow in the upstream direction however this is not enough to meet all load at node 35.

Figure 4.9 shows the energy mix corresponding to Case C. In this case, there is no any imported power during valley hours, because demand can be fully covered by the locally produced wind power. Here, one can see network reconfiguration helps in the absorption of more wind power because the reconfiguration always adapts the network by finding the best hourly topology to direct the wind power to the nodes where it is consumed in real-time. From hour 8, demand starts to grow to levels where the combination of wind and solar cannot fully cover. Hence, the system is forced to import energy from the upstream grid to meet the demand at peak hours. Generally, DNR plays an important role in terms of efficient utilization of available resources and reduction of losses in comparison to the previous cases.

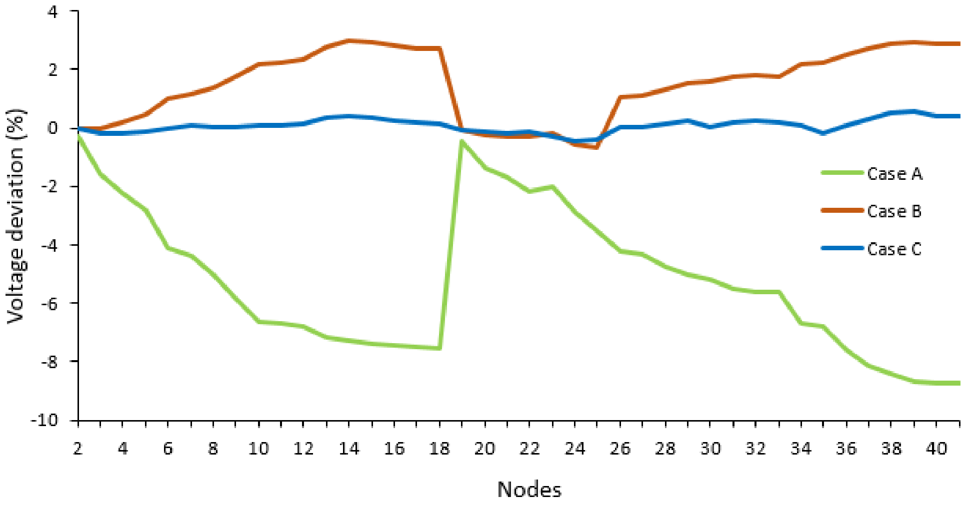

Figure 4.8 - Comparison of voltage deviation profiles in the system for Case A, Case B and Case C.

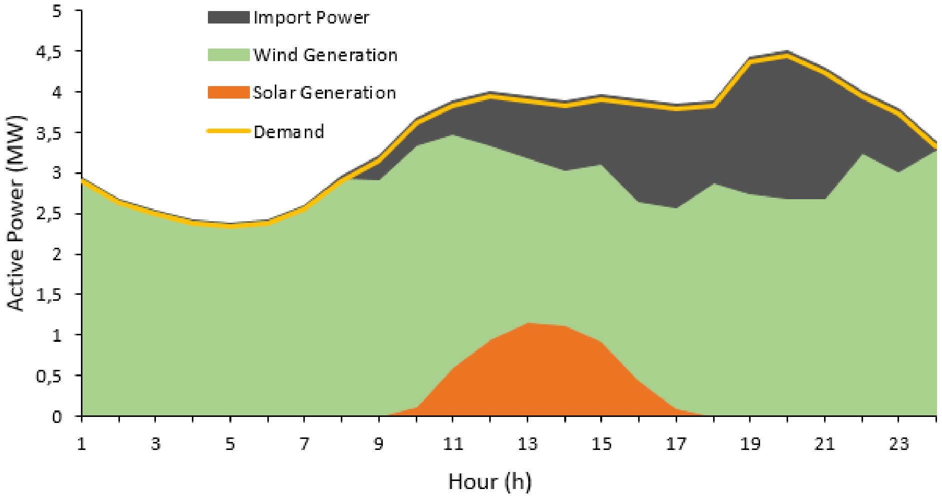

Figure 4.9 - Energy mix in Case C.

4.3.4 Case D - Considering Distribution Network Reconfiguration and Distributed Energy Resources

Case D is similar to the previous case but now ESSs are connected to the system. This case is used to analyse the impacts of ESS technologies along with dynamic network reconfiguration and the other DER technologies (DGs and SCBs).

The results of DNR operation corresponding to Case D are featured in Table 4.4. The results in this table show the off-line hours of each line. As in the previous cases, not all lines are shown here; the ones connected all the time are not shown. In this case, the integration of ESS offers more flexibility to the system, being easier to match the demand than Case C. Therefore, as it can be seen in Table 4.4, DNR is not required so often, the frequency and number of switching operations are lower than the previous case.

Table 4.4 – Dynamic reconfiguration outcome of a typical day, in Case D.

Lines	Hours with $x_{l,h} = 0$
Line 20	1-3, 5-7, 9, 22-24
Line 29	9-21
Line 34	All day long off
Line 39	8-13, 17-18, 22-24
Line 41	4, 8, 10-21
Line 42	1-8, 22-24
Line 43	All day long off
Line 45	1-7, 14-16, 19-21
Line 46	All day long off
Line 47	All day long off

However, this does not mean that reconfiguration is not important in this case. For example, as it can be seen in Figure 4.10, during the most part of valley hours, the system imports power from the substation in order to help wind type DGs to supply the demand and charge the storage systems. As such, from hour 1 to 8, line 42 is disconnected, which reveals that node 22 will be supplied mainly by the local production from node 7 and the substation (as line 20 and 41 are alternating), while the local wind production in node 32 and 29 will charge the storage systems in nodes 32 and 30. On the other hand, line 42 is connected during hours 10 to 21 while line 29 is disconnected, which means that DG power production at node 29 flows towards node 6, and DG power production and ESS power discharged flows in the direction of node 2. In the other side of the grid, a similar event is happening. Line 45 is an important way to easily store excess power in the ESSs connected at either side of this line.

Figure 4.11 the average values of voltage deviation in the system for case D and all the previous cases. Is possible to see that average voltage deviation is always lower than 2%, reaching a maximum of 1,25% in node 14. This represents a stable system regarding to voltage control however, comparing with case C, it presents a higher voltage deviation throughout the day. This can be explained by the power injected by ESS in the system. As it can be seen in that figure, nodes 14 and 40 are the nodes which features higher average values. In addition, results of hourly voltage profile show that at hour 20 is the time which voltage deviation registered higher values. A voltage deviation of 3,17% in node 14 was presented because ESS are discharging the higher amount of power of all day in hour 20. Note that node 14 has installed capacity of 2 MW of wind-type DG which makes this node to be always locally supplied, and more 2 MW installed of ESS technology. Hence, with the amount of power injected in this node at this hour, is normal to present the higher voltage deviation. Still, outside that hours which ESS are fully discharging, the system is presenting a very good voltage profile.

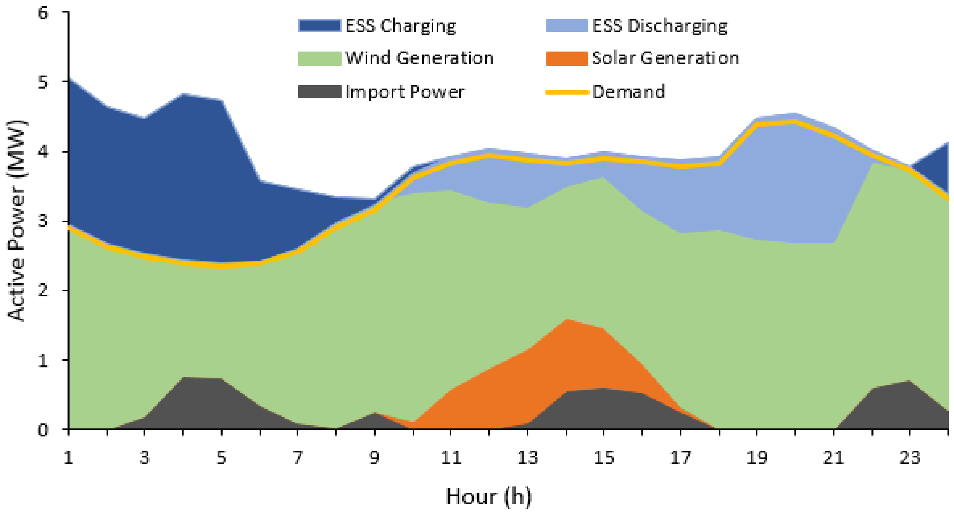

Figure 4.10 - Energy mix for Case D.

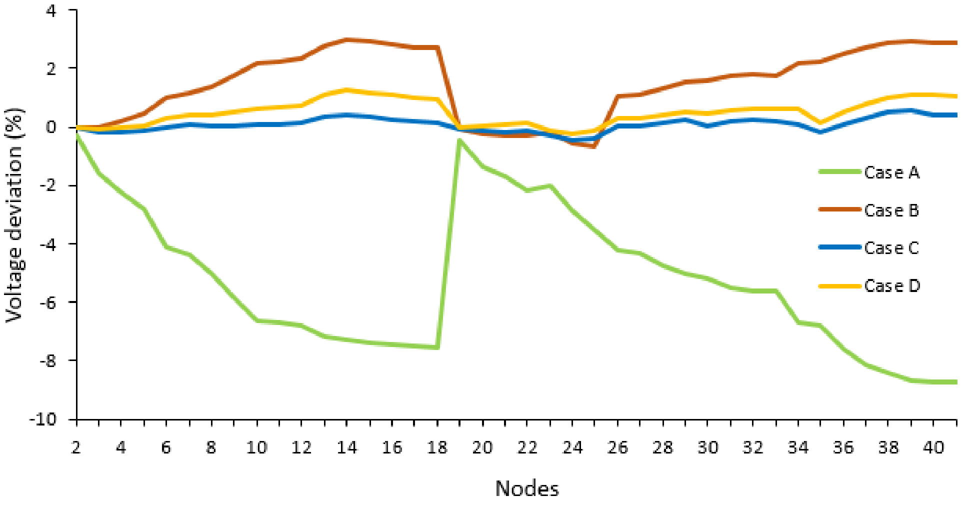

Figure 4.11 - Comparison of voltage deviation profiles in the system for Case A, Case B, Case C and Case D.

Figure 4.10 features the energy mix corresponding to Case D. This figure is very similar with Figure 4.7 from case B which the only difference is the inclusion of the DNR methodology. As dynamic reconfiguration cannot generate power, the energy mix will be very close to Case B. What dynamic reconfiguration can do is to lead the power flow more efficiently decreasing losses and taking it to the demand (and this is possible to be seen carefully in this figure). The difference of the amount of injected power and the demand is representing the active power losses, and this difference is lower than the difference represented in Case B. This denotes that when DNR was introduced, the system operated more efficiently. However, comparing with Case C, results show higher losses in this case resulting of the inclusion of ESS. In fact, the average power losses are higher than Case C due to the amount of extra power that need to flow to charge the ESSs during the valley hours.

4.3.4.1. Sensitivity Cases – D.1

In this subsection it will be analysed the first sensitivity case. Having Case D as base case, including DGs and ESSs connected to the system and also DNR, it is interesting change some parameters and sees the impacts changes. Therefore, in sensitivity case D.1 was altered the variable cost of energy injected in the system by ESSs, from 5 to 3 $€/MWh$. With that change, it was expected the increased use of energy storage.

Looking at Table 4.5, it seems that hourly reconfiguration is less used than in Case D. Lines 20 and 42 are only changed twice throughout the day alternating with lines 41 and 29 respectively. These lines are disconnected when ESSs are charging from hour 1 to 7, so node 20 will be supplied by the substation. From hour 10 to 21, when ESSs are discharging, lines 20 and 42 are connected to lead the power generated by DGs from node 32, injected by ESSs from nodes 32 and 30 to supply the demands towards the upstream nodes. On the other side of the grid, the switching operation of lines 39 and 45 seems to be equal as case D. As usual, line 34 remains disconnected and line 44 is always connected through all day long to interconnect the demand nodes with the large amount of RES production in nodes 38 and 39 and the injected power from node 40. As it was seen in previous cases, the more use of ESS will have effects on less switching operations frequency.

