UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Renewable Energy Sources Integration in Smart Grids

Diploma Thesis

Gkivalos Sokratis-Konstantinos

Supervisor: Bargiotas Dimitrios

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

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Ενσωμάτωση Ανανεώσιμων Πηγών Ενέργειας στα Ευφυή Δίκτυα

Διπλωματική Εργασία

Γκίβαλος Σωκράτης-Κωνσταντίνος

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Diploma Thesis

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Abstract

Electricity is the most widespread form of energy today, with its consumption in the European Union (EU) growing annually at rates of between 2% and 4%. The need for a shift to more economically and environmentally sustainable energy sources solutions in terms of electricity generation is undeniable in today's world. The existing grid uses non-renewable and polluting resources. In particular, in 2019, 43.6% of the energy produced in the EU came from fossil fuels, while in 2020, for the first time ever, the energy produced from renewable energy sources (38%) exceeded that of fossil fuels (37%). However, many more efforts are needed to reach an ecologically ideal model. Smart Grids (SG) can help in this direction. This paper specifically deals with the integration of Renewable Energy Sources (RES) in the smart grid and in particular the exploitation of solar energy through photovoltaic panels, wind energy through Wind Turbines (WT) and electric cars as power stations through Vehicle to Grid(V2G) technology. The main objective of the paper is to introduce the reader to the technology of the intelligent grids and to try to convince him/her of their usefulness, presenting their multiple benefits and trying to provide solutions to the problems arising from their use. This is achieved after a thorough presentation of the parts of the smart grid, how it works, the characteristics of wind and solar energy and finally after commenting on various applications of integrating renewable energy sources in smart grids, making all the above clear to the ordinary reader but at the same time maintaining scientific discourse and terminology. Stability is also addressed, by diving into the fault types, and the system's response after clearing them. A simulation using Siemens Power Systems Software (PSS),is presented in order to determine the maintenance of system's stability after fault clearing, when integrating RES in the classic IEEE 14 bus system. Three phase (3φ) and Single-Line-to-Ground (SLG) fault are put into test. Moreover, Flexible Alternate Current (AC) Transmission System (FACTS) devices are addressed for better voltage and power flow support. Various cases, including the classic Institute of Electrical and Electronics Engineers (IEEE) 14 bus system with and without RES and FACTS devices are implemented, and by comparing the graphs of voltage, frequency, relative rotor angles and others, the results of this study show that when wind turbines and FACTS devices are used, the system can return in its stable condition more effectively. Finally, losses are reduced substantially and the voltage profile of the buses is enhanced.

Keywords:

Smart Grids, renewable energy sources, Siemens Power System Software, IEEE 14 bus system, stability, Flexible AC Transmission Systems.

Διπλωματική Εργασία

Ενσωμάτωση Ανανεώσιμων Πηγών Ενέργειας στα Ευφυή Δίκτυα

Γκίβαλος Σωκράτης-Κωνσταντίνος

Περίληψη

Η ηλεκτρική ενέργεια αποτελεί την πιο διαδεδομένη μορφή ενέργειας σήμερα, με την κατανάλωσή της στην Ευρωπαϊκή Ένωση να αυξάνεται ετησίως σε ποσοστά που κυμαίνονται από 2% έως 4%. Η ανάγκη για στροφή σε πιο, οικονομικά και περιβαλλοντικά, βιώσιμες λύσεις όσον αφορά την παραγωγή ηλεκτρικής ενέργειας είναι αδιαμφισβήτητη στις μέρες μας. Το υπάρχον δίκτυο χρησιμοποιεί μη ανανεώσιμους και ρυπαντικούς πόρους. Συγκεκριμένα, το 2019 το 43,6% της παραγόμενης ενέργειας στην Ε.Ε. προήλθε από ορυκτά καύσιμα ενώ, για πρώτη φορά στα χρονικά, το 2020 η ενέργεια που παράχθηκε από ανανεώσιμες πηγές ενέργειας (38%) ξεπέρασε αυτή των ορυκτών καυσίμων (37%). Ωστόσο, χρειάζονται πολλές ακόμα προσπάθειες για να φτάσουμε σε ένα οικολογικά ιδανικό μοντέλο. Προς αυτή την κατεύθυνση μπορούν να βοηθήσουν τα ευφυή δίκτυα. Η εργασία αυτή συγκεκριμένα, πραγματεύεται την ενσωμάτωση των Ανανεώσιμων Πηγών Ενέργειας (Α.Π.Ε.) στο ευφυές δίκτυο και ειδικότερα την εκμετάλλευση της ηλιακής ενέργειας μέσω φωτοβολταϊκών πάνελ, της αιολικής ενέργειας μέσω ανεμογεννητριών και των ηλεκτρικών αυτοκινήτων ως σταθμούς ηλεκτρικής ενέργειας μέσω της τεχνολογίας Vehicle to Grid (V2G). Κύριο στόχο της εργασίας αποτελεί η μύηση του αναγνώστη με την τεχνολογία των ευφυών δικτύων και η προσπάθεια να τον πείσει για τη χρησιμότητά τους, παρουσιάζοντας τα πολλαπλά οφέλη τους και προσπαθώντας να δώσει λύσεις στα προβλήματα που προκύπτουν από τη χρήση τους. Αυτό θα επιτευχθεί μετά από ενδελεχή παρουσίαση των μερών του ευφυούς δικτύου, του τρόπου λειτουργίας του, τα χαρακτηριστικά της αιολικής και ηλιακής ενέργειας και τέλος μετά από σχολιασμό διαφόρων εφαρμογών ενσωμάτωσης ανανεώσιμων πηγών ενέργειας σε ευφυή δίκτυα, κάνοντας σαφή όλα τα παραπάνω στον απλό αναγνώστη αλλά ταυτόχρονα διατηρώντας τον επιστημονικό λόγο και ορολογία. Η ευστάθεια είναι ακόμα ένα θέμα έρευνας, μετά από παρουσίαση των διάφορων ειδών σφάλματος σε ενα ηλεκτρικό δίκτυο, και την αντίδραση του συστήματος μετά από την εκκαθάρρισή τους. Παρουσιάζεται επίσης, προσομοίωση του δικτύου 14 ζυγών της IEEE, στο οποίο θα ενσωματωθούν ΑΠΕ και θα μελετηθεί η διατήρηση της ευστάθειας του συστήματος μετά από εκκαθάριση σφάλματος. Τα είδη σφάλματος που θα χρησιμοποιηθούν είναι τριφασικό και μονοφασικό βραχυκύκλωμα ως προς τη γη. Επιπρόσθετα, Οι συσκευές ευέλικτου συστήματος μετάδοσης εναλλασσόμενου ρεύματος αναλύονται για την ικανότητα τους να βελτιώνουν τη ροή ισχύος και του προφίλ των τάσεων του συστήματος. Διάφορες περιπτώσεις εξετάζονται, συμπεριλαμβανομένου του συστήματος 14 ζυγών της IEEE με ή χωρίς ΑΠΕ και συσκευές ευέλικτου συστήματος μετάδοσης εναλλασσόμενου ρεύματος, και συγκρίνοντας τα αποτελέσματα των γραφημάτων των τάσεων, των συχνοτήτων, των σχετικών γωνιών των γεννητριών και άλλων, τα αποτελέσματα δείχνουν ότι όταν ενσωματώνονται ανεμογεννήτριες και συσκευές ευέλικτου συστήματος μετάδοσης εναλλασσόμενου ρεύματος, το σύστημα επιστρέφει στην κατάσταση ευστάθειας με πιο αποτελεσματικό τρόπο. Τέλος, οι απώλειες του συστήματος μειώνονται σημαντικά και το προφίλ των τάσεων των ζυγών βελτιώνεται.

Λέξεις-κλειδιά:

Ευφυή δίκτυα, ανανεώσιμες πηγές ενέργειας, Siemens Power System Software, σύστημα 14 ζυγών της IEEE, ευστάθεια, ευέλικτο σύστημα μετάδοσης εναλλασσόμενου ρεύματος.

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Abbreviations

3φ	Three phase
AC	Alternate Current
ACO	Ant Colony Optimization
AMI	Advanced Metering Infrastructure
ARCB	Auto Recloser Circuit Breakers
CAES	Compressed Air Energy Storage
CCA	Critical Clearing Angle
CCT	Critical Clearing Time
CMS	Central Monitoring Station
CPP	Critical Peak Pricing
CSFD	Current Sensor Fault Detector
DBP	Demand Biding Programs
DLC	Direct Load Control
DLG	Double Line to Ground
DMS	Distribution Management System
DR	Demand Response
DRAS	Demand Response Automation Server
DSM	Demand Side Management
ESS	Energy Storage Systems
EU	European Union
EV	Electric vehicle
FACTS	Flexible Alternate Current Transmission System
DER	Distributed Energy Resources
GDP	Gross Domestic Product
GTO	Gate Turn-Off Thyristors

HAN	Home Area Network
HAWT	Horizontal-Axis Wind Turbines
HEDNO	Hellenic Electricity Distribution Network Operator
HEMS	Home Energy Management Systems
HV	High-Voltage
HVRT	High Voltage Ride Through
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
IPTO	Independent Power Transmission Operator
LAN	Local Area Network
LTC	Local Trading Center
LV	Low-Voltage
LVRT	Low Voltage Ride Through
MDMS	Meter Data Management System
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NIST	National Institute For Standards and Technology
PLC	Programmable Logic Controller
PPC	Public Power Corporations
PSH	Pumped Storage Hydropower
PSS	Power Systems Software
PV	Photovoltaic
RCCB	Remote Control Circuit Breakers
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SoC	State of Charge
SG	Smart Grids
SLG	Single-Line-to-Ground
SM	Smart Meters
SMES	Superconducting Magnetic Energy Storage
SSSC	Static Synchronous Series Compensator

STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TCR	Thyristor-Controlled Reactors
TLBO	Teaching-Learning Based Optimization
TOU	Time of Use
UHV	Ultra High-Voltage
UPFC	Unified Power Flow Controller
VAWT	Vertical-Axis Wind Turbines
V2G	Vehicle to Grid
WAN	Wide Area Network
WT	Wind Turbines

Chapter 1

Introduction

1.1 Smart Grid's definition and features

Nowadays, a change in the way we produce electric energy is essential, mainly because the production rate rises rapidly every year. Another reason to follow this path, is that non-renewable sources that are used in production are harming the environment producing various pollutants that increase the greenhouse gas emissions and are depleting faster than ever making them more expensive. This makes the traditional grid insufficient and paves the way towards an environmentally safer, cheaper, and more reliable way of producing electric energy. Smart Grids can play this role and provide the solutions we seek [1].

There is no distinctive definition of the term "Smart Grid". Since it was first defined by Energy Independence and Security Act in 2007, it is a rather new technology but has already set its sights high on establishing its position in the power grid.

Its advantages are numerous. It offers improved security, more consumer participation, reduced peak demand, higher integration of RES and fast restoration from power disturbances to mention a few. The majority of these benefits will be analyzed in this section [2].

Smart Grid's operation relies on Smart Meters (SM), smart devices, services, power generators, power substations, transmission lines and transmission control centers, distribution lines and distribution control centers and RES [3]. Those components are examined in **Section 2**.