In Figure 4.12 is presented the average values of voltage deviation in the system for Case D and sensitivity case D.1. The difference between the two are not very significant. However, we can see that the greater use of ESSs have increased the voltage deviation in the nodes which storage systems are connected. For example, in node 14 is shown a slightly higher voltage deviation in case D.1. It is also confirmed in hourly results which at hour 20, when ESS are discharging more, node 14 has a voltage deviation of 3,19% in case D.1 comparing to the 3.17% of Case D. The difference is not very significant because in the previous case, ESSs were already near the fully operation.

Table 4.5 – Dynamic reconfiguration outcome of a typical day, in sensitivity case D.1.

Lines	**Hours with $x_{l,h} = 0$**
Line 20	1-9, 22-24
Line 28	3
Line 29	8-21
Line 34	All day long off
Line 39	8-13, 17-18, 22-24
Line 41	10-21
Line 42	1-7, 22-24
Line 43	1-2, 4-24
Line 45	1-7, 14-16, 19-21
Line 46	All day long off
Line 47	All day long off

In Figure 4.12 is presented the average values of voltage deviation in the system for Case D and sensitivity case D.1. The difference between the two are not very significant. However, we can see that the greater use of ESSs have increased the voltage deviation in the nodes which storage systems are connected. For example, in node 14 is shown a slightly higher voltage deviation in case D.1. It is also confirmed in hourly results which at hour 20, when ESS are discharging more, node 14 has a voltage deviation of 3,19% in case D.1 comparing to the 3.17% of Case D. The difference is not very significant because in the previous case, ESSs were already near the fully operation.

The energy mix corresponding to sensitivity case D.1 is plotted in Figure 4.13, and it is evident that this sensitivity case D.1 and Case D are very similar. The alteration of the variable cost of energy injected in the system by ESSs to a lower level, has proved that ESSs were already an asset to be used in the system, even with a discharging cost of 5 €/MWh. Hence, with a lower cost, it continues to operate in a very similar way.

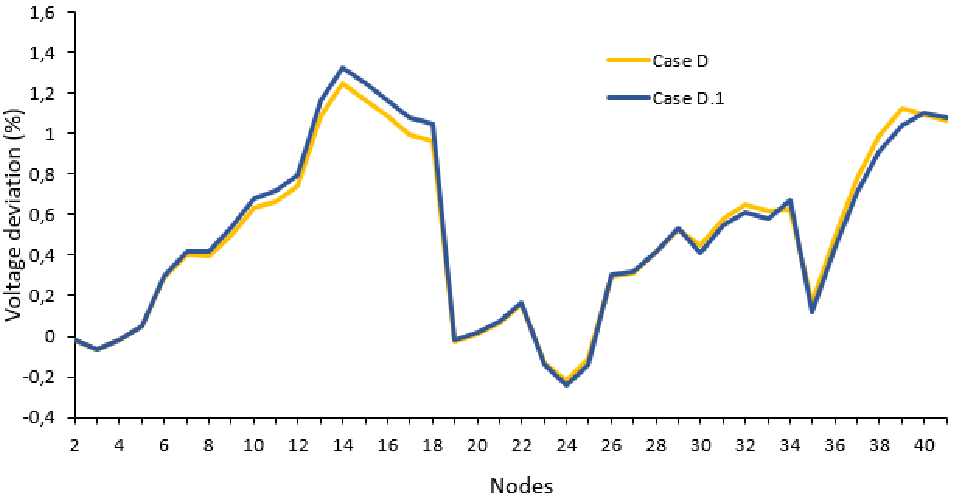

Figure 4.12 - Comparison of voltage deviation profiles in the system for Case D and sensitivity case D.1.

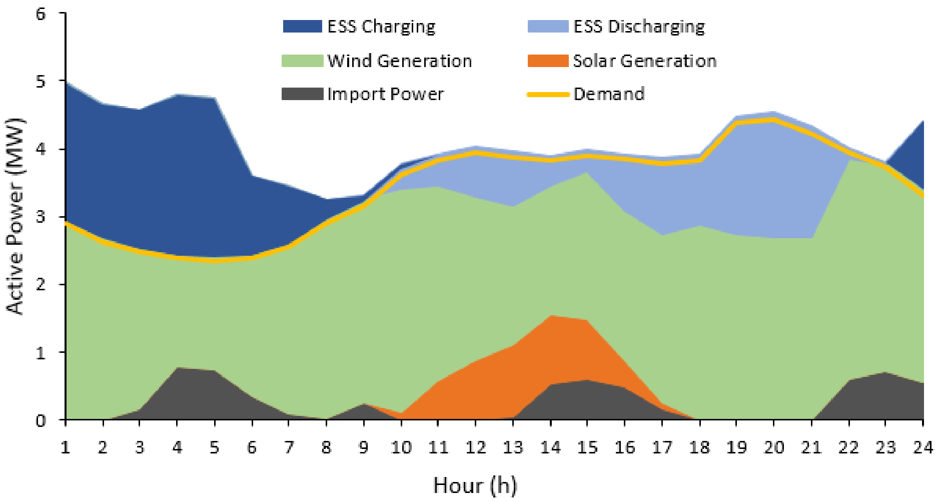

Figure 4.13 - Energy mix for sensitivity case D.1.

4.3.4.2. Sensitivity Cases – D.2

Similarly to what it was done with the former sensitivity case, this one is also based from Case D. On sensitivity case D.2 the only parameter that was changed was the efficiency of the storage system from 90% to 70%. The impacts with this alteration will affect directly the ESS but also, the system will need to adapt to find the best solution to supply the consumers.

In Table 4.6 is featured the hourly reconfiguration throughout a typical day. As it was done before, the table show the hours which each line is disconnected from the system. The big difference to the last sensitivity case is the higher amount of switching operations. In comparison with the previous cases, is possible to see the increased frequency that lines are experiencing reconfiguration. For example, line 20 alternates with line 41 for ten times in a day, also line 39 switches with line 45 for seven times. Line 47 which usually stays off for all day long is connected in hours 6 and 18 to lead power to node 33. In fact, modifying the efficiency of ESS, lead to a decrease in the utilization of these systems, since it would require more energy to use them efficiently. Hence, as the system cannot rely on ESSs as it did in Case D and sensitivity case D.1, results show that DNR plays a bigger role in this sensitivity case D.2.

The average values of voltage deviation in the system for sensitivity case D.2 is plotted in Figure 4.14 when can be compared with Case D and sensitivity case D.1. As it can be seen, this case presents lower average values throughout the day due to the lower amount of power efficiently injected in the grid by the energy systems. Results show the higher average value in the system is 1,07% in node 14 due to the presence of DGs (which always supply this node and its voltage never drop below 0) in coordination with SCBs and the power injected by ESS at some hours. Also in the hourly results, node 14 has the higher voltage of the day (3,37%) at hour 19. This hour is when is presented more discharged power by ESS, which can be seen in Figure 4.15.

Table 4.6 – Dynamic reconfiguration outcome of a typical day, in sensitivity case D.2.

Lines	Hours with $x_{l,h} = 0$
Line 20	1, 3-9, 13-14, 17, 20, 22-24
Line 28	2-3
Line 29	10-16, 18-21
Line 32	6, 18
Line 34	All day long off
Line 39	7-10, 18, 20, 22-24
Line 41	2, 10-12, 15-16, 18-19, 21
Line 42	1-9, 17, 22-24
Line 43	1, 4-24
Line 45	1-6, 11-17, 19, 21
Line 46	All day long off
Line 47	1-5, 7-17, 19-24

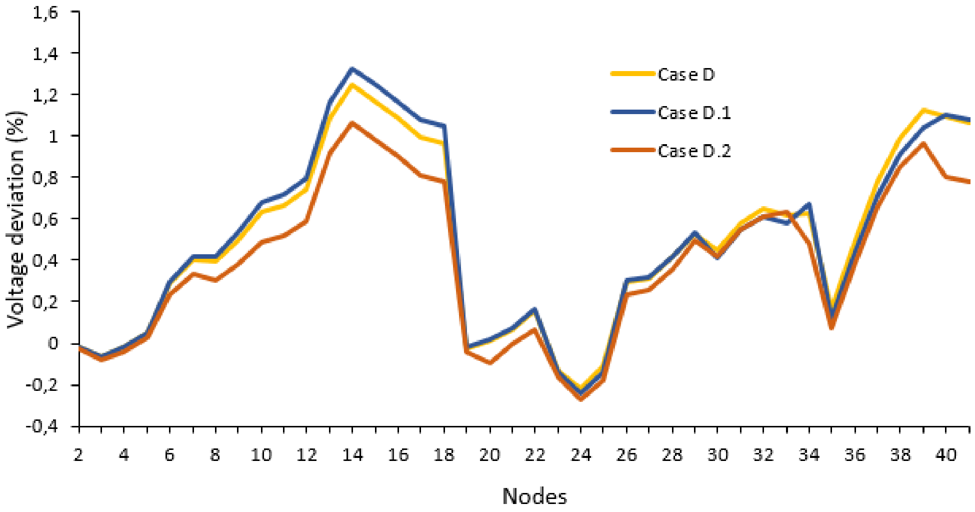

Figure 4.14 - Comparison of voltage deviation profiles in the system for Case D, sensitivity case D.1 and sensitivity case D.2.

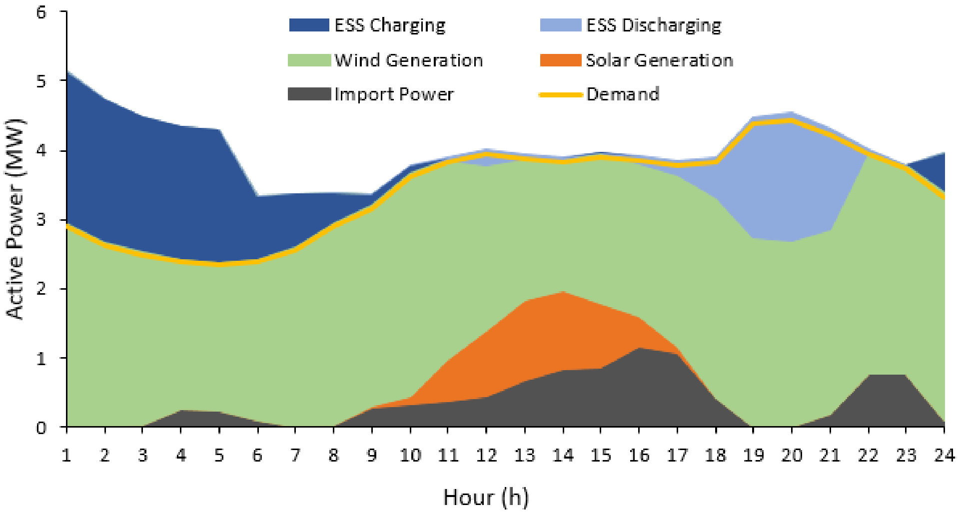

Figure 4.15 - Energy mix for sensitivity case D.2.

The energy mix corresponding to sensitivity case D.2 is presented in Figure 4.15. In these case during valley hours, the same amount of wind energy generated locally is used to charge ESSs as a little imported energy is needed to meet the remaining demand. From hour 10, the demand starts to reach to levels where wind and solar cannot be able to meet. Since at this time of the day electricity prices are not very high, the system import power from the upstream grid. At peak hours, the imported power has decreased due to the high prices to buy electricity and this power is substituted by the energy stored in ESSs. Is important to note, the change made in the ESSs, the efficiency reduction has forced the system to save the stored energy to a time in the day where import energy had higher prices. As the injected power from these technologies would be lower than Case D, for example, the system only started to use it from hour 16 instead of what happened in Case D at hour 9.

4.3.4.3. Sensitivity Cases – D.3

At last, sensitivity case D.3 is formed in a similar way as the previous cases. Having Case D as base, with DGs and ESSs connected to the grid and also considering DNR, the difference is on the alteration of parameter, price of emissions which was 7 $€/tCO_2e$ and in this case, it was increased to 15 $€/tCO_2e$. It is expected that will affect both imported power but also the integration of DGs.

In Table 4.7 are presented the results of DNR operation corresponding to sensitivity case D.3. As it was done before, all lines not shown in that table remain connected throughout the day. Comparing the results of this case with the results of Case D is clear that switching operations are similar. For example, in the hour range 1-10 (charging ESS period), line 20 is disconnected at hour 4 and 8 in Case D, and in sensitivity case D.3 is only disconnected at hour 5. On the remaining period of the day, line 20 is connected from hour 10 to 21 in case D, and in this case line 20 is connected from hour 10 to 21 (except hour 14). The same happens for example with pair lines 39/45 which present a difference only at hours 17 and 18. Line 45, in this case is connected from hour 8 to 13 and from hour 22 to 24, while in Case D, line 45 is connected from hour 8 to 13, from hour 17 to 18 and from hour 22 to 24. Those similarities are a first sign that price of emissions affected the cost of imported power and power produced from DGs, but the system is operating in the same way.