1.1.1 Thesis Contribution

The contribution of this Diploma Thesis consists of:

1. Wide literature review concerning topics such as the basic components of the Smart Grid and their function, the adoption of RES in Smart Grids and the obstacles surrounding it etc.

2. Examination of various proposed models of a Smart Grid with renewable sources.

3. System proposition with the addition of RES and FACTS devices.

1.2 Structure of Diploma Thesis

1. In **Section 1**, the definition and the multiple characteristics of the Smart Grid are presented and discussed.

2. In **Section 2**, the architecture of the Smart Grid and its multiple components are analyzed in depth.

3. In **Section 3**, not only is the significance of RES examined presenting their advantages regarding today's problems, but also the challenges that emerge and complicate their integration. Furthermore, this section explores, several ways of storing energy and the collaboration of RES and Smart Grids, specifically solar energy, wind energy and the V2G technology.

4. **Section 4** will closely consider the barriers in integrating RES in Smart Grids and will try to offer some solutions thereby persuading consumers to trust and use this technology.

5. **Section 5** Greek grid is taken into consideration, and its components in transmission, distribution and others sectors are presented. Moreover, several examples of the evolvement into a smart grid in Greece, are widely examined.

6. In **Section 6** the prospect of pairing RES and smart grids is discussed, portraying its most common applications. The types of faults in an electrical system, the categories of stability analysis and the characteristics of the FACTS devices, which are also reviewed in this section, are used to perform a simulation to identify the advantages of integrating wind turbines and FACTS devices in the IEEE 14 bus system.

7. Finally, the synopsis and results of this diploma thesis, as well as recommendations for future studies are included in **Section 7**.

Chapter 2

Smart Grid Components

2.1 Introduction

Smart grid is a concept where electricity and communication are combined. The most popular framework model for a smart grid is National Institute For Standards and Technology (NIST) conceptual model and has seven layers, as seen in Figure 2.1; customer, markets, operation, service providers, operation, transmission and distribution [4]. All these layers work together towards the same goals for the grid which are control, protect, measure, record, optimize and stabilize. A typical smart grid architecture model is presented in Figure 2.2.

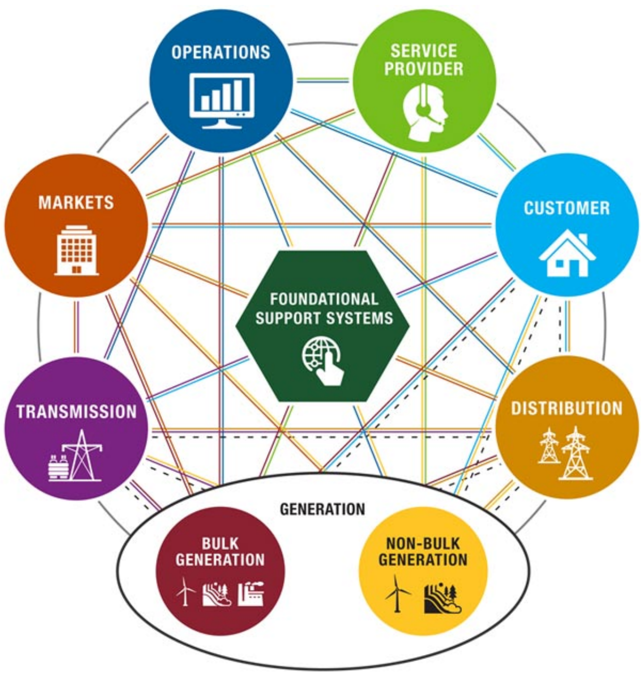

Figure 2.1: Smart Grid's domains

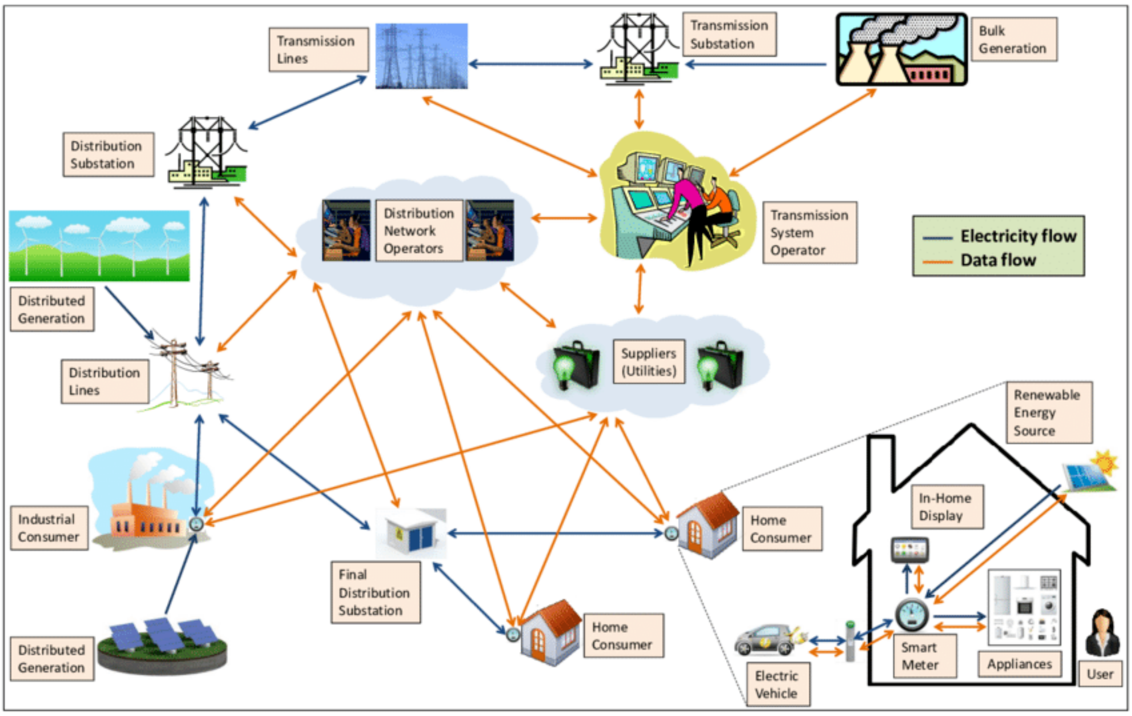

Figure 2.2: Typical Smart Grid architecture

NIST model layers come with intelligent devices like smart meters and sensors that facilitate grid operation. Communication is achieved by advanced network technologies like WiFi or power line carriers, to support bidirectional flow of data, and system monitoring is accomplished by data decision-making management systems for supply-demand stability and overall system control. Information from Home Area Network (HAN) are distributed to Local Area Network (LAN) and then to Wide Area Network (WAN) and each of these sectors analyzes the data to set the power components to their needs [5].

2.1.1 Customers

The grid was designed to support the participant known as the customer, who is responsible for power consumption and management. Certain stakeholders provide control and flow among the customer and the other domains, as well as the customer's management of energy use and generation. By diving this section into three sub-sections residential, commercial and industrial sectors arise and the energy needs for each one of them are:

- less than 20kW for residences
- 20-200 kW for commercial buildings

- over 200kW for industrial buildings

Energy services interface help customers communicate with other domains via the Advanced Metering Infrastructure (AMI) or other means, such as the internet. An AMI consists of smart meters, sensors, meter data management systems, HAN, LAN and wide-area communication systems [6]. These elements will be reviewed deeply in following subsections. Examples of communication with other domains are the control of various building features including temperature, lighting and appliance operation in domestic use, and machine control in industry, renewable energy exploitation and energy storage via batteries and thermal units in order to save energy and use it when necessary.

2.1.2 Markets

Market field is where the energy transactions take place. Generation and consumption data determine market's characteristics with fluctuating prices depending on energy use with the intention to match production and demand in the grid. Customers and Generation are two other domains that are indissolubly connected with the market domain. In particular, Distributed Energy Resources (DER), including Photovoltaic (PV) arrays, wind turbines etc., play a major role in energy price because they do not generate the same amount of energy at every time, but can solve peak demand problems. DER with renewables and their advantages is a topic that will be observed in another section. Customers on the other hand, when they sell electricity to others, can set the price that suits them and the consumers the most thus making them active players in the energy market. Moreover, regulatory framework through tariffs and incentives takes a toll in prices including flat rates, hours of use, or other more dynamic pricing designs (Real-time pricing). Pricing is primarily a means by which utilities can meet their licensed sales needs. In addition, tariffs can also signal customers when electricity consumption is more or less expensive, thereby encouraging customers to shift their consumption to other times. New technologies that can dynamically and autonomously interpret customer preferences while at the same time responding to price, resource availability, and service signals enable customers to develop a leading role in the power grid.

2.1.3 Service Providers

Service providers are very important in every aspect of the smart grid. In Figure 2.3, it can be pointed out, that they communicate with every domain and orchestrate the whole process of energy distribution by creating new and creative services to satisfy the demands and opportunities presented by emerging smart grids. Electric energy providers and other parties in network technology, work together to achieve better security, reliability and integrity for their customers. Some of the Service Provider's functions are mentioned below.

- Grid's stability and control is ensured by communicating with the operation domain by setting the right requirements according to on-time energy information.
- Communication with market and customer domain can offer more benefits in energy pricing and user satisfaction, due to monitoring of home and building energy, responding to outages, providing appropriate billing information, developing smart services and ensuring better customer relationships in energy transactions.
- Providing the best services in producers and distributors in terms of their operation and maintain machinery and equipment function, while guaranteeing they get the best economic deal they can.

2.1.4 Operations

Those involved in the operational field are in charge of the power system's flawless operation. Most of these features are currently the responsibility of regulated utilities. Energy management systems are utilized to assess and run the power system in a reliable and efficient manner. Operations affect every other domain in NIST conceptual model, as seen in Figure 2.4, offering assistances such as better monitor and control including fault and load analysis, maintaining machinery operation, meter reading, security management, financial and customer data record etc.

- The operational planning and optimization role is to simulate network operations, plan switching actions, notify clients, and plan power imports, maintaining low cost of imported electricity through peak power generation, and enabling Demand Response (DR) techniques.

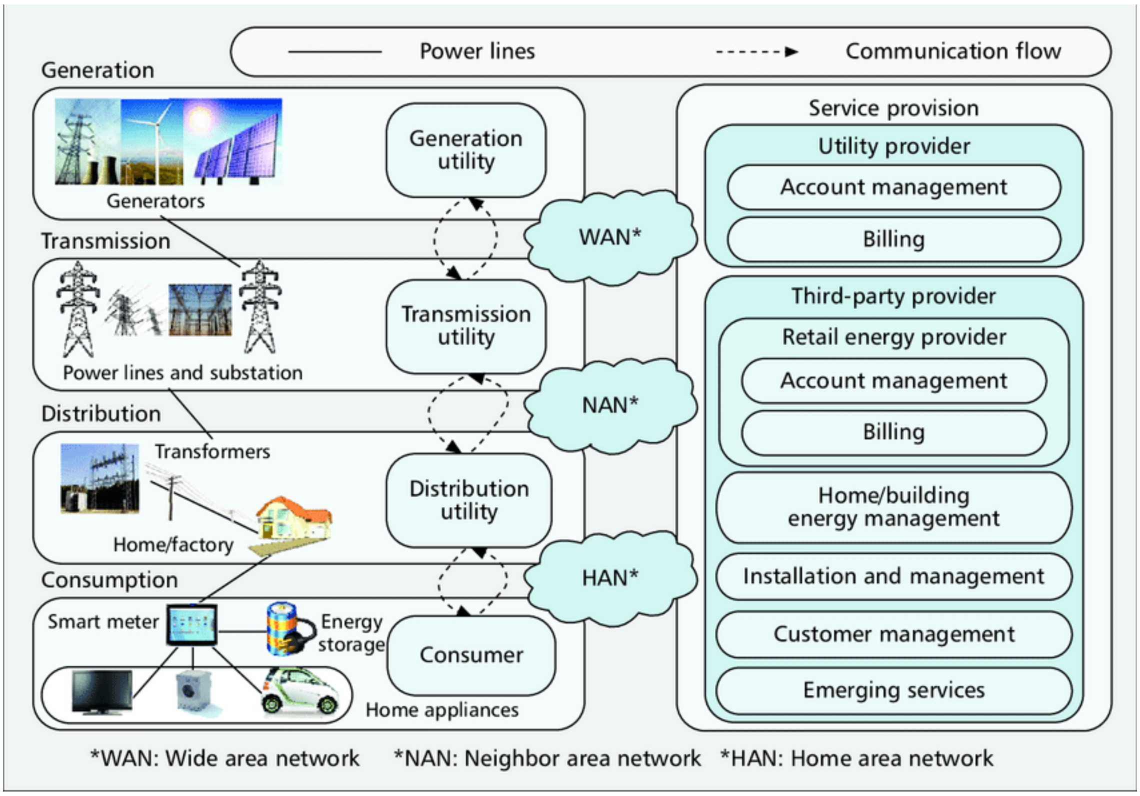

Figure 2.3: Layers of Service Providers

- By altering breaker and switches states and monitoring equipment status, operations supervise network topology and load condition and manage substations, wide area and local area network control. Moreover, fault analysis helps in punctual identification and location of systems' and grid's errors and outages. Consequently, faults are restored and customers are informed more quickly than in traditional grid. Harvested data from previous outages and errors facilitate fault prevention and overall smart grid performance.

- The purpose of operational feedback analysis is to compare real-time operations records to optimize regular upkeep by storing online data and analyzing feedback on system efficiency and reliability in reports saved in the system. Real-time network bookkeeping helps operators examine the security of the power grid.

- In terms of substations and DER units infrastructure, operations maintain equipment functioning through real-time running inspection, and manage machinery repair and replacement when needed by informing and guiding technicians.

- The grid expansion plan role creates a long-term plan for grid reliability for the purpose of monitoring cost, performance and construction schedule. New projects emerge that extend the network and upgrade grid performance including new transmission and distribution lines, branches, improved RES units etc.

- Finally, customer support by operations, inspires trust to the consumers by providing security services and assistance thus maintaining grid's function both in performance and economic terms.

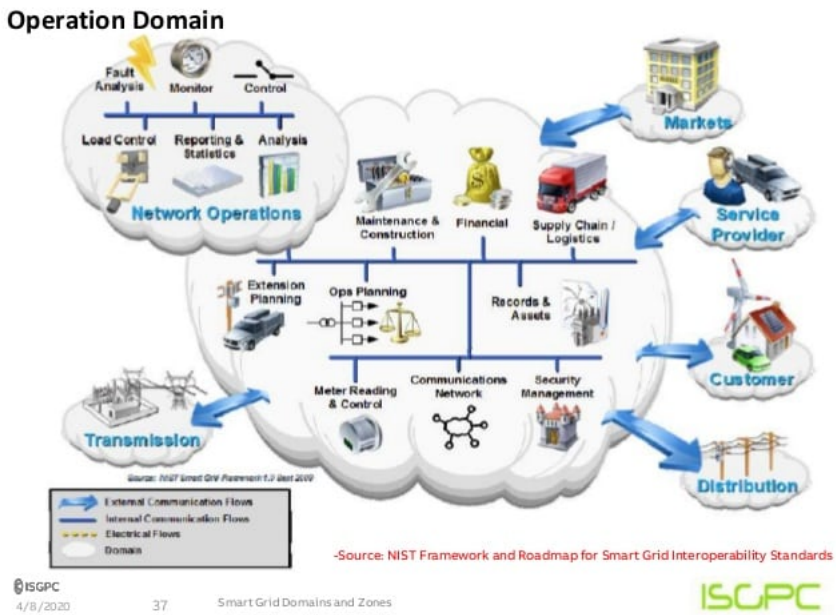

Figure 2.4: Operation domain

2.1.5 Generation

Power generation is the process of generating electricity from various sources of energy, from chemical combustion and fission to running water, wind, solar radiation, and geothermal energy, and providing this energy to customers. Generated power is electrically linked to transmission and distribution domains and connects with households and small-scale or large-scale industries. Communication with transport and distribution domains is important because without a forwarding mechanism, you cannot provide services to clients. Creations that include the DER domain should report major performance and quality of service issues, such as generator outages and failures. Distribution referred only to large scale high voltage transmission systems, but in nowadays smaller energy units like DER and RES have gained their popularity thus upgrading distribution models in order to accommodate these new components. In order to adhere to the new terms in generation, this domain has set some extra priorities including GHG emissions control, increase in RES units, and storage management for renewables. Various actors and equipment have been drafted to make this happen both in communication and application layer. Some of the applications of generation are presented below.

- Generation helps operation domain to have a view of power flow and system condition enabling it to manage the flow and making the system more reliable. Such measurements give an in depth perspective of a unit's operation and can be collected though the Supervisory Control and Data Acquisition (SCADA).
- Being able to supervise the way electricity is generated, this domain can respond fast to power outages and faults by shutting down or powering units and equipment both in local and wide area scale.
- Communication flows with markets and operation domains help keep track with financial and operational data and use them for forecasting purposes. Paired with operation domain, generation helps determining equipment state and life expectancy in view of operational conditions.

2.1.6 Transmission

Transmission is the transfer of electric power from generation to distribution and the customers. Regional transmission operators or independent system operators are responsible for this delivery while balancing supply and demand, with the help of terminal units, protection relays, power quality monitors, fault recorders, substation meters etc. Moreover;

- Substations can affect system's control, protection and efficiency by altering the voltage to meet grid's demands.
- Switching charging or discharging state in storage units also helps in meeting supply-demand needs.
- As stated in all the previous domains, transmission also keeps record of power and data flow to facilitate forecasting and ensure grid's protection and operation.

2.1.7 Distribution

Distribution sector is the electrical connection of Transmission and Customer domain. Like in Generation domain, base on the design of distribution domain in Figure 2.5, some DER like storage units or small RES units may be included to support the grid. Unlike the unidirectional flows in traditional grid, in smart grid distribution offers many communication interfaces, connected to Operations and Markets domains, with high-speed data exchange in order to respond to problems emerging in the grid, manage power flow and guarantee beneficial, both in economic and operational scale, energy generation-consumption in LANs or HANs. Moreover, like some domains mentioned above, this sector can also control charging or discharging states, monitor system operation for environmental and security purposes and record energy data for forecasting and grid protection.

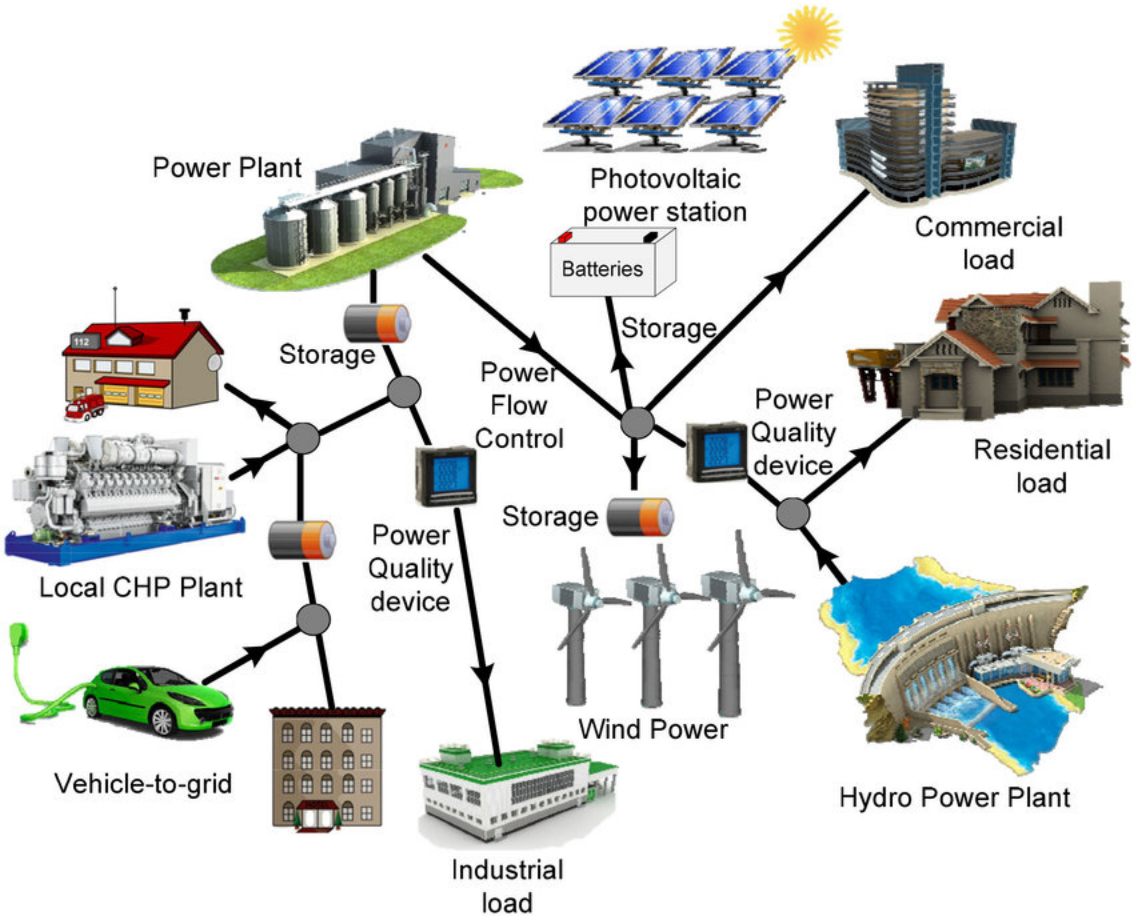

Figure 2.5: Distribution domain

Chapter 3

Renewable Energy Sources and Smart Grids

3.1 Renewable energy sources characteristics and EU renewable energy integration statistics

As stated earlier, produced electricity derives mainly from fossil fuels. These sources come from hydrocarbons that form in earth for many years, such as petrol, oil, and natural gas. They are non-renewable sources and because of their continuously rising exploitation, are soon to be extinct. Another aspect of the conventional energy sources is that they are harming the environment that we live in by producing solid, gas and liquid waste during their use, and discharge them in water, soil, and air [7].