In Figure 4.16 is represented the average values of voltage deviation in the system for sensitivity case D.3, compared with Case D and all the other sensitivity cases. It can be immediately seen that sensitivity case D.3 is always very close to the voltage profile represented by Case D. Also, hourly results show similar results between the two cases featuring the higher voltage deviation (3,12%) in node 14, at hour 20.

Table 4.7 – Dynamic reconfiguration outcome of a typical day, in sensitivity case D.3.

Lines	Hours with $x_{l,h} = 0$
Line 20	1-4, 6-9, 14, 22-24
Line 28	2-3
Line 29	8-21
Line 32	6, 9
Line 34	All day long off
Line 39	8-13, 22-24
Line 41	5, 10-13, 15-21
Line 42	1-7, 22-24
Line 43	1, 4-24
Line 45	1-7, 14-21
Line 46	All day long off
Line 47	1-5, 7-8, 10-24

The energy mix corresponding to sensitivity case D.3 is represented in Figure 4.17. Once more, is evident the similarities between this case and case D. It was expected with the alteration of the emission cost to higher values, to penalise DGs production and also imported energy. However, that alteration was not significant enough to force the system to operate in different way, favouring other types of energy sources (i.e. ESSs). Also, the energy storage systems were already operating at their full capacities, like it was shown in sensitivity case D.1, thus the system needed to use DG production and imported power in the same way.

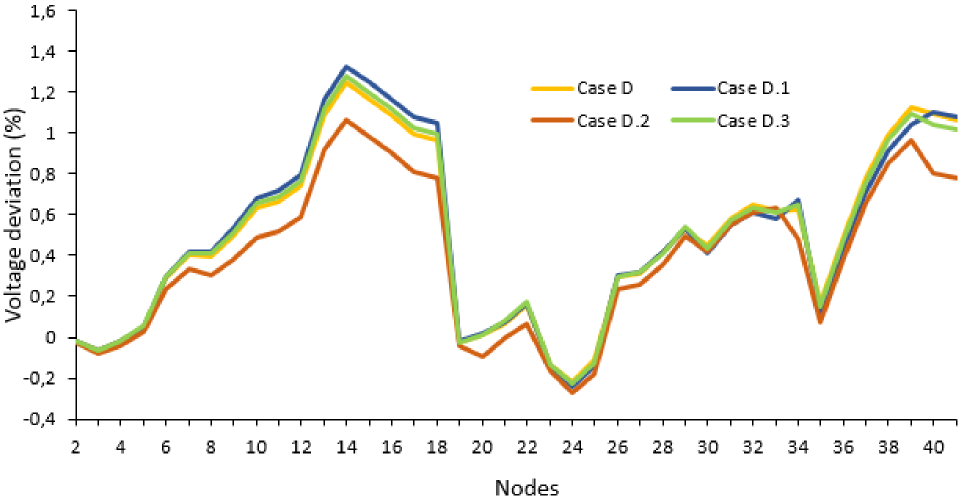

Figure 4.16 - Comparison of voltage deviation profiles in the system for Case D and all sensitivity cases.

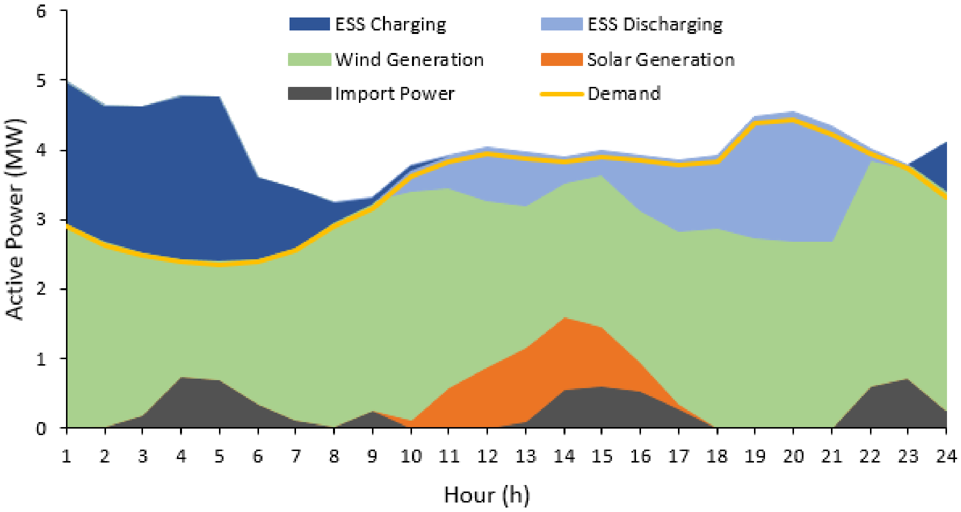

Figure 4.17 - Energy mix for sensitivity case D.3.

4.3.5 Total Costs and Average Losses

Table 4.8 summarizes the costs and average losses for each case. The results in this table reveal the significant differences in the total cost and average losses for the different cases. As it can be seen in this table, Case A has the highest overall cost and losses as the demand in the system is met only by importing power through the substation, which is relatively more expensive than local power production using DGs. In Case A, active power losses in some operational situations (peak hours) can reach as high as approximately 1 MW. In Case B, losses and costs are slashed each by more than 67% with respective to the values in the base case (i.e. Case A). The results of Case C further demonstrate the positive impacts of dynamic reconfiguration. In this case, ESSs are not deliberately connected to further observe the potential of DNR in scaling up vRES utilization while managing well their imminent side effects. Hence, DNR enables a reduction of active power losses by 41%, however, the lack of any storage system and the need to import power from upstream has increased the total overall costs by 26%. The slight increase in costs in Case C, in comparison to Case B, is rather expected because unlike in Case B, this one does not have a mechanism to store excess wind or solar power which can be utilized in times of high demand and electricity prices. This obviously leads to a higher cost and a lower overall efficiency in the system. The fact that the losses are lower in Case C compared to any other case may be to the absence of extra flows that would be required in certain lines for storing in ESS nodes. Case D compared with Case C is representing the impacts of the storage system. Hence, the total costs dropped by 22% due to more flexibility to match the demand in peak hours. Yet, average power losses increased 25% which denotes that are extra flows in the system to charge ESSs. From Case B to Case D, active power losses are further reduced by 26%, and system costs by more than 34€ per day (about 2%). Note that the only difference between cases B and D is that the first one does not consider reconfiguration but the latter does. Therefore, the further reduction in losses and costs in Case D reveal an increased utilization of local power productions (8% more than in Case B). This is due to the fact that DNR enables the system to better manage the variability of vRESs by dynamically and optimally changing the topology that matches various operational situations in comparison to a static topology as in Case B.

Table 4.8 – Costs and average losses for each case.

	Cases						
	A	**B**	**C**	**D**	**D.1**	**D.2**	**D.3**
TC [€]	6526.59	2179.24	2741.83	2145.09	2122.05	2421.94	2183.80
PL [MW]	0.289	0.093	0.055	0.069	0.069	0.065	0.069
QL [MVAr]	0.214	0.075	0.044	0.056	0.057	0.052	0.056

Regarding the sensitivity cases only, a comparison with Case D can also be analysed from the results in table 4.8. From Case D to the first sensitivity case (i.e. D.1), the change to a lower cost of the energy discharged by ESSs to the system has made a reduction of 1.1% of the overall costs maintaining the same power losses. In sensitivity case D.2, and also comparing with case D, total costs are further increased by 13%. As in this sensitivity case, efficiency of ESSs are lowered, the system needed to find the remaining energy from the upstream at higher prices. In addition, active power losses are reduced by 6% which denotes that power has not gone through long distances as power from ESSs and the substation cover the rest of the demand at the remaining nodes. At last, sensitivity case D.3 presents some difference comparing with Case D. In fact, the change of price of emissions has not changed the operation mode of the system. However, when this parameter is set to a higher value, the total cost goes higher by 2%. Regarding the average losses of this case, it can be seen that it remains similar to Case D.

4.4 Chapter Summary

Generally, the analysis of this chapter clearly shows the substantial benefits of DNR can have in terms of providing more flexibility to the system, which is highly desired to integrate and efficiently utilize a large quantity of intermittent power at distribution levels. Case D, presents the lower value for total cost which denotes an increased utilization of local power productions instead of buying energy from the grid. DNR enables the system to better adapt the continuously changing situations, and distribute the locally produced “cleaner” and cheaper power to the demand while meeting the technical requirements. However, this case is not the best regarding to power losses. In fact, Case C has the lower average values and the most stable voltage profile mainly due to the disconnection of ESSs. In Case D, the presence of energy storage systems forced extra power flows in hours of lower demand, in order to charge themselves, resulting in a slightly increased average loss. Therefore, when similar cases are compared regarding power generation technologies (i.e. Case B and Case D), it has been revealed that the case which consider DNR can reduce power losses and improve voltage profiles dramatically.

In addition, three sensitivity cases have been analysed in order to see the impacts on the operational performance of the system and their effects in the dynamic switching operations. While sensitivity case D.1 has a lower overall cost while, sensitivity case D.2 presents higher costs. This is only related with the more (in the first) or less (in the latter) utilization of ESSs. In the last sensitivity case (D.3), similar results are observed when compared with case D. However, this may be case-dependent. DNR outcomes show differences in the switching operations and in the ESS charging/discharging operation times.

Chapter 5

Conclusions and Future Works

In this chapter, the main conclusions of the thesis are presented as well the limitations of the work in this thesis, and some directions of future work are also discussed. Finally, the contributions of this work are highlighted by presenting the publication, a result of this thesis work.

5.1 – Conclusions

In this thesis, a new operational model which incorporates dynamic reconfiguration of distribution systems has been developed, which allows effective management of large scale intermittent renewable energy sources.

The new contribution comes from the new formulation of the problem, with stochastic MILP, using dynamic reconfiguration. The model is used to investigate the impacts of DNR in the smart grids context in enabling a significant amount of distributed energy resources, particularly, wind and solar type DGs, ESSs and reactive power sources.

The optimization problem is based on a linearized AC network model, and minimizes the sum of the most relevant cost terms subject to a number of technical and economic constraints. In a dynamic operation framework, the proposed model delivers multiple optimal topologies of the existing network system that fits well with the system's varying hourly operational conditions.

Numerical results generally show that DNR can lead to significantly reduced costs and losses in the considered system. Both cases considered in the analysis which involve network reconfiguration (Cases C and D) registered a drop in the total active and reactive power losses, while Case D achieve also to reduce overall costs by 34€ per day (about 2%), when compared with similar cases without DNR methodology, i.e. Case B.

In addition, those cases have shown a considerable improvement on system's performance resulting in better voltage stability profiles with maximum average values of less than 1.5%. Furthermore, another benefit of DNR is the flexibility enhancement.

Dynamically changing the topology of the grid enables to better manage the variability of RESs, which is highly desirable to integrate and efficiently utilize a large quantity of intermittent DG power at distribution levels, while helping policies to promote the integration of more renewable power capacities. In fact, in Case D, the utilization level of local power productions has increased by 8% more than in Case B. Another important point is that, when ESSs are integrated to the system, the frequency of switching operations has decreased due to more solutions to supply the demand.

The proposed methodology has revealed to be particularly interesting and an efficient solution to this case study, allowing to achieve good results in cases where distribution systems are considering dynamic reconfiguration.

5.2 – Future Works

Some of the possible future works are:

- The application of this methodology to a real-life network system;
- The application of this methodology considering newer and more realistic demand scenarios e.g. without assuming demand scenarios as uniform throughout the system. Each consumer should be independent of the others;
- The analysis of sensitivity cases can be further extended by changing the same parameters with bigger gaps between their values, or even try to change different parameters, for instance, operation cost of DGs, switching cost, etc.

5.3 - Works Resulting from this Thesis

This thesis has resulted in one IEEE conference paper that has already been presented at the 17th IEEE International Conference on Environment and Electrical Engineering — EEEIC 2017 (technically co-sponsored by IEEE), Milan, 6-9 June 2017. This paper can be found in Appendix C. A scaled up version of this paper is also a work in progress to be submitted for a journal publication.