New energy sources needed to be taken into consideration that could be always exploited without depleting and watch out for the environment. Renewable Energy Sources come from the sun, the wind, the waves of the ocean, biomass etc. and their abundancy offer many opportunities regarding their integration to the grid. PV panels, wind farms , dams, turbine generators for tidal energy and geothermal energy are the most common ways producing energy [8].

Incentives have been taken from the International Renewable Energy Agency and their target is for RES to produce the 75% of the total global energy by 2050 [9]. As far as Europe is concerned, previous goals for RES set the overall energy production and energy used in transportation to 20% and 10% respectively. In addition every country has to reach their own goals that have been set according to their characteristics that will be addressed later in this paper. But what really happened exceeded those expectations. Energy production by renewables rose to near double of what was expected with 38% and 51 TWh, but more important was the fact that fossil fuels produced 37% making 2020 a historic year, because for the first time the main source of electricity in EU was the RES. 14% of the energy came from wind and 5% from solar [10]. Figure 3.1 depicts the increase in renewable energy exploitation in Europe over the last decade. Europe has set the next objective for 2030 which is producing 100 TWh/year almost double the amount produced in 2020 applying some pressure in countries that despite their geographical position, have not yet meet EU's expectations. On the other hand, the 5 countries that helped the most achieving the goal of renewable energy production are Denmark (62%), Ireland (35%), Germany (33%), Spain (29%) and Greece (27%) [11], [12], [13].

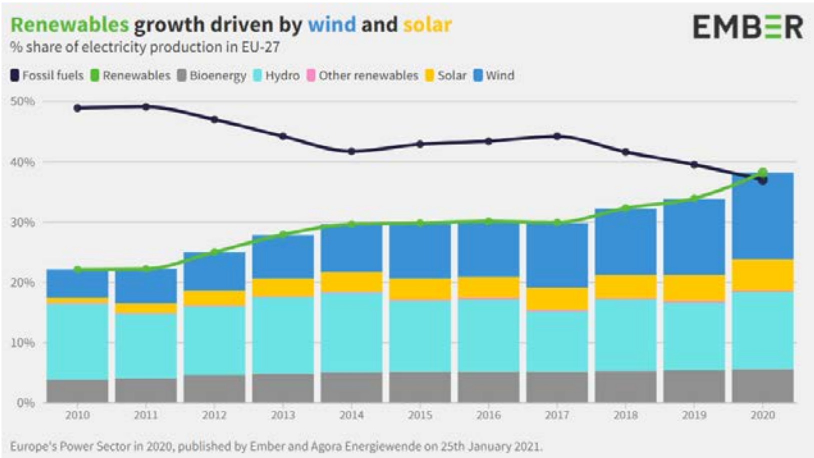

Figure 3.1: Rise of RES integration over the last decade

3.2 Types of photovoltaic panels and wind turbines

Solar and wind energy thus in this section the characteristics and prices of the various types of photovoltaic panels and wind turbines are highlighted. The continuous drop of these units' prices adds to the significance of RES adoption. Prices are at their lowest they have ever been in 30 years making a suitable ground for a widespread endorsement of renewables among greek people [14].

Regarding solar energy, there are 3 distinctive types of PV panels in terms of the material used, and are depicted in Figure 3.2.

- **Thin-film**. They come with metal or glass equipment making them the most affordable choice, but may take up lots of space in order to meet energy needs.

- **Polycrystalline**. They are made of silicon pieces and have a distinctive blue colour. In spite of being slightly less affordable, they are more efficient than Thin-film ones.

- **Monocrystalline**. This is the most efficient type which comes with a singular black colour, covers energy's needs with the minimum amount of panels than the other types and can operate effectively up to 20 years.

Figure 3.2: PV panel categories according to material

Panels can also be divided in respect of their mount type. Basically, they can be stationary or moving for maximum solar irradiation exploitation according to the time of the day and sun's position.

- **Fix-mount**. While they are less efficient because they cannot move to capture more sunlight, they are the most affordable and can prove very useful for areas with all-day sunlight.

- **Adjustable-mount**. The most significant feature of this type is that it can alter its position for maximum solar energy production or lay flat during a storm to avoid any damage. Even though, they are more expensive they can meet energy demands more effectively in areas with sun presence fluctuation.

- **Tracking-mount**. It can align to sun's trajectory and upgrade energy production up to 45%. On the contrary. However the expense of installation and maintenance raise some serious concerns among consumers.

Concerning wind energy units things are much more simple. There are only two types of wind turbines the Horizontal-axis and Vertical-axis Figure 3.3 [15], [16].

Vertical-Axis Wind Turbines (VAWT) were invented in 1931 and are not used so often in nowadays. They can reach up to 100 feet in length and 50 feet in width and have a unique oval shape. The main components are situated at the base of the unit so that monitoring and repairing are simplified. The rotors are set transverse to the wind and it is not necessary to be pointed directly at it, but they move in the same direction as it. This is crucial because orientation of the unit is not an issue, the unit operates under omnidirectional winds, hence this type is an excellent solution for a small residential wind turbine in urban areas. Studies have shown that, while all roof types are suitable for producing energy from the wind, curved roofs seem to produce the greatest wind acceleration effects and create the least amount of turbulence. Finally, the significance of VAWT in urban areas is highlighted by the fact that despite the low wind speeds and the turbulence caused by buildings, they can produce a important amount of energy if installed in the right place.

Horizontal-Axis Wind Turbines (HAWT) are the most popular type of wind turbines and can be easily identified as they are tall structures with 2 or 3 aerodynamic blades adapted to a rotor. They usually consist of an odd number of blades because they offer better energy efficiency and architectural stability. Adding extra blades to a turbine raises the cost and decelerates the blades' start, so the the fewer blades the better. As a result, the best choice is a 3 blade HAWT which has an odd number of blades and the smaller possible. Rotors can be faced upwind or downwind. Towers with upwind rotors call for a tail vane, a tool that helps them adjust to the wind's speed and direction whereas downwind ones come with conical shaped rotors and adapt to wind conditions on their own. Larger wind turbines in the countryside use anemometers and other devices to orient with the wind.

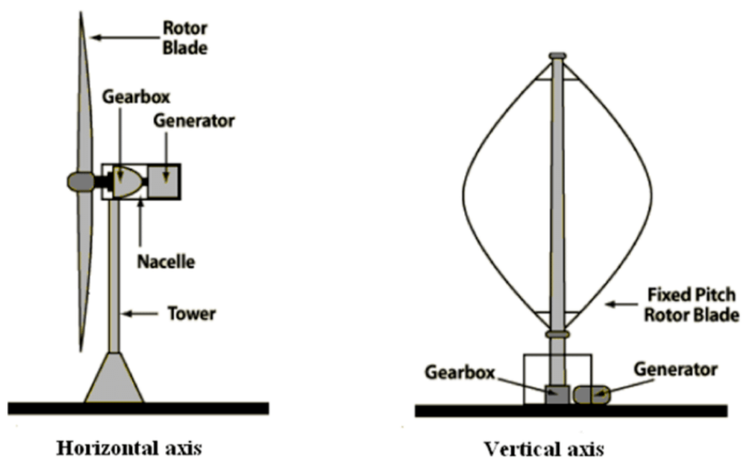

Figure 3.3: Wind turbines and their features

3.3 Energy Storage Systems

As far as energy storage is concerned, there are many ways to save excess energy and use it for backup. Some of these are presented below.

- **Ultracapacitors**. They store and release energy faster than batteries, through positive and negative ions and liquid electrolyte. Better known for faster charge and discharge times, they are ideal for quick bursts of power or quick storage. With a capability of over 1 million charge cycles, they are a reliable storage solution for storing excess energy from RES and in transportation (regenerative braking).

- **Flywheels**. Energy storage by accelerating a rotor to high speed and maintaining the energy as rotational kinetic energy. The rotor's speed is increased or decreased during energy storage or release, respectively. Frequency and voltage are managed by electronic devices to ensure an ordinary operation. They are distinguished among other ways of energy storage because of their durability, low maintenance, endurance over different weather changes, zero CO_2 emissions and infinite charge cycles. On the other hand, they are also characterized by short operational duration and high losses.

- **Superconducting Magnetic Energy Storage (SMES)**. Direct current flows through superconducting coil which is cooled by cryogenically cooled refrigerator to maintain its superconducting abilities. While being one of the most efficient ways of energy storage (>95%) and having the least amount of power losses out of every one of them, SMES units are relatively harmful for the environment and their operation is expensive because of the refrigeration and superconducting materials.

- **Compressed Air Energy Storage (CAES)**. CAES units play the role of load balancer between low and peak demand periods, by compressing air via a rotary compressor and storing it in an underground chamber. When needed, high pressure air is released and goes through a turbine generating electric energy. This is one of the least used ways of ESS, in fact only two major CAES plants have been constructed, a 390MW plant in Germany and a 110MW plant in USA.

- **Hydrogen Fuel Cells**. While hydrogen and water are passed through a negative and a positive electrodes surrounding an electrolyte, a catalyst separates protons and electrons from the hydrogen molecules and then electrons are passed through a circuit that produces electric energy. For storage purposes, electric power is converted into hydrogen by electrolysis of water, which is basically the separation of water molecules to hydrogen and oxygen. Consequently, the produced hydrogen is stored for use, when demand is high.

- **Pumped Storage Hydropower (PSH)**. PSH is the most common way of energy storage, responsible for almost 95% of this sector. There are two types of PSH Energy Storage Systems (ESS), the open-loop when the system is connected to a naturally flowing loch, and contrarily the closed-loop. PSH philosophy involves two water containers in different elevations, which interact for charging and discharging the unit. Water is pumped from the lower repository to the upper one in low demand periods or when electricity prices are cheap thus charging the storage system. When needed, water from the upper reservoir is released to the lower and through a turbine that offers electric energy back to the grid. PSH contributes to electric shutdowns because by opening the gates of the reservoirs require much less energy to start their operation in contrast to other ESS systems. Moreover, they account for electricity inertia, thus maintaining a steady frequency and voltage levels, and they are a low-cost, high endurance totally environmental friendly solution.

Greek grid accommodates a few ESS units, but they are likely to increase significantly in number and capacity in the foreseeable future. A big construction from TERNA is underway in Agios Georgios (460MW) and Pyrgos (220MW) for pumped hydro energy storage that will offer new jobs, protect forests and facilitate farming and agriculture. Standalone battery units are a trend. Greek government offers subsidies for many projects up to 100 MW to ensure that these units can be scattered across the whole country. The national planning for energy and climate has stated that until 2030 more than 5 billion euros will be invested in energy storage. Moreover, this will be achieved by 5.3 GW storage units, 3,1 GW of battery units and 2,2 GW of pumped hydro units.

3.4 Renewable energy sources opportunities and advantages

Electric energy is everywhere in today's life and its use rises every single year. So, it is mandatory to provide stability and security for every consumer by balancing supply and demand, and nullifying outages and faults in production and consumption. RES have gained lots of attention both in industrial and domestic sector, because of they generate clean energy and if used correctly (proper size and right operating conditions of RES units) can serve as an inexpensive and sustainable alternative. Benefits of renewable energy can be divided into many categories such as environmental, economic, and technical.

3.4.1 Environmental sector

- **Low or even zero production of pollutants (NO_2, SO_2, CO_2)**. In 2020 electricity was almost 30% cleaner than in 2015. Europe's goal for 2030 is to minimize Greenhouse Gas emissions to 55%.Additionally, every member of the EU saw a decrease in pollutants but there are still much to be done for this direction. For example, Germany and Greece are still in the upper tier of carbon intensity regardless the fact that they where among the most developed countries in renewable energy.
- **Reduce of soil pollution**. It has been stated that, important nutrients of soil, like nitrogen, near power plants that use fossil fuels, can deteriorate by fly ash and alter the pH of the soil.
- **Reduce of water pollution**. Like in soil, fly ash and other harmful emissions harm the water endangering both people drinking from it and sea life.

3.4.2 Technical sector

- **Duality of RES**. They can act as a peak shaving for load peak hours and as an independent system for a building, house or a small area.
- **Preventing power outages and losses**. By connecting to the grid these sources may come in handy providing electric energy in times of need.
- **Contribute in voltage and capacity**. Setting the proper size of the unit and operational specifications, will offer the optimum capacity and stable voltage preventing reverse power flows at the same time.

3.4.3 Economic sector

- **Large savings from utilities**. Companies that operate lots of machines spend lots of money in electricity by the traditional grid. With RES the cost is significantly lower and

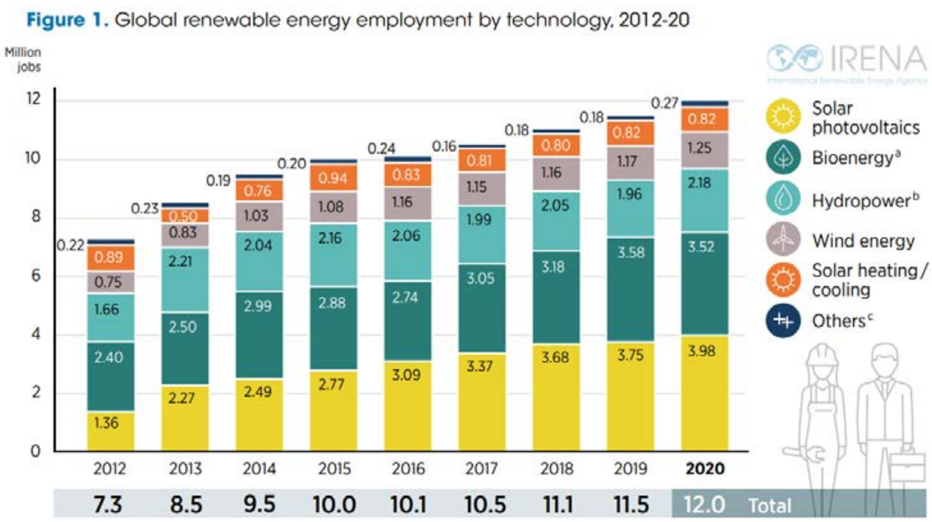

Figure 3.4: RES results in working positions

the fact that losses in distribution lines are reduced, make the sources very beneficial for utilities.

- **Consumers' savings**. The rapid increase of electricity price has created many problems in households. Some people that cannot meet the expense of this raise are deprived of some needs such as heating, but with renewables the electricity bill will be much more affordable for them. In addition, some severe power losses are charged to the consumers by utilities, so RES will help them save some extra money because of the technical benefits stated earlier.

- **New job opportunities**. RES integration will create many working positions, as shown in Figure 3.4, in different sectors such as maintenance, research and operating giving the chance to engineers, technicians, machine operators, economists and others, to improve the sources' operation.

3.5 Integrating renewable energy sources in a Smart Grid

In earlier sections, both RES and Smart Grids were profoundly investigated in light of their benefits in today's grid. It is obvious that, these technologies combined can deliver numerous positive results. Control systems presented in Section 1 manage the operation and coordinate all the elements to ensure better performance, meet demands' needs and accomplish long-lasting function of components. In other words, they create the most suitable environment in technical and economical aspect.

3.5.1 Vehicle to Grid technology

In addition to solar and wind energy, that were discussed previously, a new initiative is in the spotlight of RES in Smart Grids and that is V2G technology. Electric vehicle (EV) technology or plug-in hybrids in EU, experience major growth recording 143% rise in sales in 2020 than the previous year. Europe and each country's government individually, trying to persuade people to buy EVs, offer deals that can prove beneficial in long term [17]. If V2G is added in this equation, the benefit from this purchase is increased significantly because customers can now power their own grid when needed, or even sell the energy to others. V2Gs work in two ways.

The first one is Smart Charging. Through User-Managed Smart Charging, the customer defines how the EV will be charged according to time and energy price. Therefore, charging takes place when the price is low and in off-peak times. On the contrary, Supplier-Managed Smart Charging, uses data from nearby EVs or the electricity supplier and decides whether to charge or discharge the vehicle based on real-time power production/consumption and on-peak/off-peak hours. Even though Smart Charging shifts a part of load to off-peak hours and serves as a backup tool, thus making the system more efficient in terms of peak load management, there are many concerns about the way the vehicles are charged and battery degradation [18].

Secondly, V2G can offer subsidiary work in the grid. Excessive produced energy can be stored in batteries and then they can play the role of a spinning reserve which is an energy provider that despite being connected to the grid do not always produce energy. They only deliver electricity back to the grid when it is necessary ensuring grid's stability [19]. The bidireactional flow of energy in V2G technology is illustrated in Figure 3.5

Figure 3.5: V2G operation

3.5.2 Benefits from Smart Grids combined with renewable energy sources

1. Electric energy from renewables can differ in range of some Kilowatts up to many Megawatts. This implies that it can provide to both houses or small buildings and serve the needs of microgrids but also to the industrial field.

2. Provided supplementary assistance such as peak shaving, voltage/frequency regulation and protection from power blackouts prove useful in matching today's electricity demands [20].

3. In social aspects, this new mechanism incorporates consumers as participants in energy production, consumption and market. For example, they decide whether to power up their appliances by their own RES units, charge or discharge their EVs in V2G technology and sale their energy to those who need it in the right price. This is a major contradiction with the traditional grid, in which customers had not such role and only paid the bill [21], [22].

4. New working positions are been introduced due to this modern technology in engineering, computer, construction and economic fields.

5. The bidirectional flow in smart grids help utilities deal with problems before they even occur. Not only they provide better security in the grid preventing faults and outages, but also to customers observing their voltage, frequency and other parameters through smart meters [23], [6].

Chapter 4

Obstacles in Integration of renewable energy sources in Smart Grids

4.1 Introduction

Despite being linked to numerous benefits, Renewable Energy Sources and Smart Grids face many challenges in their adoption. Governments, utilities and customers are still reluctant to adopt this technology thus decelerating their integration. Some of the concerns have to do with the intermittency of RES, the geographical characteristics of the units, social denial, lack of infrastructure and well-trained personnel, and lack of regulatory framework and inadequate funding. This section will try to shed more light into the obstacles and propose some actions that need to be taken in order to raise the bar and convince of the effects RES and Smart Grids offer to economy, environment and our life in general [24], [25].

4.1.1 Instability of produced energy

It is well known that electricity produced by those power plants is variable due to their intermittent nature. They rely on factors that are not persistent and cannot be optimized by human interaction. Those factors are sunlight, solar irradiation, wind presence, time of the day, etc. As a result, energy is not produced whenever is needed and not available for use at all times. In addition, variations in voltage and frequency emerge, and endanger grid's stability [26]. So in order to face this large amounts of conventional electricity backup and large energy storage capacity is needed to use this energy in times of need [24].

4.1.2 Location of renewable energy sources units

RES power plants are situated mostly far from urban areas, in mainland and islands. For example, a new trend that emerges is the Offshore wind farms as shown in Figure 4.1. Consequently, this energy is not distributed in its full potential to cities, where the most problems concerning the grid are emerged. In order to take advantage of the wind farm, the electricity generated needs to be transmitted over long distances, which results to a need for quicker and more efficient transmission lines thus weighing the energy provider and customers down. Moreover the bigger the distance the greater the fluctuations in voltage and frequency which indicates grid instability. Large amounts of GHG emissions, many utilities, buildings and households, lots of transportation and big energy demand characterize these urban areas, so it is obvious that renewables are more useful there. Moreover secluded areas tend to be cut off from RES and Smart Grid infrastructure and rely on traditional old-fashioned grid [27], [28].

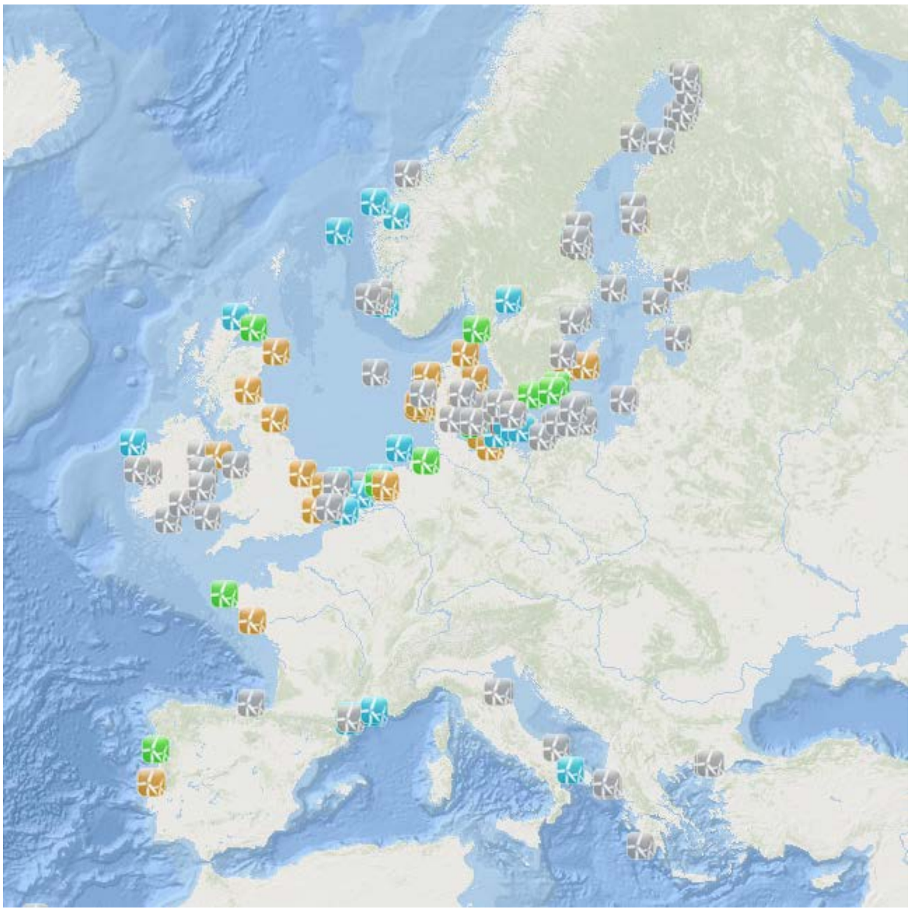

Figure 4.1: Offshore wind farms (Blue: Approved, Grey: Planned, Orange: Currently producing, Green: Currently under testing)

4.1.3 Privacy concerns

Although smart grids play a vital role in grid's reliability, as far as performance is concerned, they encounter many problems in terms of privacy. Devices like smart meters and smart sensors and the continuous bi-directional flow of data jeopardize private information of users and utilities and creates a breeding ground for cyber-attacks. Smart meters store information several times within an hour so these data might expose patterns of energy usage, types of household appliance and the presence or absence of people in the house according to the energy usage and scheduled activities. On the other hand, V2G technology faces bigger challenges because of its e-mobility. Electric vehicles can be connected to multiple charging spots threatening the driver's location and personal data such as his ID, payment methods, financial status, visited places etc. Low privacy awareness in V2G and Smart Grids facilitates malicious cyber-attacks. For instance attackers can eavesdrop the system and gather personal information, modify a charging spot's or a vehicle's specifications in order to steal energy, or even connect a forged charging spot to the real one with the intention of stealing energy [29], [30]. Location and payment are essential specs of the system, that means that someone can not only detect where you are but also hack your billing information, so user's assuredness in privacy plans is more than essential for further persuasion.