F.V. Dantas, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "Dynamic reconfiguration of distribution network systems: a key flexibility option for RES integration", in: Proceedings of the 17th IEEE International Conference on Environment and Electrical Engineering — EEEIC 2017, Milan, Italy, 6-9 June, 2017.

Appendices

54 Appendix’s

Appendix A

SOS2-Piecewise Linearization

In this work, was selected an appropriate linearization model in order to integrate the calculation of the OPF (optimal power flow) in distribution systems. The model approach based on the use of Special Ordered Sets of type 2 (*SOS2*) (presented in [89]) was selected due to its great accuracy in estimated losses and not big computational complexity.

Defined as a piecewise linear function, it is usually modeled by introducing a set of positive variables $Z\_P_l^{pt}$, where $pt \in (0, 1, \dots, 5)$, that will form an *SOS2*. It should be noted that *pt* represents the intersection points where the linear approximation will meet the quadratic function. The $Z\_P_l^{pt}$ variable will act as a weight associated to the points with the purpose to force at the most of two consecutive variables among them to have non-zero values, as it is shown in equation A.1.

Each flow partition is calculated by the product of the number of each partition *(pt)* and the line capacity ($LineCap$ = 6.986 MW) divided by the total intersection points considered, in order to obtain equally spaced intersection points. In equation A.2, the absolute power flow in a line is expressed as the sum of the products of the $Z\_P_l^{pt}$ variables and the flow values at the partitions. This equation guarantees that values of the power flow correspond to a point in one of the linear segments between two consecutive intersection points. Also, the quadratic power flow can be expressed as in equation A.3 in a similar form as in equation A.2. The reactive power flow and the quadratic reactive flow can be calculated in a similar way as equations A.2 and A.3.

$$\sum_{pt=0}^{PT} Z\_P_l^{pt} = 1 \tag{A.1}$$

$$P_{l,s,h} = \sum_{pt=0}^{PT} Z\_P_l^{pt} * \left(\frac{LineCap}{5} * pt\right) \tag{A.2}$$

$$P_{l,s,h}^2 = \sum_{pt=0}^{PT} Z\_P_l^{pt} * \left(\frac{LineCap}{5} * pt\right)^2 \tag{A.3}$$

Appendix B

Appendix B.1 - Test System: IEEE 41 Bus Distribution System

Table B.1 — IEEE 41 Bus Distribution System Data.

Lines	FROM	TO	R [Ω]	X [Ω]	Node	Active Power [kW]	Reactive Power [kVAr]
1	1	2	0.0992	0.0470	2	100	60
2	2	3	0.4930	0.2511	3	90	40
3	3	4	0.3660	0.1864	4	120	80
4	4	5	0.3811	0.1941	5	60	30
5	5	6	0.8190	0.7070	6	60	20
6	6	7	0.1872	0.6188	7	200	100
7	7	8	0.7114	0.2351	8	200	100
8	8	9	1.0300	0.7400	9	60	20
9	9	10	1.0440	0.7400	10	60	20
10	10	11	0.1966	0.0650	11	45	30
11	11	12	0.3744	0.1238	12	60	35
12	12	13	1.4680	1.1550	13	60	35
13	13	14	0.5416	0.7129	14	120	80
14	14	15	0.5910	0.5260	15	60	10
15	15	16	0.7463	0.5450	16	60	20
16	16	17	1.2890	1.7210	17	60	20
17	17	18	0.7320	0.5470	18	90	40
18	2	19	0.1640	0.1565	19	90	40
19	19	20	1.5042	1.3554	20	90	40
20	20	21	0.4095	0.4784	21	90	40
21	21	22	0.7089	0.9373	22	90	40
22	3	23	0.4512	0.3083	23	90	50
23	23	24	0.8980	0.7091	24	420	200

(Continuation of the previous table)

Lines	FROM	TO	R [Ω]	X [Ω]	Node	Active Power [kW]	Reactive Power [kVAr]
24	24	25	0.8960	0.7011	25	420	200
25	6	26	0.2030	0.1034	26	60	25
26	26	27	0.2842	0.1447	27	60	25
27	27	28	1.0590	0.9337	28	60	20
28	28	29	0.8042	0.7006	29	120	70
29	29	30	0.5075	0.2585	30	200	600
30	30	31	0.9744	0.9630	31	150	70
31	31	32	0.3105	0.3619	32	210	100
32	32	33	0.3410	0.5302	33	60	40
33	10	34	0.2030	0.1034	34	60	25
34	34	35	0.2842	0.1447	35	60	25
35	35	36	1.0590	0.9337	36	60	20
36	36	37	0.8042	0.7006	37	120	70
37	37	38	0.5075	0.2585	38	200	600
38	38	39	0.9744	0.9630	39	150	70
39	39	40	0.3105	0.3619	40	210	100
40	40	41	0.3410	0.5302	41	60	40

Appendix B.2 - Installed capacity of DGs and their placement.

Table B.2 — Installed capacity of DGs and their placement.

DG type	Node	Installed Power [MW]
PV	32	1
PV	38	1
Wind	7	1
Wind	14	2
Wind	29	1
Wind	32	1
Wind	38	1
Wind	39	1
	Total MW	9

Appendix B.3 - Installed capacity of ESSs and their placement

Table B.3 — Installed capacity of ESSs and their placement

Node	Installed Power [MW]
14	2
30	1
32	1
40	1
Total MW	5

Appendix B.4 - Installed capacity of SCBs and their placement

Table B.4 — Installed capacity of SCBs and their placement

Node	Installed Power [MVar]
7	0.9
14	1.3
24	0.1
25	0.3
29	0.3
30	1
31	0.2
32	0.5
37	0.1
38	2
39	0.1
40	0.6
Total MVar	7.4

Appendix C

Publications

F.V. Dantas, D.Z. Fitiwi, S.F. Santos, J.P.S. Catalão, "Dynamic reconfiguration of distribution network systems: a key flexibility option for RES integration", in: Proceedings of the 17th IEEE International Conference on Environment and Electrical Engineering — EEEIC 2017, Milan, Italy, 6-9 June, 2017

Dynamic Reconfiguration of Distribution Network Systems: A Key Flexibility Option for RES Integration

F.V. Dantas[1], D.Z. Fitiwi[2], S. F. Santos[2], J.P.S. Catalão[1,2,3]
INESC TEC and FEUP[1], Porto, C-MAST/UBI[2], Covilhã, INESC-ID/IST-UL Lisbon[3], Portugal
flaviovd94@gmail.com; dzf@ubi.pt; sdfsantos@gmail.com; catalao@fe.up.pt

***Abstract*—The growing trend of variable energy source integration in power systems (especially at a distribution level) is leading to an increased need for flexibility in all levels of the energy flows in such systems: the supply, the network and the demand sides. This paper focuses on a viable flexibility option that can be provided by means of a dynamic network reconfiguration (DNR), an automatic changing of line statuses in response to operational conditions in the system. The ultimate aim is to assess the impacts of such flexibility on the utilization levels of variable power sources (mainly, solar and wind) integrated at a distribution level. To perform this analysis, a stochastic mixed integer linear programming (S-MILP) operational model is developed in this work. The objective of the optimization problem is to minimize the sum of the most relevant cost terms while meeting a number of model constraints. The proposed model dynamically finds an optimal configuration of an existing network system in accordance with the system's operational conditions. The operation scale in the current work is one day, but with the possibility of an hourly reconfiguration. The standard IEEE 41-bus system is employed to test the proposed model and perform the analysis. Numerical results generally show that DNR leads to a more efficient utilization of renewable type DGs integrated in the system, reduced costs and losses, and a substantially improved system performance especially the voltage profile in the system.**

Keywords—Distributed generation; network reconfiguration; renewable energy sources; stochastic mixed integer linear programming;

I. NOMENCLATURE

A. Sets/Indices

c/Ω^c	Index/set of capacitor banks
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
$\varsigma/\Omega^\varsigma$	Index/set of substations
Ω^1/Ω^0	Set of normally closed/opened lines

B. Parameters

$E_{es,n,s,h}^{min}$, $E_{es,n,s,h}^{max}$	Energy storage limits (MWh)
ER_g^{DG}, ER_ς^{SS}	Emission rates of DGs and energy purchased, respectively (tCO_2e/MWh)
g_l, b_l, S_l^{max}	Conductance, susceptance and flow limit of line *l*, respectively (Ω^{-1}, Ω^{-1}, MVA)
OC_g	Cost of unit energy production (€$/MWh$)
pf_g, pf_{ss}	Power factor of DGs and substation
$P_{g,n}^{DG,min}$, $P_{g,n}^{DG,max}$	Power generation limits (MW)
$P_{es,n}^{ch,max}$, $P_{es,n}^{dch,max}$	Charging/discharging upper limit (MW)
$PD_{s,h}^n$, $QD_{s,h}^n$	Demand at node *n* (MW, MVAr)
$Q_{c,n,s,h}^{c,0}$	Block of capacitor bank (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)
η_{es}^{ch}, η_{es}^{dch}	Charging/discharging efficiency
λ^{CO_2}	Cost of emissions (€/tCO_2e)
λ^{es}	Variable cost of storage system (€$/MWh$)
λ_h^ς	Price of electricity purchased
μ_{es}	Scaling factor (%)
$\upsilon_{s,h}^P$, $\upsilon_{s,h}^Q$	Unserved power penalty (€$/MW$, €$/MVAr$)
ρ_s	Probability of scenario s

C. Variables

$E_{es,n,s,h}$	Reservoir level of ESS (MWh)
$I_{es,n,s,h}^{ch}$, $I_{es,n,s,h}^{dh}$	Charging/discharging binary variables
$P_{g,n,s,h}^{DG}$, $Q_{g,n,s,h}^{DG}$	DG power (MW, MVAr)
$P_{es,n,s,h}^{ch}$, $P_{es,n,s,h}^{dch}$	Charged/discharged power (MW)
$P_{\varsigma,s,h}^{SS}$, $Q_{\varsigma,s,h}^{SS}$	Imported power from grid (MW, MVAr)
$P_{n,s,h}^{NS}$, $Q_{n,s,h}^{NS}$	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)
$Q_{c,n,s,h}^c$	Reactive power injected by SCBs (MVAr)
$x_{c,n,h}$	Integer variable of capacitor banks
$x_{l,h}$	Binary switching variable of line *l*
$\Delta V_{n,s,h}$, $\Delta V_{n,s,h}$	Voltage deviation magnitude (kV)
$\theta_{l,s,h}$	Voltage angles between two nodes line *l*

D. Functions

EC^{DG}, EC^{ES}, EC^{SS}	Expected cost of energy produced by DGs, supplied by ESSs and imported (€)

978-1-5386-3917-7/17/$31.00 ©2017 IEEE

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

II. INTRODUCTION

Electrical distribution systems need to cope up with challenges induced by the increasing global concerns on environmental change and energy security among others. All this is driving the evolution of existing distribution network systems into smarter ones. Smart network systems are expected to be equipped with advanced technologies such as emerging flexibility options that can support the integration and effective utilization of non-conventional energy sources such as wind and solar. Such energy resources are particularly gaining interest globally, and their share in the final energy delivery is growing dramatically [1], [2]. This development will be further accelerated following the favorable agreement of states to curb global warming and mitigate climate change. Many policy makers across the globe are now embarking on ambitious sustainable energy production targets [3], [4].

However, increased level of variable renewable energy sources (vRESs) such as wind and solar comes with certain challenges [5] mainly due to their intermittent nature. This increases uncertainty and variability in the system, leading to technical problems and enormous difficulty in the critically important minute-by-minute balancing requirement of supply and demand. Particularly, at distribution levels, there is little room for any compromise on the stability and integrity of the system as well as the reliability and quality of power delivered to the end-users. Generally, the intermittent nature of such resources (vRESs) substantially increases the flexibility needs in the system. Flexibility in this paper should be understood as the capability of the system to balance variations in the demand and supply sides. Traditionally, this has been mostly handled by the supply side i.e. any variation in demand has been instantly balanced by generators designed for this purpose. However, this norm is nowadays changing, where flexibility options that can be provided by the supply, demand, network and/or other means are largely sought.