4.1.4 Additional Infrastructure

It goes without doubt that, RES units such as wind farms or photovoltaic panels are big constructions that require space and lots of money. Also, small RES units for residential use in urban areas are still not affordable enough to persuade consumers. Wind and hydroelectric energy being the most used renewable energy sources in Greece should contribute to smart grids but their location and lack of expensive, high-quality components that could carry, store and distribute this energy cannot help the smart grid operate to its full potential. On the other hand, traditional grid's infrastructure only needs maintenance and does not include many additional elements like smart meters or two-way communication lines. Programming, managing and constructing the various components of smart grids are more than essential, and so require suitable workforce and plenty of training especially the communication system which is a very complex asset of this new technology. The communication is essential for all consumers, energy providers, RES units and through the energy distribution, after all the bidirectional communication through its components is one of the main reasons it is called a smart grid [31]. These facts induce substantial financial concerns, thus impeding RES and Smart Grid integration [32].

4.1.5 Financial Issues

Whilst they offer vast economic profit, as discussed in previous sections, there is still a gap in implementing RES and Smart Grids due to lack of investment. Investors in general, are sceptical because compensation will take longer than they except and sometimes is not even certain. European Union's states have set some feed-in tariffs and financial incentives that helped the integration through the years but in order to meet EU's 2030 energy demands they should do even more. Greek government proceeded to new subsidizations in domestic PV panels implementations but there is a discouraging limit in system's peak power. In addition, the EU's "Fit for 55" plan, the reduction of CO_2 emissions by 55% in 2030, forces Greek authorities to find a way to generate additional GW of energy from RES. Without the right prices and incentives, given Greece's aching economy consumers will not turn to renewables so easy. Finally, the cost of EVs is another concern because of the financial situation in our country. The average consumer prefers new or used conventional vehicles that are cheaper in purchase and maintenance.

4.1.6 Public's opposition

People tend to oppose to new ideas or let go off their habits, even though sometimes they are aware of the problems in their conventional way of life. In that case, it comes with no doubt that Smart Grids and RES are treated accordingly. Consumers are still doubting these innovations mainly because they are not educated enough, and if they are educated sometimes, it is financially difficult for them to change their ways. For example, everyone knows that cars that use diesel or gasoline harm the environment at a great extent, but not all of them can buy an electric or a plug-in hybrid vehicle. The same thing occurs in residential solar panels or wind turbines [33]. Moreover, many activists try to slow down the expansion of solar wind farms and PV panels, stating that this would result to the destruction of mountains, fields in rural areas and overall the nature's beauty, and often forget the many benefits from minimizing energy production from non renewable sources.

4.1.7 Companies' opposition

On the same wavelength as the previous subsection, companies often distrust novelties that do not aspire reassurance in their implementation. Additionally, the complexity of the smart grid technology and the absence of edification from the scientists responsible heightens this issue. Traditional ways tend to come in handy for them, because of the continuous use throughout the years and the fear of failing to address the needs of their customers. Public's view is crucial for a firm to survive in today's market. Also, the financial issues play their role in the companies' hesitation, the acquisition of smart devices, RES units and overall update of their current infrastructure are risks that some companies are not willing to take.

4.1.8 Battery degradation in electric vehicles

The other problem in integrating EVs to smart grids is the battery degradation and its cost of replacement. The results of battery degradation can be Capacity Fade and Power Fade.

- **Capacity Fade** refers to a decrease in battery's exploitable energy and range of the EV.
- **Power Fade** indicates an increase in the impedance of the cell which creates many issues in vehicle's and system's performance.

But what causes battery degradation? It derives from some components that are called "ageing stress factors". Capacity throughput, indicates the amount of energy a battery can accommodate during its lifetime. Temperature changes can have a negative effect in electrochemical components of batteries resulting in a short life cycle. State of Charge (SoC) of the cell signifies the level of battery's capacity that is available the exact moment (0-100%), swing in SoC denotes that various cells with the same SoC have different voltages causing troubles in battery's management system [34].

4.2 Overcoming the obstacles

In this section, obstacles presented in the previous section will be addressed with provided solutions in order to persuade even more the reader about Smart Grid and RES services [35]. In other words this section will:

- Deal with economic and policy initiatives that facilitate the adoption

- Suggest technical measures like developed infrastructure and workforce that result in grid efficiency

- Answer to public opposition and assure their security

- Take up battery degradation in V2G technology.

4.2.1 Economic-policy factors

In order to, address the economic solutions, we should take into consideration the Gross Domestic Product (GDP) per capita of every member of the European Union. This refers to the amount of wealth or domestic production value for every single resident of a country. Economic growth is equivalent to faster and finer integration of RES and Smart Grid techniques and contributes to big investments because both utilities and consumers are more than willing to take a minor risk in these technologies, that can be proven beneficial for them.

Governments with thriving economies provide more incentives with several regulations and policies such as feed-in tariffs, special funding, guarantees and pricing strategies, and tax in carbon emissions among others. These motives apply to companies and residents persuading them to adopt the new techniques in electric energy and invest in research and enhancement in Smart Grid infrastructure, improved renewable energy production and utilization etc [36].

Europe is now the driving force of renewables in the world. The market mechanisms and rising GDP of EU and every country individually along with the decreasing cost of RES implementation and high costs of fossil fuels and carbon, will result in a great success towards fossil-fuel free energy production and consumption [37].

4.2.2 Technical Factors

Being the region with the most significant renewable energy implementation, Europe must raise the standards in technical aspects, assuring the best generation and utilization framework.

This will be executed by improved RES units, Smart Grid components, transmission and distribution lines. Moreover, a highly educated work force including scientists and workers managing research, communication, energy market and machines' operation will raise the bar for energy's best possible exploitation and reduction of development costs [38]. Some of these factors are presented later on.

4.2.3 Social factors

In the contemporary world, everyone is aware of Greenhouse gas effects, global pollution and the negative effects these have in our and planet's health. It is obvious that each and every one of us really want to make a difference and help as much as we can.

The main problem is that people are not that educated about today's grid problems, and benefits of RES or Smart so as to take action and actually help. So, governments, with help from academic workforce, engineers and others have to enlighten their residents about the beneficial use of RES and Smart Grids. A presentation of the estimated savings, environmental advantages and user's active participation in this new trend will influence public opinion for the best.

Media on the other hand, influence public's thoughts and actions resulting in a great means of persuading. Both in television and on the internet, media can broadcast simple and viewer-friendly programs for people to become acquainted with these strategies [39].

4.2.4 Grid stability and efficiency

Most renewable sources units are situated far from the grid, in mainland, islands or even the sea, with vast solar irradiation and wind presence. In order to, use the produced energy to its full potential in cities and densely populated areas, where energy needs are bigger, improved additional transmission lines must be adopted and connected to the grid. Not only, will they ensure sufficient transfer of the energy but also, advanced communication with the grid, exchanging data about peak demand, frequency and voltage level supporting its stability. [28]. Solar PV panels impact the energy demand, especially during daytime when solar irradiation is at its highest, thus reducing demand's value remarkably

Area's characteristics such as presence of sun and wind, RES units' and load's size, and system configuration are very important in making these sources viable. Not responding to these operational requirements generates adverse effects like power losses and overload in transmission lines. Prediction schemes of natural phenomenons in wind and solar energy, will also prove useful, because RES units will be programmed to operate according to these data for the best outcome [40].

4.2.5 Multiple renewable distributed generation sources

Although, as mentioned earlier, big RES units are often located in areas far from cities, rooftop solar photovoltaic panels and residential-use wind farms connected to microgrids, are thriving. If the produced energy of small units is combined with this from big ones, instability of energy production due to intermittency will diminish significantly, and long-distance transmission will no longer be an issue [4]. Finally, if a power loss occurs, microgrids have the ability to disconnect power plants from the main grid and reconnect them when it is necessary.

4.2.6 Customer protection

Security is one of the largest concerns in adopting smart grids or V2G technology. Overcoming this challenge will open the way to public acceptance and trust in Smart Grids. System and consumer's framework should be user friendly and simple in the interest of fully understanding its operation. Bi-directional information flow systems should be accompanied by security standards that prevent information leakage and identity theft. Electricity providers should hire properly educated personnel preventing malicious cyber attacks and private information leaks. Serious consequences must be applied to those who try anything illegal [41].

4.2.7 Development of infrastructure and workforce

Building new or using existing infrastructure, demands functionality and control. These structures must adhere to energy regulations and be functional in order, for Smart Grids, to use them. In addition, homeowners must act upon the instructions given by the grid. Infrastructure should contain advanced communication systems, high quality machinery and well-trained workforce who will be instructed by government and colleges in order to specialize in certain sectors [31].

4.2.8 Vehicle-to-Grid and battery degradation

While V2G offers many benefits to smart grids, there are still a lot to be done in order to battle battery degradation. In fact many studies show that V2G facilitates this effect, because of the shift from charging and discharging state. From literature review, this happens mostly in high SoC in battery storage. The contribution in degradation is not big but still considerable. Although, some studies show that with specific strategies battery degradation can be minimized. One study shows that, setting SoC to a value that implies low storage degradation cost and the cycling range where battery degradation occurs, if the EV provides V2G services when storage degradation is higher than battery's, then the problem will be minimized. There are a lot of studies suggesting some solutions, but in my opinion benefits from saving money in electricity can surpass the negative effects of V2G services in batteries. Right now average battery replacement cost is $5,500, an 89% drop since 2010, and average years till replacement set from 10 to 20 [42], [43].

Chapter 5

Observing the Greek Grid

In this chapter we take a deep look into the components that form the Greek Grid in terms of Production, Transmission, Distribution and Communication, and we discuss future actions that can modernize it and make it smarter like a Demand Response initiative in Thessaloniki, Xanthi's islanded microgrid, and upgraded infrastructure in the sectors stated above.

5.1 Greek Grid Statistics

Big production units offer a power of 20-30 kV. Then this power is stepped up to 400 kV in Transmission level, in order to be transfered to costumers with the least amount of power losses. Then, voltage is stepped down to 150 kV and can either serve High-Voltage (HV) customers like large-scale industries or transmitted to other substations that step down the voltage to 20 kV (Medium Voltage (MV)) and connect to small-scale industries (with power over 250 kVA) via MV transmission lines. Moreover, MV can be converted to Low-Voltage (LV) via transformers that step down voltage to 3-phase 400 V or 1-phase 230 V and distributed via LV transmission lines to LV consumers such as households. As of 2017, the transmission network is portrayed in Figure 5.1. In Greece the leader in Electrical Energy sector is the Public Power Corporations (PPC) and is divided into three subsidiary companies the Hellenic Electricity Distribution Network Operator (HEDNO) which aims at the development and maintenance of the distribution sector, the Independent Power Transmission Operator (IPTO) whose role is to supply power to the greek grid in an efficient and inexpensive way and PPC Renewables which handles the many dispersed RES units and monitors their activity.

In transmission sector there are two levels of HV at 66 kV and 150 kV, and one level of

Ultra-High-Voltage (UHV) of 400 kV each one having a short-circuit current value of 12 kA, 20 kA and 40 kA respectively. More than 330 HV to MV substations and HV control centers have been introduced and coupled with 732 transformers with a total power of 55.391 MVA, as well as 950 km of HV transmission lines. Distribution sector consists of transformers, voltage regulators, that keeps the voltage value regardless of load fluctuations, and safety tools that offer help in the event of a malfunction. It contains 111.000 km of MV 20 kV lines that transfer electricity from transmition substations to distributions and 125.000 km of LV 230/400 kV lines that provides electric energy to LV customers from distribution substations are connected to the grid as of 2013. In addition, more than 160.000 MV to LV substations have been installed. Greece is also connected to its neighbour countries, to Albania through a 400 kV transmission line (1600 MVA apparent power) with terrestrial connection of 45 km in Greek land and 100 km in Albanian land, to Italy with an underwater direct current cable connection developing the existing network and raising its transmission capacity to 1500 MW, to North Macedonia with 2 400 kV lines connecting Greece to Bitola and Dubrovo, to Bulgaria with a 400 kV line reaching Blagoevgrad, and also to Babaeski, Turkey.

5.2 Problems in Greek grid

A major problem of the traditional electrical grid, is that generation units are mainly located in the northern region of Greece, where lignite reserve is higher, complicating electricity distribution because they are far from the major urban centers. As a result, distribution relies on HV lines that are more expensive and because of the large distances, information about the grid's state are often delayed and electrical system faces many losses, therefore a proper energy monitoring and exploitation cannot be achieved. Moreover, the lack of sufficient energy storage units makes energy management more difficult, because energy suppliers need to calculate the required energy for the day ahead, which in turn can lead to three scenarios· the optimal one being that the energy consumption is same as the estimated, consumed energy exceeds calculations thus the remaining energy is lost, and the calculated energy is insufficient resulting in a power outage. The lack of plentiful automation techniques often requires the human presence to power up the grid after a blackout.

5.3 Greek Smart Grid

In order for this system to work in its full potential, there are some actions need to be taken towards the amelioration of the grid and incentives surrounding this topic. These include more investments, tax initiatives for integrating RES in households and others.

5.3.1 New investments

A new investment from the European Investment Bank is coming to help modernize thousands of kilometers of distribution and increase the use of smart meters, which is essential for the further assimilation of renewables in Greece's energy production, from the European Investment Bank. This is a 20-year loan to support investment in modernizing and strengthening the Greek distribution network on the mainland and islands. The program features a large number of MV and LV distribution systems, including 6,600 km new and 7,600 km upgraded MV and LV network, as well as automated components and advanced measurement infrastructure distributed nationwide. The program's CO2 equivalent emission source is the ohm loss of for newly installed network equipment. Upon completion of the program, the corresponding absolute emissions of will be estimated at 74.5 kt CO2e per year. However, these absolute emissions are offset by the system loss reductions made possible by Program compared to the non-alternatives. Therefore, when the project is completed, a net reduction of 31.5kt CO2e per year is expected. Strategic long-term financing can modernize distribution networks, benefit consumers, improve supply security and protect the environment. With the new € 330 million European Investment Bank loan, HEDNO and PPC will increase their use of renewable energy with wind and solar power generation connected to the national electricity network, increase energy efficiency, introduce smart meters to build smarter national power grids and combat climate change. This will contribute to the smart and green energy conversion of Greece.

Regarding electromobility, Greece offered a €100 million plan that focused to sponsor EVs and charging stations until 2021. This featured a 25% cut in over 14,000 vehicle models and the construction of thousands charging points all over Greece. Also, the program included numerous benefits for people and companies including a 20% grant for the purchase of a vehicle under €30,000 and 15% for over €30,000 or a hybrid car, €1,000 for scraping the old car, full exemption for some taxes, €500 grant and personal parking space for a purchased smart home charging point. A new cycle of incentives, that is underway and will come into force in June 2022, will offer larger benefits than the previous one. Those include a new 30% grant for buying or leasing a electric vehicle, extra €1000 for people under the age of 29, or persons with disabilities, extra funding for families with 3 or more offspring etc. Taking into consideration these amounts and the profit from not using gasoline or petrol, EVs have a favourable Return Of Investment (ROI) potential in addition to environmental contribution [44].

5.3.2 Upgrading urban areas

It has been profoundly stated that cities are in greater need of contemporary energy alternatives. In the light of dense population and intense transportation, various associations have to promote renewables suitable for domestic use. For example, taking into consideration the several types of PV panels and wind turbines, they should test different areas for solar irradiation and wind potential to produce the maximum energy possible. Greek government should offer varied initiatives for different areas according to the harvested data e.g. Heraklion, Patras and some parts of Athens have larger PV power potential than other areas, so consumers may prefer Fix-mount or Adjustable-mount PV panels that are more affordable and suitable for areas that have sunlight all daylong. In other cities like Thessaloniki or Ioannina where the presence of the sun is lesser, wind potential can be a decisive factor for energy production. In rural areas Horizontal-axis wind turbines can prove beneficial and support city's grid together with the use of Vertical-axis turbines that turn out to be more useful in urban areas, where the wind changes direction. In both situations, towers should be placed in the right height for the best result and reduction of energy production turbulence. Computational Fluid Dynamics simulations offer a helping hand in discovering zones with the best wind potential especially in urban areas with wind speed and direction instability. Moreover, by collecting wind history data and buildings' height, these simulations predict the wind capability in several city's rooftops and compare the amount of wind energy they can produce. Wind alters its speed and orientation by impacting with large or small buildings, trees etc. Things get more complex when we deal with areas that face multidirectional winds everyday, so it is important to have a tool that shows these alterations in real time 3D presentation. With the help of wind forecasting methods and the presentations, tests will be taken to decide whether a rooftop is suitable for a VAWT manufacture or not. This will result in a much more effective plan that can save lots of money and prove very effective in energy production. Figure 5.2 shows the mean wind speed of a part of the administrative region of Attiki, and it can be noticed that within central Athens, the wind speed reduces drastically due to the presence of buildings.

The continuous worldwide EV fleet expansion affected Greece and it can be distinct through EU stats showing that Greeks were persuaded the most to buy a EV. Particularly, in 2021 6,967 electric cars were listed in Greek electrotransportation market, whereas only 480 were on streets two years prior. Adding to this, the fact that a series of incentives for electric taxis makes a breeding ground for V2G technology. New bidirectional charging points should be added all over the big urban centers and owners will be able to access charging and energy production data through an app. They can contribute to their own charging unit and consequently to their house, but also to others, both local or domestic, that are available at this time [45]. The availability of EV charging stations will be accessed through the app, data from the energy transactions will be sent to the user's energy service provider and the results will be tangible in electricity bills [46].

Greece's rejuvenated grid will incorporate profoundly advanced transmission lines and smart devices. In addition to the propositions made above, this paves the way for a general smart grid adoption. Creating virtual neighborhoods in which people may help each other by trading energy from renewables or V2G, is a path to decentralizing the grid and establishing the client as a protagonist in the process of producing and consuming electric energy [47], [48]. As stated in earlier chapters, smart meters will gather information from smart devices and home appliances and take decisions in order to maintain stability on the grid. Furthermore, the client can keep an eye on electricity stats and energy demands through an app, and interfere according to the provider's guidance, by switching off a device that's not in use, programming an appliance to operate in certain hours and shifting electricity consumption to meet energy efficiency measure's demands [49].

It is reported that there are various projects, costing over 2 billion euros, underway, to ensure that electricity distribution and consumption will be handled by SG technology. By 2009, users could check their business energy consumption or the produced energy of their RES unit, through a PPC platform, thanks to the project carried by the company, that included the installation of smart meters in MV customers for the benefit of remote energy metering and overall better customer service. In addition, one of the main goals of PPC will be the control of energy distribution, all across the mainland and the islands, with the use of

SCADA and Distribution Management System (DMS) technology, to ensure the automated optimal operation and management using smart Remote Control Circuit Breakers (RCCB), Auto Recloser Circuit Breakers (ARCB), Current Sensor Fault Detectors (CSFD) and MV Substations control centers. Using Geographic Information System and SCADA/DMS, the aim is to illustrate the Greek grid with all its components, in real time. DMS offers real-time data that support load flow analysis and load forecast, finding the most favorable in order to provide energy fast and with as less losses as possible and maintaining voltage value at appropriate levels. SCADA and DMS not only can they enhance several energy reliability indexes System Average Interruption Duration Index, measuring the average blackout duration, and System Average Interruption Frequency Index, measuring the average blackouts of a customer throughout a year, but also can guarantee the prolonged function of grid's components with the aid of fault, overload and voltage value fluctuations prevention. HEDNO is going to equip the overhead lines with RCCBs and ARCBs, which in turn can offer grid stability by remotely rejecting loads to avoid power outages, keeping voltage in the preferred levels and mitigate power losses. These devices will be supervised by MV or HV Remote Terminal Unit (RTU) which, according to signals, can identify short circuit current, isolate short circuit maintaining the flow of power for the rest of the system and as a result reduce the time needed to restart the power supply. Last but not least, CSFDs are placed in specific spots in both overhead and underground MV lines, or in LV substations for regional use, and can promptly detect short circuit current flow. Overall, their smart technology offers the opportunity for RTUs to identify the exact location of the issue and act fast to deal with it.