This paper focuses on a viable flexibility option that can be provided by means of a dynamic network reconfiguration (DNR). DNR deals with a continuous and automated change of line statuses depending on the operational conditions in the distribution system. This should generally lead to a more efficient operation of the system by maximizing the utilization level of variable energy resources (mainly, wind and solar), and minimizing their side effects such as voltage rise issues.

References [6], [7] present a detailed review of the most relevant works in the subject area of distribution network reconfiguration by mainly focusing on the methods employed to handle the resulting optimization problem, and the main objectives of carrying out such an optimization. Generally, the purpose of reconfiguration in existing studies has been mainly to minimize network losses [8], [9], [10], [11]. However, a properly (optimally) executed network reconfiguration can simultaneously meet a number of additional objectives such as improving the voltage profile and reliability in the system [12], [13], [14], [15]. In addition, a more frequent reconfiguration (which is alternatively called an intelligent reconfiguration) can substantially enhance the flexibility of existing systems, paving the way to an increased penetration and use levels of vRESs. Authors in [16] propose a joint optimization model for simultaneously planning distributed generations (DGs) and expanding the distribution network systems, embedding a reconfiguration algorithm. However, the reconfiguration task involves a yearly switching operation of distribution feeders i.e. a more frequent switching of feeders is not considered. The work in [17] also uses a static network reconfiguration for the purpose of "mitigating voltage sags and drops" in the presence of distributed energy resources (DERs).

Reference [18] develops a MILP optimization model, incorporating a static network reconfiguration in the presence of wind and energy storage, with the specific aim of reducing the impacts of outages and losses. In [19], network reconfiguration is used to achieve three objectives: minimizing DG curtailments, congestion and voltage rise issues. In a similar line, Ref. [20] investigates the impact of network reconfiguration on the integration level of DGs in distribution systems. Authors in [21] develop a reconfiguration model for increasing the penetration level of plug-in electric vehicles (PEVs) and reducing system costs.

As mentioned earlier, the vast literature in the network reconfiguration area focuses on a static switching of lines, and mainly for the purpose of minimizing network losses and/or improving reliability by balancing load and restoring supply in the event of contingencies. The DNR problem is not adequately addressed from the smart-grids perspective and under high penetration level of variable energy sources. The technological advances make it possible to carry out an hourly (or generally a more frequent) network reconfiguration. This provides a key flexibility option that can partly help to counterbalance the fluctuations in vRESs, and increase their efficient utilization. All this is widely covered in the current work.

The main contributions of this paper are the following:

- The stochastic MILP operational model for dynamic reconfiguration problem of distribution networks in the presence of variable renewable and other distributed energy resources;
- The extensive analysis made with regards to the economic and technical benefits of dynamic reconfiguration, as well as efficient utilization of intermittent power sources.

The remainder of this paper is organized as follows. Section III presents mathematical details of the developed model. Numerical results are discussed in Section IV. The last section concludes the paper.

III. MATHEMATICAL FORMULATION

A. *Objective Function*

The objective of the formulated DNR problem is to minimize the sum of relevant cost terms, namely, switching costs SWC, expected costs of operation TEC, emissions $TEmiC$ and unserved power $TENSC$ in the system as:

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

where TC refers to the total cost.

A switching cost is incurred when the status of a given line changes from 0 (open) to 1 (closed) or 1 (closed) to 0 (open). This leads to the absolute value of difference in successive switching variables. In order to linearly represent such a module, two non-negative auxiliary variables $y^{+}_{l,h}$ and $y^{-}_{l,h}$ are introduced. Thus, SWC can be expressed as a function of the sum of these variables:

$$SWC = \sum_{l\in\Omega^l}\sum_{h\in\Omega^h} SW_l * \left(y^{+}_{l,h} + y^{-}_{l,h}\right) \tag{2}$$

where

$$x_{l,h} - x_{l,h-1} = y^{+}_{l,h} - y^{-}_{l,h};\ y^{+}_{l,h} \geq 0;\ y^{-}_{l,h} \geq 0 \tag{3}$$

$$x_{l,0} = 1;\ \forall l \in \Omega^1\ and\ x_{l,0} = 0;\ \forall l \in \Omega^0 \tag{4}$$

As stated earlier, *TEC* is given by the sum of the cost of power produced by DGs, discharged from energy storage systems (ESSs) and imported from upstream as in (5).

$$TEC = EC^{DG} + EC^{ES} + EC^{SS} \tag{5}$$

where each in (5) is calculated as:

$$EC^{DG} = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{g\in\Omega^g} OC_g P^{DG}_{g,n,s,h} \tag{6}$$

$$EC^{ES} = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{es\in\Omega^{es}} \lambda^{es} P^{dch}_{es,n,s,h} \tag{7}$$

$$EC^{SS} = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{\varsigma\in\Omega^\varsigma} \lambda^{\varsigma}_{h} P^{SS}_{\varsigma,s,h} \tag{8}$$

The cost of load shedding *TENSC* is determined as:

$$TENSC = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{n\in\Omega^n} \left(\upsilon^{P}_{s,h} P^{NS}_{n,s,h} + \upsilon^{Q}_{s,h} Q^{NS}_{n,s,h}\right) \tag{9}$$

where $\upsilon^{P}_{s,h}$ and $\upsilon^{Q}_{s,h}$ are penalty terms corresponding to active and reactive power demand curtailment.

Equation (10) represents the total cost of emissions as a result of power production using DGs and imported power.

$$TEmiC = EmiC^{DG} + EmiC^{SS} \tag{10}$$

where each of the terms in (10) are determined by:

$$EmiC^{DG} = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{g\in\Omega^g}\sum_{n\in\Omega^n} \lambda^{CO_2} ER^{DG}_{g} P^{DG}_{g,n,s,h} \tag{11}$$

$$EmiC^{SS} = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\sum_{\varsigma\in\Omega^\varsigma}\sum_{n\in\Omega^n} \lambda^{CO_2} ER^{SS}_{\varsigma} P^{SS}_{\varsigma,s,h} \tag{12}$$

B. Constraints

According to Kirchhoff's law, the sum of all incoming flows to a node should be equal to the sum of all outgoing flows. This constraint applies to both active (13) and reactive (14) power flows, and should be respected all the time:

$$\begin{aligned}&\sum_{g\in\Omega^g} P^{DG}_{g,n,s,h} + \sum_{es\in\Omega^{es}}\left(P^{dch}_{es,n,s,h} - P^{ch}_{es,n,s,h}\right) + P^{SS}_{\varsigma,s,h}\\&+ P^{NS}_{n,s,h} + \sum_{in,l\in\Omega^l} P_{l,s,h} - \sum_{out,l\in\Omega^l} P_{l,s,h} = PD^{n}_{s,h}\\&+ \sum_{in,l\in\Omega^l}\frac{1}{2}PL_{l,s,h} + \sum_{out,l\in\Omega^l}\frac{1}{2}PL_{l,s,h}\ ;\forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon n;\ l\epsilon n\end{aligned} \tag{13}$$

$$\begin{aligned}&\sum_{g\in\Omega^g} Q^{DG}_{g,n,s,h} + Q^{c}_{c,n,s,h} + Q^{SS}_{\varsigma,s,h} + Q^{NS}_{n,s,h} + \sum_{in,l\in\Omega^l} Q_{l,s,h}\\&- \sum_{out,l\in\Omega^l} Q_{l,s,h} = QD^{n}_{s,h} + \sum_{in,l\in\Omega^l}\frac{1}{2}QL_{l,s,h}\\&+ \sum_{out,l\in\Omega^l}\frac{1}{2}QL_{l,s,h}\ ;\forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon n;\ l\epsilon n\end{aligned} \tag{14}$$

The well-known AC power flow equations (which are naturally complex nonlinear and non-convex functions of voltage magnitude and angles) are linearized according to [22]. The linearized active and reactive flows in a line are given by the disjunctive inequalities in (15) and (16), respectively.

$$\begin{aligned}&\left|P_{l,s,h} - \left(V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)g_k - V^2_{nom} b_k \theta_{l,s,h}\right)\right|\\&\qquad \leq MP_l\left(1 - x_{l,h}\right)\end{aligned} \tag{15}$$

$$\begin{aligned}&\left|Q_{l,s,h} - \left(-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)b_k\right.\right.\\&\qquad \left.\left. - V^2_{nom} g_k \theta_{l,s,h}\right)\right| \leq MQ_l\left(1 - x_{l,h}\right)\end{aligned} \tag{16}$$

Moreover, power flows in each line should not exceed the maximum transfer capacity, which is enforced by:

$$P^2_{l,s,h} + Q^2_{l,s,h} \leq x_{l,h}\left(S^{max}_{l}\right)^2 \tag{17}$$

The following constraints are related to the active (18) and reactive (19) power losses in a line *l*.

$$PL_{l,s,h} = R_l\left(P^2_{l,s,h} + Q^2_{l,s,h}\right) / V^2_{nom} \tag{18}$$

$$QL_{l,s,h} = X_l\left(P^2_{l,s,h} + Q^2_{l,s,h}\right) / V^2_{nom} \tag{19}$$

Note that the quadratic flows in (17)—(19) are linearized using an SOS2 approach, presented in [23].

Constraints (20)—(25) represent the energy storage model employed in this work. The amount of power charged and discharged are limited as in (20) and (21). Constraint (22) ensures charging and discharging operations do not happen at the same time. The state of charge constraint is given by (23). The storage level should always be within the permissible range (24). Equation (25) sets the initial storage level, and makes sure the storage level at the end of the time span is equal to the initial level. For sake of simplicity, both η^{dch}_{es} and η^{ch}_{es} are often set equal.

$$0 \leq P^{ch}_{es,n,s,h} \leq I^{ch}_{es,n,s,h} P^{ch,max}_{es,nh} \tag{20}$$

$$0 \leq P^{dch}_{es,n,s,h} \leq I^{dch}_{es,n,s,h} P^{ch,max}_{es,n} \tag{21}$$

$$I^{ch}_{es,n,s,h} + I^{dch}_{es,n,s,h} \leq 1 \tag{22}$$

$$E_{es,n,s,h} = E_{es,n,s,h-1} + \eta^{ch}_{es} P^{ch}_{es,n,s,h} - P^{dch}_{es,n,s,h} / \eta^{dch}_{es} \tag{23}$$

$$E^{min}_{es,n} \leq E_{es,n,s,h} \leq E^{max}_{es,n} \tag{24}$$

$$E_{es,n,s,h0} = \mu_{es} E_{es,n}^{max}; \;\; E_{es,n,s,h24} = \mu_{es} E_{es,n}^{max} \tag{25}$$

Equations (26) and (27) impose the active and reactive power limits of DGs, respectively.

$$P_{g,n,s,h}^{DG,min} \leq P_{g,n,s,h}^{DG} \leq P_{g,n,s,h}^{DG,max} \tag{26}$$

$$-\tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG} \leq \tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \tag{27}$$

The reactive power supplied by switchable capacitor banks (SCBs) is limited by inequality (28):

$$0 \leq Q_{c,n,s,h}^{c} \leq Q_{c,n,s,h}^{c,0} x_{c,n,h} \tag{28}$$

For stability reasons, the reactive power at the substation is subject to bounds as:

$$-\tan\left(cos^{-1}(pf_{ss})\right) P_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS} \leq \tan\left(cos^{-1}(pf_{ss})\right) P_{\varsigma,s,h}^{SS}. \tag{29}$$

In addition, distribution networks are normally operated in a radial configuration. Hence, in addition to the aforementioned ones, the radiality constraints in [16] are being used in this paper. Furthermore, it should be noted that, in (15) and (16), the angle difference $\theta_{l,s,h}$ is defined as $\theta_{l,s,h} = \theta_{n,s,h} - \theta_{m,s,h}$ where n and m correspond to the same line l.

IV. NUMERICAL RESULTS AND DISCUSSIONS

A. *Data and Assumptions*

A standard IEEE 41-bus test system, shown in Fig. 1, is employed to test the proposed operational model, and perform the technical and economic analysis of DNR. Details of this test system and further information can be found in [24]. The system has optimally placed distributed energy resources such as wind and solar type DGs, ESSs and SCBs in [24]. The only exception is at bus 14, where instead of the optimal DG size (3 MW) reported in [24], a 2 MW DG is considered throughout this analysis. Fig. 1 shows the locations of the DGs and ESSs. A 24-hour period is considered, with the possibility of an hourly configuration. The range of permissible voltage deviation at each node is ±5% of the nominal value (which, in this case, is 12.66 kV). The substation is the reference node, whose voltage magnitude and angle are set equal to the nominal value and 0, respectively. Further input data considered in this paper are as follows. Both charging and discharging efficiency of ESSs is 90%. The power factor of the substation is set constant at 0.8 while the power factor of all DG types is considered to be 0.95. Electricity prices are assumed to follow the same trend as demand, varying between 108 $€/MWh$ during peak and 30 $€/MWh$ during shallow hours. The emission rate at the substation is assumed to be 0.4 tCO_2e/MWh, and the emission rates of solar and wind type DGs are set to 0.0584 and 0.0276 tCO_2e/MWh, respectively. The price of emissions is considered to be 7 $€/tCO_2e$.

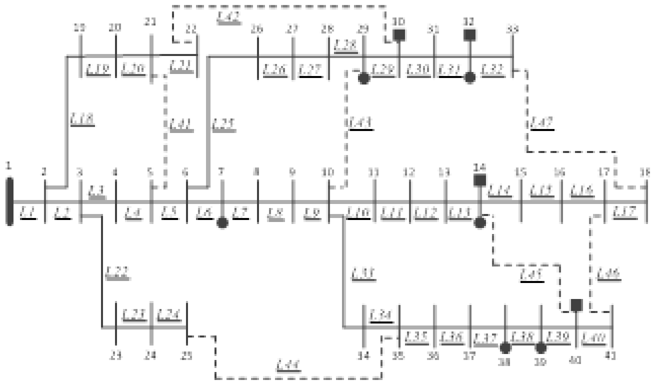

Fig. 1. IEEE 41-bus distribution system with new tie-lines (square and circle dots represent the locations of ESSs and DGs, respectively)

The tariffs of solar and wind power generation are set equal to 40 and 20 $€/MWh$, respectively. The variable cost of ESSs is considered as 5 $€/MWh$. The penalty for unserved power (active and reactive alike) is 3000 $€/MW$. In addition, the power generation profiles of solar and wind type DGs as well as the demand profiles are assumed to be uniform throughout the system. The uncertainty pertaining to demand, wind and solar power outputs are accounted for by considering three different scenarios for each uncertain parameter. It should be noted that each scenario represents an hourly profile of the uncertain parameter under consideration. The combination of the individual scenarios (which in this case are 27) form the set of scenarios finally considered for the analysis.

B. *Discussion of Numerical Results*

Four different cases (designated as Case A to D) form part and parcel of the extensive analysis carried out in this work. A summary of the different cases considered in the analysis is shown in Table I. In this table, the control parameters clearly distinguish each case. Case A represents the base case, where there is no reconfiguration and without any DER connected to the system. For this case, the lower bound of voltage is relaxed to avoid unrealistically high unserved power (reactive power, in particular). In Case B, all DERs (DGs, SCBs and ESSs) are connected, but without a dynamic reconfiguration. Case C is similar to Case B but now considering DNR. To further investigate the impacts of DNR on the system's performance and vRES utilization level, Case D is formed, which is similar to third case but excluding ESSs.

Table II compares the total cost and losses for the different cases throughout the 24-hours period. As it can be seen in this table, Case A has the highest overall cost and losses as the demand in the system is met only by importing power through the substation, which is relatively more expensive than local

TABLE I. DETAILS OF THE CONSIDERED CASES

Cases	Reconfiguration	DGs	SCBs	ESSs
A	No	No	No	No
B	No	Yes	Yes	Yes
C	Yes	Yes	Yes	Yes
D	Yes	Yes	Yes	No

TABLE II. COSTS AND AVERAGE LOSSES FOR EACH CASE

	Cases			
	A	B	C	D
TC (€)	6526.59	2179.23	2145.09	2741.83
PL (MW)	0.289	0.092	0.068	0.055
QL (MVAr)	0.214	0.075	0.056	0.044

power production using DGs. Note that the losses in Table II are average values. For example, in Case A, active power losses in some operational situations (peak hours) can reach as high as approximately 1 MW. In Case B, losses and costs are slashed each by more than 67% with respective to the values in the base case (i.e. Case A). In Case C, active power losses are further reduced by 26%, and system costs by about 2%. Note that the only difference between Case B and C is that the former does not consider reconfiguration but the latter does. Hence, the further reductions in losses and costs in Case C reveal an increased utilization of local power productions (8% more than in Case B). This is as a result of the dynamic reconfiguration considered in Case C. This is due to the fact that DNR enables the system to better manage the variability of vRESs by dynamically and optimally changing the topology that matches various operational situations in comparison to a static topology as in Case B.

The results Case D in Table II further demonstrate the positive impacts of dynamic reconfiguration. In this case, ESSs are not deliberately connected to further observe the potential of DNR in scaling up vRES utilization while managing well their imminent side effects. Compared to Cases B and C, total costs in Case D are understandably higher while network losses are surprisingly lower. Yet, the total costs and losses in Case D are substantially lower than that of the base case (by about 58% and 80%, respectively). The slight increase in costs in Case D, in comparison to Cases B and C, is rather expected because unlike in Cases B and C, this one does not have a mechanism to store excess wind or solar power which can be utilized in times of high demand and electricity prices. This obviously leads to a higher cost and a lower overall efficiency in the system. The fact that the losses are lower in Case D compared to any other case may be because of the absence of extra flows that would be required in certain lines for storing in ESS nodes.

The results of hourly switching operations corresponding to Cases C and D are summarized in Table III. Note that all other lines not shown here do not experience switching operations i.e. the statuses of those lines remain 1 throughout the day. Generally, this table shows more switching operations (in terms of frequency and number of lines "participating" in DNR) in Case D than in Case C. This reveals that, in the absence of a storage medium, the network system tries to efficiently adapt to the continuously changing operational situations, with the aim of routing the actual generation to the nodes where it is being consumed in real-time. For example, line L44 is always turned on in order to interconnect the demand nodes with the RES nodes. Dynamically switching line L45 seems to pave the way to easily store excess power productions in the ESSs connected at either side of this line. Line L42 increases the flexibility of partly meeting the demand at node 21 and its vicinity by routing local power production from the wind reach nodes 29 and 32. Generally, DNR leads to a more efficient operation of the system.

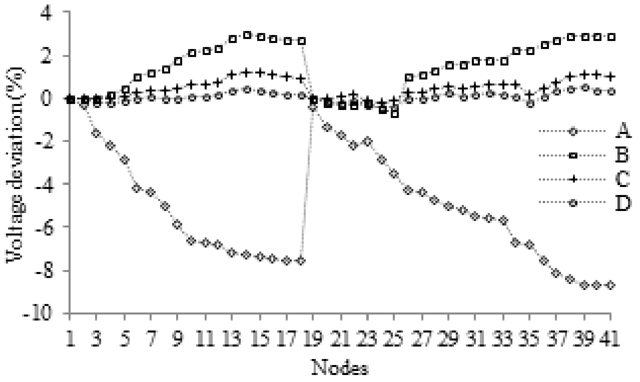

Fig. 2. Average voltage profiles in the system for different cases

TABLE III. RECONFIGURATION OUTCOME OF A TYPICAL DAY.

	Hours with $x_{l,h} = 0$	
	Case C	**Case D**
Line 20	1—3, 5—7, 9, 22—24	8—10, 13—15, 17, 18, 22—24
Line 28	none	1, 3, 4
Line 29	9—21	1—8, 9—16, 24
Line 32	none	2
Line 34	all day long off	all day long off
Line 39	8—13, 17, 18, 22—24	8—10, 18, 22—24
Line 40	none	20, 21
Line 41	4, 8, 10—21	1—7, 11—12, 16, 19, 21
Line 42	1—8, 22—24	9, 17—23
Line 43	all day long off	2, 5—24
Line 45	1—7, 14—16, 19—21	1—7, 11—17, 19—21
Line 46	all day long off	1—19, 22—24
Line 47	all day long off	1, 3—24

Fig. 2 plots the average voltage profiles in the system for all cases. Note that this figure displays only the average values; in some operational situations, in the base case, voltage deviations at the farthest nodes can be as high as 18%. The voltage profile of the base case indicates that the system is highly lossy and poorly compensated. As a result, voltages at most of the nodes exceed the technically permissible limit (5%). Furthermore, by closely studying the voltage profiles in Fig. 2, one can observe the dramatic impact of optimally placed DERs (DGs, ESSs and SCBs in this case). In addition, the positive contribution of DNR in improving voltage profile in the system is also evident in this figure by comparing the profiles corresponding to Cases B and C (see the first and the second curves from above). Compared to Case B (where a static topology is considered), Case C leads to a largely smoother voltage profile and the voltage in every node is closer to the nominal value.

Generally, the analysis here clearly shows the substantial benefits DNR can have in terms of providing more flexibility to the system, which is highly desired to integrate and efficiently utilize a large quantity of intermittent power at distribution levels. DNR enables the system to better adapt continuously changing situations, and distribute the locally produced "cleaner" power to the demand while meeting the technical requirements.

Fig. 3 presents the energy mix corresponding to Case C. This shows that more than 90% of the electricity demand in the system is met by energy that comes from wind and solar type DGs. A small quantity of electricity is imported only during valley hours (when the electricity price is low) mainly to charge the ESSs in the system and during peak hours to meet the portion of demand that could not be locally met.

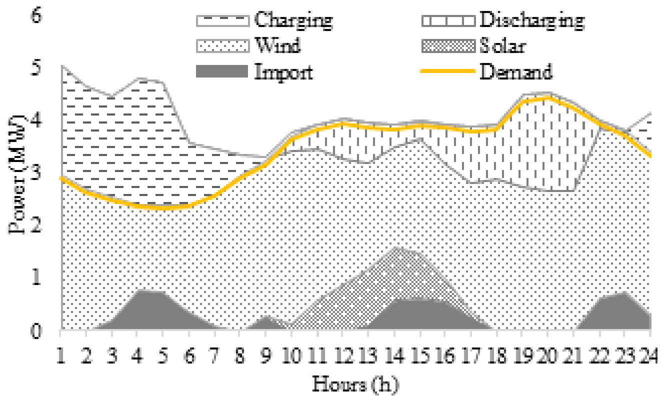

Fig. 3. Energy mix in Case C

V. CONCLUSIONS

This paper has proposed a stochastic MILP optimization model to investigate the impacts of DNR in the smart grids context featuring a significant amount of distributed energy resources, particularly, wind and solar type DGs, ESSs and reactive power sources. The optimization problem, which is based on a linearized AC network model, minimizes the sum of the most relevant cost terms subject to a number of technical and economic constraints. In a dynamic operation framework, the proposed model delivers multiple optimal topologies of the existing network system that fits well with the system's varying hourly operational conditions. Numerical results generally show that DNR leads to a more efficient utilization of renewable type DGs integrated in the system, reduced costs and losses, and a substantially improved system performance especially the voltage profile in the system.

ACKNOWLEDGMENT

This work was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

REFERENCES

[1] J. Yan, T. Shamim, S. K. Chou, U. Desideri, and H. Li, "Clean, efficient and affordable energy for a sustainable future," *Appl. Energy*, Jun. 2016.

[2] *Renewables 2015 - Global Status Report*, Renewable Energy Policy Network for the 21st Century. .

[3] A. Aslani, P. Helo, and M. Naaranoja, "Role of renewable energy policies in energy dependency in Finland: System dynamics approach," *Appl. Energy*, vol. 113, pp. 758–765, Jan. 2014.

[4] V. Krakowski, E. Assoumou, V. Mazauric, and N. Maïzi, "Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis," *Appl. Energy*, vol. 171, pp. 501–522, Jun. 2016.

[5] P. S. Georgilakis and N. D. Hatziargyriou, "Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3420–3428, Aug. 2013.

[6] O. Badran, S. Mekhilef, H. Mokhlis, and W. Dahalan, "Optimal reconfiguration of distribution system connected with distributed generations: A review of different methodologies," *Renew. Sustain. Energy Rev.*, vol. 73, pp. 854–867, Jun. 2017.

[7] B. Sultana, M. W. Mustafa, U. Sultana, and A. R. Bhatti, "Review on reliability improvement and power loss reduction in distribution system via network reconfiguration," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 297–310, Dec. 2016.

[8] D. Q. Hung and N. Mithulananthan, "Loss reduction and loadability enhancement with DG: A dual-index analytical approach," *Appl. Energy*, vol. 115, pp. 233–241, Feb. 2014.

[9] S. M. M. Larimi, M. R. Haghifam, and A. Moradkhani, "Risk-based reconfiguration of active electric distribution networks," *Transm. Distrib. IET Gener.*, vol. 10, no. 4, pp. 1006–1015, 2016.

[10] H.-C. Chang and C.-C. Kuo, "Network reconfiguration in distribution systems using simulated annealing," *Electr. Power Syst. Res.*, vol. 29, no. 3, pp. 227–238, May 1994.

[11] C.-T. Su, C.-F. Chang, and J.-P. Chiou, "Distribution network reconfiguration for loss reduction by ant colony search algorithm," *Electr. Power Syst. Res.*, vol. 75, no. 2–3, pp. 190–199, Aug. 2005.

[12] M. R. Dorostkar-Ghamsari, M. Fotuhi-Firuzabad, M. Lehtonen, and A. Safdarian, "Value of Distribution Network Reconfiguration in Presence of Renewable Energy Resources," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1879–1888, May 2016.

[13] I.-K. Song, W.-W. Jung, J.-Y. Kim, S.-Y. Yun, J.-H. Choi, and S.-J. Ahn, "Operation Schemes of Smart Distribution Networks With Distributed Energy Resources for Loss Reduction and Service Restoration," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 367–374, Mar. 2013.

[14] D. Q. Hung, N. Mithulananthan, and R. C. Bansal, "A combined practical approach for distribution system loss reduction," *Int. J. Ambient Energy*, vol. 36, no. 3, pp. 123–131, May 2015.

[15] R. Rajaram, K. Sathish Kumar, and N. Rajasekar, "Power system reconfiguration in a radial distribution network for reducing losses and to improve voltage profile using modified plant growth simulation algorithm with Distributed Generation (DG)," *Energy Rep.*, vol. 1, pp. 116–122, Nov. 2015.

[16] G. Munoz-Delgado, J. Contreras, and J. M. Arroyo, "Joint Expansion Planning of Distributed Generation and Distribution Networks," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2579–2590, Sep. 2015.

[17] A. Asrari, T. Wu, and S. Lotfifard, "The Impacts of Distributed Energy Sources on Distribution Network Reconfiguration," *IEEE Trans. Energy Convers.*, vol. 31, no. 2, pp. 606–613, Jun. 2016.

[18] P. Meneses de Quevedo, J. Contreras, M. J. Rider, and J. Allahdadian, "Contingency Assessment and Network Reconfiguration in Distribution Grids Including Wind Power and Energy Storage," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1524–1533, Oct. 2015.

[19] N. C. Koutsoukis, D. O. Siagkas, P. S. Georgilakis, and N. D. Hatziargyriou, "Online Reconfiguration of Active Distribution Networks for Maximum Integration of Distributed Generation," *IEEE Trans. Autom. Sci. Eng.*, vol. PP, no. 99, pp. 1–12, 2016.

[20] F. Capitanescu, L. F. Ochoa, H. Margossian, and N. D. Hatziargyriou, "Assessing the Potential of Network Reconfiguration to Improve Distributed Generation Hosting Capacity in Active Distribution Systems," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 346–356, Jan. 2015.

[21] A. Kavousi-Fard, A. Abbasi, M.-A. Rostami, and A. Khosravi, "Optimal distribution feeder reconfiguration for increasing the penetration of plug-in electric vehicles and minimizing network costs," *Energy*, vol. 93, Part 2, pp. 1693–1703, Dec. 2015.

[22] S. F. Santos, D. Z. Fitiwi, M. Shafie-Khah, A. W. Bizuayehu, C. M. P. Cabrita, and J. P. S. Catalão, "New Multistage and Stochastic Mathematical Model for Maximizing RES Hosting Capacity - Part I: Problem Formulation," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 304–319, Jan. 2017.

[23] D. Z. Fitiwi, L. Olmos, M. Rivier, F. de Cuadra, and I. J. Pérez-Arriaga, "Finding a representative network losses model for large-scale transmission expansion planning with renewable energy sources," *Energy*, vol. 101, pp. 343–358, Apr. 2016.

[24] S. F. Santos, D. Z. Fitiwi, M. Shafie-khah, A. W. Bizuayehu, C. M. P. Cabrita, and J. P. S. Catalão, "New Multi-Stage and Stochastic Mathematical Model for Maximizing RES Hosting Capacity - Part II: Numerical Results," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 320–330, Jan. 2017.

Bibliography

[1] FS UNEP Centre, "Global Trends in Renewable Energy Investment 2016." [Online]. Available: http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2016. [Accessed: 02-Jun-2017].

[2] "Department of Energy." [Online]. Available: https://energy.gov/. [Accessed: 15-Jun-2017].

[3] U.S. Department of Energy, "Maintaining Reliability in the Modern Power System.pdf." [Online]. Available: https://www.energy.gov/sites/prod/files/2017/01/f34/Maintaining%20Reliability%20in%20the%20Modern%20Power%20System.pdf. [Accessed: 25-May-2017].

[4] "Annual Energy Outlook 2017 with projections to 2050 - 0383(2017).pdf." [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf. [Accessed: 24-May-2017].

[5] European Commission, "2020 climate & energy package," *Climate Action - European Commission*, 23-Nov-2016. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en. [Accessed: 25-May-2017].

[6] European Commission, "2030 Energy Strategy - Energy," *Energy*. [Online]. Available: /energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy. [Accessed: 25-May-2017].

[7] IEO2016, "World energy demand and economic outlook." [Online]. Available: https://www.eia.gov/outlooks/ieo/pdf/world.pdf. [Accessed: 30-May-2017].

[8] European Commission, "Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources.pdf." [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf. [Accessed: 24-May-2017].

[9] V. H. Méndez *et al.*, "Impact of distributed generation on distribution investment deferral," *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 4, pp. 244–252, maio 2006.

[10] M. L. Tuballa and M. L. Abundo, "A review of the development of Smart Grid technologies," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 710–725, Jun. 2016.

[11] "The Smart Grid: An Introduction." [Online]. Available: https://www.smartgrid.gov/document/smart_grid_introduction.html. [Accessed: 27-Apr-2017].

[12] "'GRID 2030' A NATIONAL VISION FOR ELECTRICITY'S SECOND 100 YEARS | Department of Energy." [Online]. Available: https://energy.gov/oe/downloads/grid-2030-national-vision-electricity-s-second-100-years. [Accessed: 27-Apr-2017].

[13] "Flexibility in 21st Century Power Systems - 61721.pdf." [Online]. Available: http://www.nrel.gov/docs/fy14osti/61721.pdf. [Accessed: 23-May-2017].

[14] "20130703 RES-E-NEXT: Next Generation of RES-E Policy Instruments_2013.pdf." [Online]. Available: http://iea-retd.org/wp-content/uploads/2013/07/RES-E-NEXT_IEA-RETD_2013.pdf. [Accessed: 23-May-2017].

[15] "Renewable energy sources and climate change mitigation: summary for policymakers and technical summary, special report of the intergovernmental panel on climate change. Published for the intergovernmental panel on climate change." [Online]. Available: https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf. [Accessed: 24-May-2017].

[16] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1513–1524, abril 2011.

[17] A. Colmenar-Santos, C. Reino-Rio, D. Borge-Diez, and E. Collado-Fernández, "Distributed generation: A review of factors that can contribute most to achieve a scenario of DG units embedded in the new distribution networks," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1130–1148, Jun. 2016.

[18] P. Paliwal, N. P. Patidar, and R. K. Nema, "Planning of grid integrated distributed generators: A review of technology, objectives and techniques," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 557–570, dezembro 2014.

[19] IEA, *Distributed Generation in Liberalised Electricity Markets*. Paris: Organisation for Economic Co-operation and Development, 2002.

[20] C. L. T. Borges, "An overview of reliability models and methods for distribution systems with renewable energy distributed generation," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 4008–4015, agosto 2012.

[21] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 569–596, fevereiro 2015.

[22] P. Denholm, J. C. King, C. F. Kutcher, and P. P. H. Wilson, "Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage," *Energy Policy*, vol. 44, pp. 301–311, maio 2012.

[23] "Electric utility transmission and distribution upgrade deferral benefits from modular electricity storage.pdf." [Online]. Available: http://prod.sandia.gov/techlib/access-control.cgi/2009/094070.pdf. [Accessed: 17-May-2017].

[24] M. Welsch, M. Howells, M. Bazilian, J. F. DeCarolis, S. Hermann, and H. H. Rogner, “Modelling elements of Smart Grids – Enhancing the OSeMOSYS (Open Source Energy Modelling System) code,” *Energy*, vol. 46, no. 1, pp. 337–350, outubro 2012.

[25] B. Sultana, M. W. Mustafa, U. Sultana, and A. R. Bhatti, “Review on reliability improvement and power loss reduction in distribution system via network reconfiguration,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 297–310, dezembro 2016.

[26] R. E. Brown, “Impact of Smart Grid on distribution system design,” in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1–4.

[27] G. A. Pagani and M. Aiello, “From the grid to the smart grid, topologically,” *Phys. Stat. Mech. Its Appl.*, vol. 449, pp. 160–175, maio 2016.

[28] J. A. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, “Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities,” *Electr. Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, Jul. 2007.

[29] A. Keane *et al.*, “State-of-the-Art Techniques and Challenges Ahead for Distributed Generation Planning and Optimization,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1493–1502, maio 2013.

[30] I. Konstantelos, S. Giannelos, and G. Strbac, “Strategic Valuation of Smart Grid Technology Options in Distribution Networks,” *IEEE Trans. Power Syst.*, vol. PP, no. 99, pp. 1–1, 2016.

[31] F. Capitanescu and I. Bilibin, “A tractable two-step MILP–QCP approach to on-line thermal constraint management in large radial active distribution systems,” *Electr. Power Syst. Res.*, vol. 140, pp. 580–587, Nov. 2016.

[32] A. Elmitwally, M. Elsaid, M. Elgamal, and Z. Chen, “A Fuzzy-Multiagent Self-Healing Scheme for a Distribution System With Distributed Generations,” *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2612–2622, Sep. 2015.

[33] T. T. H. Pham, Y. Besanger, N. Hadjsaid, and D. L. Ha, “Optimizing the re-energizing of distribution systems using the full potential of dispersed generation,” in *2006 IEEE Power Engineering Society General Meeting*, 2006, p. 8 pp.-.

[34] T. Thakur and Jaswanti, “Study and Characterization of Power Distribution Network Reconfiguration,” in *2006 IEEE/PES Transmission Distribution Conference and Exposition: Latin America*, 2006, pp. 1–6.

[35] W. A. Vasquez and F. L. Quilumba, “Load flow method for radial distribution systems with distributed generation using a dynamic data matrix,” in *2016 IEEE Ecuador Technical Chapters Meeting (ETCM)*, 2016, vol. 01, pp. 1–5.

[36] F. Guo *et al.*, “Comprehensive Real-Time Simulation of the Smart Grid,” *IEEE Trans. Ind. Appl.*, vol. 49, no. 2, pp. 899–908, Mar. 2013.

[37] C. Cecati, C. Citro, and P. Siano, “Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid,” *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 468–476, outubro 2011.

[38] J. Soares, M. Silva, T. Sousa, Z. Vale, and H. Morais, “Distributed energy resource short-term scheduling using Signaled Particle Swarm Optimization,” *Energy*, vol. 42, no. 1, pp. 466–476, Jun. 2012.

[39] J. Yan, T. Shamim, S. K. Chou, U. Desideri, and H. Li, “Clean, efficient and affordable energy for a sustainable future,” *Appl. Energy*, Jun. 2016.

[40] *Renewables 2015 - Global Status Report*, Renewable Energy Policy Network for the 21st Century. .

[41] A. Aslani, P. Helo, and M. Naaranoja, “Role of renewable energy policies in energy dependency in Finland: System dynamics approach,” *Appl. Energy*, vol. 113, pp. 758–765, Jan. 2014.

[42] V. Krakowski, E. Assoumou, V. Mazauric, and N. Maïzi, “Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis,” *Appl. Energy*, vol. 171, pp. 501–522, Jun. 2016.

[43] A. Verbruggen *et al.*, “Renewable energy costs, potentials, barriers: Conceptual issues,” *Energy Policy*, vol. 38, no. 2, pp. 850–861, fevereiro 2010.

[44] P. S. Georgilakis and N. D. Hatziargyriou, “Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3420–3428, Aug. 2013.

[45] M. Korpaas, A. T. Holen, and R. Hildrum, “Operation and sizing of energy storage for wind power plants in a market system,” *Int. J. Electr. Power Energy Syst.*, vol. 25, no. 8, pp. 599–606, outubro 2003.

[46] D. A. Halamay, T. K. A. Brekken, A. Simmons, and S. McArthur, “Reserve requirement impacts of large-scale integration of wind, solar, and ocean wave power generation,” in *IEEE PES General Meeting*, 2010, pp. 1–7.

[47] A. K. Srivastava, A. A. Kumar, and N. N. Schulz, “Impact of Distributed Generations With Energy Storage Devices on the Electric Grid,” *IEEE Syst. J.*, vol. 6, no. 1, pp. 110–117, Mar. 2012.

[48] P. M. de Quevedo, J. Allahdadian, J. Contreras, and G. Chicco, “Islanding in distribution systems considering wind power and storage,” *Sustain. Energy Grids Netw.*, vol. 5, pp. 156–166, Mar. 2016.

[49] P. Finn and C. Fitzpatrick, “Demand side management of industrial electricity consumption: Promoting the use of renewable energy through real-time pricing,” *Appl. Energy*, vol. 113, pp. 11–21, Jan. 2014.

[50] Y. Pradeep, P. Seshuraju, S. A. Khaparde, and R. K. Joshi, “Flexible open architecture design for power system control centers,” *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 4, pp. 976–982, maio 2011.

[51] E. Haesen, A. D. Alarcon-Rodriguez, J. Driesen, R. Belmans, and G. Ault, “Opportunities for active DER management in deferral of distribution system reinforcements,” in *2009 IEEE/PES Power Systems Conference and Exposition*, 2009, pp. 1–8.

[52] F. Pilo, G. Pisano, and G. G. Soma, “Optimal Coordination of Energy Resources With a Two-Stage Online Active Management,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4526–4537, outubro 2011.

[53] O. Badran, S. Mekhilef, H. Mokhlis, and W. Dahalan, “Optimal reconfiguration of distribution system connected with distributed generations: A review of different methodologies,” *Renew. Sustain. Energy Rev.*, vol. 73, pp. 854–867, Jun. 2017.

[54] D. Q. Hung and N. Mithulananthan, “Loss reduction and loadability enhancement with DG: A dual-index analytical approach,” *Appl. Energy*, vol. 115, pp. 233–241, fevereiro 2014.

[55] S. M. M. Larimi, M. R. Haghifam, and A. Moradkhani, “Risk-based reconfiguration of active electric distribution networks,” *Transm. Distrib. IET Gener.*, vol. 10, no. 4, pp. 1006–1015, 2016.

[56] H.-C. Chang and C.-C. Kuo, “Network reconfiguration in distribution systems using simulated annealing,” *Electr. Power Syst. Res.*, vol. 29, no. 3, pp. 227–238, maio 1994.

[57] C.-T. Su, C.-F. Chang, and J.-P. Chiou, “Distribution network reconfiguration for loss reduction by ant colony search algorithm,” *Electr. Power Syst. Res.*, vol. 75, no. 2–3, pp. 190–199, agosto 2005.

[58] M. R. Dorostkar-Ghamsari, M. Fotuhi-Firuzabad, M. Lehtonen, and A. Safdarian, “Value of Distribution Network Reconfiguration in Presence of Renewable Energy Resources,” *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1879–1888, maio 2016.

[59] I. K. Song, W. W. Jung, J. Y. Kim, S. Y. Yun, J. H. Choi, and S. J. Ahn, “Operation Schemes of Smart Distribution Networks With Distributed Energy Resources for Loss Reduction and Service Restoration,” *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 367–374, Mar. 2013.

[60] D. Q. Hung, N. Mithulananthan, and R. C. Bansal, “A combined practical approach for distribution system loss reduction,” *Int. J. Ambient Energy*, vol. 36, no. 3, pp. 123–131, maio 2015.

[61] R. Rajaram, K. Sathish Kumar, and N. Rajasekar, “Power system reconfiguration in a radial distribution network for reducing losses and to improve voltage profile using modified plant growth simulation algorithm with Distributed Generation (DG),” *Energy Rep.*, vol. 1, pp. 116–122, Nov. 2015.

[62] N. G. Paterakis, S. F. Santos, J. P. S. Catalão, A. G. Bakirtzis, and G. Chicco, “Multi-objective optimization of radial distribution networks using an effective implementation

of the #x03B5;-constraint method," in *2014 Australasian Universities Power Engineering Conference (AUPEC)*, 2014, pp. 1–6.

[63] N. G. Paterakis *et al.*, "Multi-objective reconfiguration of radial distribution systems using reliability indices," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T D)*, 2016, pp. 1–1.

[64] C. Lueken, P. M. S. Carvalho, and J. Apt, "Distribution grid reconfiguration reduces power losses and helps integrate renewables," *Energy Policy*, vol. 48, pp. 260–273, setembro 2012.

[65] F. Capitanescu, L. F. Ochoa, H. Margossian, and N. D. Hatziargyriou, "Assessing the Potential of Network Reconfiguration to Improve Distributed Generation Hosting Capacity in Active Distribution Systems," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 346–356, Jan. 2015.

[66] G. Munoz-Delgado, J. Contreras, and J. M. Arroyo, "Joint Expansion Planning of Distributed Generation and Distribution Networks," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2579–2590, Sep. 2015.

[67] A. Asrari, T. Wu, and S. Lotfifard, "The Impacts of Distributed Energy Sources on Distribution Network Reconfiguration," *IEEE Trans. Energy Convers.*, vol. 31, no. 2, pp. 606–613, Jun. 2016.

[68] A. Elmitwally, M. Elsaid, M. Elgamal, and Z. Chen, "A Fuzzy-Multiagent Service Restoration Scheme for Distribution System With Distributed Generation," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 810–821, Jul. 2015.

[69] J. j Wang, L. Lu, J. Y. Liu, and S. Zhong, "Reconfiguration of Distribution Network with Dispersed Generators Based on Improved Forward-Backward Sweep Method," in *2010 Asia-Pacific Power and Energy Engineering Conference*, 2010, pp. 1–5.

[70] A. Borghetti, "A Mixed-Integer Linear Programming Approach for the Computation of the Minimum-Losses Radial Configuration of Electrical Distribution Networks," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1264–1273, agosto 2012.

[71] R. S. Ferreira, C. L. T. Borges, and M. V. F. Pereira, "A Flexible Mixed-Integer Linear Programming Approach to the AC Optimal Power Flow in Distribution Systems," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2447–2459, Sep. 2014.

[72] M. Lavorato, J. F. Franco, M. J. Rider, and R. Romero, "Imposing Radiality Constraints in Distribution System Optimization Problems," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 172–180, fevereiro 2012.

[73] R. A. Jabr, R. Singh, and B. C. Pal, "Minimum Loss Network Reconfiguration Using Mixed-Integer Convex Programming," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 1106–1115, maio 2012.

[74] J. A. Taylor and F. S. Hover, "Convex Models of Distribution System Reconfiguration," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1407–1413, agosto 2012.

[75] I. Bilibin and F. Capitanescu, “Contributions to thermal constraints management in radial active distribution systems,” *Electr. Power Syst. Res.*, vol. 111, pp. 169–176, Jun. 2014.

[76] E. Romero-Ramos, J. Riquelme-Santos, and J. Reyes, “A simpler and exact mathematical model for the computation of the minimal power losses tree,” *Electr. Power Syst. Res.*, vol. 80, no. 5, pp. 562–571, maio 2010.

[77] J. F. Franco, M. J. Rider, and R. Romero, “A mixed-integer quadratically-constrained programming model for the distribution system expansion planning,” *Int. J. Electr. Power Energy Syst.*, vol. 62, pp. 265–272, Nov. 2014.

[78] E. Lopez, H. Opazo, L. Garcia, and P. Bastard, “Online reconfiguration considering variability demand: applications to real networks,” *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 549–553, fevereiro 2004.

[79] D. P. Bernardon, A. P. C. Mello, L. L. Pfitscher, L. N. Canha, A. R. Abaide, and A. A. B. Ferreira, “Real-time reconfiguration of distribution network with distributed generation,” *Electr. Power Syst. Res.*, vol. 107, pp. 59–67, fevereiro 2014.

[80] A. S. Bouhouras, T. A. Papadopoulos, G. C. Christoforidis, G. K. Papagiannis, and D. P. Labridis, “Loss reduction via network reconfigurations in Distribution Networks with Photovoltaic Units Installed,” in *2013 10th International Conference on the European Energy Market (EEM)*, 2013, pp. 1–8.

[81] P. M. de Quevedo, J. Contreras, M. J. Rider, and J. Allahdadian, “Contingency Assessment and Network Reconfiguration in Distribution Grids Including Wind Power and Energy Storage,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1524–1533, outubro 2015.

[82] N. C. Koutsoukis, D. O. Siagkas, P. S. Georgilakis, and N. D. Hatziargyriou, “Online Reconfiguration of Active Distribution Networks for Maximum Integration of Distributed Generation,” *IEEE Trans. Autom. Sci. Eng.*, vol. 14, no. 2, pp. 437–448, Apr. 2017.

[83] A. Kavousi-Fard, A. Abbasi, M.-A. Rostami, and A. Khosravi, “Optimal distribution feeder reconfiguration for increasing the penetration of plug-in electric vehicles and minimizing network costs,” *Energy*, vol. 93, Part 2, pp. 1693–1703, dezembro 2015.

[84] A. Ameli, A. Ahmadifar, M.-H. Shariatkhah, M. Vakilian, and M.-R. Haghifam, “A dynamic method for feeder reconfiguration and capacitor switching in smart distribution systems,” *Int. J. Electr. Power Energy Syst.*, vol. 85, pp. 200–211, fevereiro 2017.

[85] X. Meng, L. Zhang, P. Cong, W. Tang, X. Zhang, and D. Yang, “Dynamic reconfiguration of distribution network considering scheduling of DG active power outputs,” in *2014 International Conference on Power System Technology*, 2014, pp. 1433–1439.

[86] S. F. Santos, D. Z. Fitiwi, M. R. M. Cruz, C. M. P. Cabrita, and J. P. S. Catalão, “Impacts of optimal energy storage deployment and network reconfiguration on renewable

integration level in distribution systems,” *Appl. Energy*, vol. 185, Part 1, pp. 44–55, Jan. 2017.

[87] A. W. Bizuayehu, A. A. S. de la Nieta, J. P. S. Catalão, P. M. de Quevedo, and J. Contreras, “Distribution system reconfiguration in economic dispatch with high wind penetration,” in *2015 IEEE Power Energy Society General Meeting*, 2015, pp. 1–5.

[88] S. F. Santos, D. Z. Fitiwi, M. Shafie-Khah, A. W. Bizuayehu, C. M. P. Cabrita, and J. P. S. Catalão, “New Multistage and Stochastic Mathematical Model for Maximizing RES Hosting Capacity #8212;Part I: Problem Formulation,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 304–319, Jan. 2017.

[89] D. Z. Fitiwi, L. Olmos, M. Rivier, F. de Cuadra, and I. J. Pérez-Arriaga, “Finding a representative network losses model for large-scale transmission expansion planning with renewable energy sources,” *Energy*, vol. 101, pp. 343–358, abril 2016.

[90] S. F. Santos, D. Z. Fitiwi, M. Shafie-khah, A. W. Bizuayehu, C. M. P. Cabrita, and J. P. S. Catalão, “New Multi-Stage and Stochastic Mathematical Model for Maximizing RES Hosting Capacity #x2014;Part II: Numerical Results,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 320–330, Jan. 2017.

[91] S. F. Santos *et al.*, “Novel Multi-Stage Stochastic DG Investment Planning with Recourse,” *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 164–178, Jan. 2017.

[92] The World Data Center for Remote Sensing of the Atmosphere, “SOLEMI database for long-term global and direct irradiance at WDC-RSAT,” 2006. [Online]. Available: https://wdc.dlr.de/data_products/SERVICES/SOLARENERGY/description.php. [Accessed: 08-Jun-2017].

[93] The SoDa Service, “Solar Radiation Data,” 2012. [Online]. Available: http://www.soda-is.com/eng/services/services_radiation_free_eng.php#top. [Accessed: 08-Jun-2017].