Contemporary needs and technology require smaller generation units, like renewable power plants, connected to MV or LV, in the interest of supplying local customers and taking advantage of the excess energy, either saving it in storage units or profit from giving it back to the distribution network to help other customers [50]. "Xanthi islanded microgrid" is a project that aims to fulfill load demand with RES and energy storage. Sunlight, the company that owns the microgrid, uses PV panels and WT for energy production, along with lead-acid batteries for storage and a diesel generator for backup. Its goal is to exchange power among the city of Xanthi based on demand response strategies, ameliorate communication at network level by automating decisions based on signals of energy requirements and availability, and maximize power usage from renewables and storage units. In the storage section, flexible algorithms for charging/discharging paired with hybrid storage options are introduced and form a virtual storage control center that offers balance to the smart grid. Last but not least, in transportation there are considerations of changing the public means of transport into new, electric ones, as well as powering up the companies forklifts and using V2G technology for peak demand periods. The EU targets for the Greek grid are -40% CO_2 emissions, over 27% increase in RES units by 2030, and development grid control and operation via satellite signals, powerline communication systems and fibre optic lines. 700 billion € will facilitate energy distribution by 2035 while 62 billion € will take part in digitalizing the grid through with smart grid control centers and smart meter installment for over 200.000 households.

Figure 5.1: Transmission network in Greece as of 2017

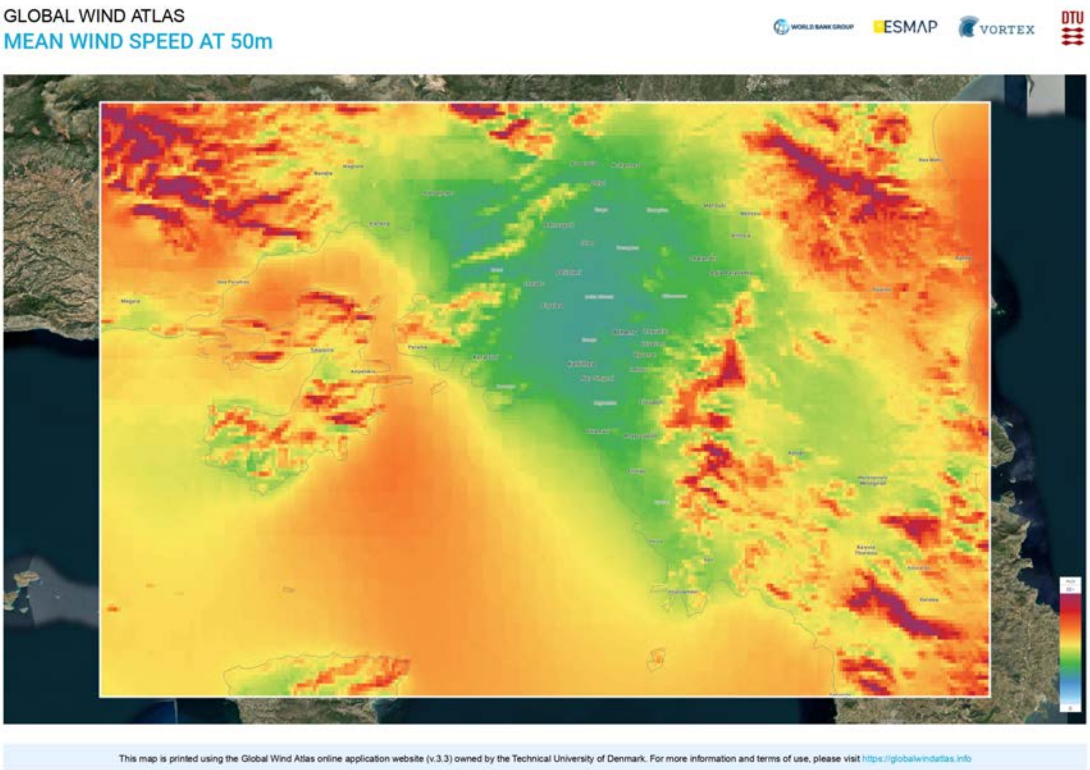

Figure 5.2: Mean wind speed in Attiki

Chapter 6

Pairing renewable energy sources and Smart Grids

6.1 Introduction

In previous sections, this diploma thesis gave a theoretical view of Smart Gids and RES, analyzing their components and discussing benefits and obstacles in their integration. As mentioned earlier, power flow and communications, through wireless and wired communication procedures, are bidirectional and some consumers have started to get used to the new mechanisms by installing smart appliances and small RES units in their homes, in order to exchange energy and information mutually and with the other domains. We can view the integration of Renewable Energy Sources in Smart Grids as the creation of a hybrid system consisting of different RES units, ESS and loads [51], [52]. The main idea is to orchestrate the interaction of these features to maximize systems' efficiency. As said before, these systems can offer ancillary services to the existing power grid, or operate as a stand-alone structure. Communication is key to achieving this, so a smart communication system guarantees the optimal bidirectional flow of energy and data from multiple devices, like smart meters and the presence of a main control system to coordinate production, storage and distribution [53]. Software and hardware advanced equipment, demand-side management schemes and communication techniques complete the system's backbone.

In this section, a more practical perspective is introduced by examining the world of smart communication systems and Demand Side Management (DSM) techniques in the exploitation of solar and wind energy in Smart Grids, such as loss mitigation techniques in energy production and distribution, optimizing the performance of generation or transmission via Energy Management Systems [3],security schemes in order to protect user's data from being infringed on, DSM procedures for better load distribution, flatten the electricity demand curve etc.

6.2 Communication Systems

6.2.1 Supervisory Control and Data Acquisition

These systems consist of software applications responsible for the management of real-time data to control devices and infrastructure, and operate several procedures. The features of SCADA are data acquisition and storage, remote control, network communication, alarms, information storage and reports. Sensors collect data and transmit them to SCADA field controllers, which communicate with SCADA supervisory computers and in turn they send commands to actuators [54]. The hierarchy of these systems is presented in Figure 6.1.

- **Sensors and Actuators**: A sensor detects a certain feature of a device and creates analog or digital signals, whereas an actuator is responsible for responding to analog and digital input signals and perform a certain action, like turning on and off a device.

- **Remote Stations**: Collects and forwards telemetery data from sensors to Central Monitoring Station (CMS). The two types of remote stations are Remote Telemetery Unit (RTU) and Programmable Logic Controller (PLC). RTUs are electronic devices using microprocessors to exchange data between sensors and the CMS, and PLCs are industrial computers that guarantee reliability, safety and effectiveness in carrying out complicated processes.

- **Central Monitoring Station**: Houses the core of SCADA supervisory computers that gather all data from RTUs and PLCs, which communicate with several RTUs via FM frequency and use Human-machine interface (HMI) to illustrate the system in monitors. Then the educated personnel can inspect and manage information with graphical user interface (GUI) and take action by changing controllers' specifications, altering systems topology, detect and counteract issues, manually operate equipment or stopping system's operation.

- **Communication network**: Communication is achieved by different ways according to the system's topology. For local systems, in example an industry, powerline communication is the right choice, while for extended, yet not secluded, systems the preferable alternative is by telephone lines. Last but not least, RF communication via modems, wireless network or radio repeaters are used in wide-range systems including remote aeras.

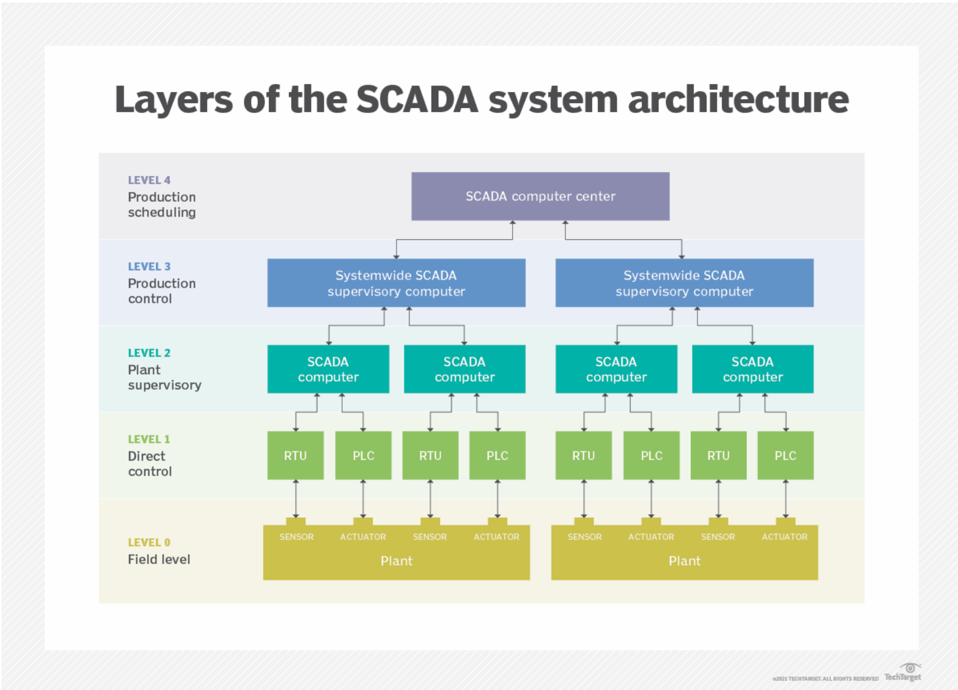

Figure 6.1: SCADA architecture

6.2.2 Advanced Metering Infrastructure and Smart Meters

AMI is a bidirectional network system that monitors electricity, gas and water levels, by exchanging information between users, utilities and energy providers. Rather than conventional meters, AMI uses the bidirectional flow of data to not only review results, but also to take action by using data-driven algorithms. Smart meters are electric meters recording electricity consumption and use the smart communication network of AMI to provide information, either connected with cable or wireless they enable the flow of information by radio signals, cellular networks or powerline communication [55]. The Data Management System, being the information storehouse, collects and reviews energy reports and decides whether to intervene, for example disconnecting appliances in the event of a power outage. Meter

Data Management System (MDMS) is the core of decision making in AMI, turning voltage and current waveforms from smart meters to valuable information which can later be used to Demand Response techniques, load forecasting etc. MDMS also offers to user the opportunity to inspect the harvested information with their smart phone or SM screens connected to the internet, to create alerts for altering their energy consumption and rely on cheaper and environmental-friendly load scheduling techniques that will be presented later on. As stated above, AMI is used in DR programs and for power outage detection, but their functionality extends to energy theft detection and the integration of RES in the power grid. Managing the intermittency of RES and regulating distributed energy is one of the key roles of AMI. It goes without a doubt that AMI has unlimited future prospects when paired with RES, controlling the unstable energy production from renewables and monitoring the distribution and storage can be a game-changer in energy section, electricity from RES will be exploited to its full extent with smart distribution algorithms that decide which household or utility needs additional energy and modern energy storage units towards the optimal exploitation of stored energy when needed [56]. AMI also offers frequency control, keeping it close to its nominal value to ensure system's integrity, and voltage control, maintaining voltage values near the rated one to ensure infrastructure preservation and blackout prevention, thus improving system stability while diminishing power losses.

Smart meters play a significant role in DSM schemes in residential and community level. Forecasting techniques are used in generation and consumption sector. In generation, renewable energy forecasting is trending and operating with complex algorithms, but it still has a lot to improve, mainly because weather forecasting even though it is helpful, it is still an imponderable factor. Additionally, SM installed in storage premises notify suppliers for the available energy and replenish it fast for future use. In consumption sector, SM separate loads to shiftable and non-shiftable for DR strategies, use demand and economical data to perform load forecasting techniques. Electricity price forecasting is an additional characteristic of SM, aiding the all the more developing sector of power trading, by using both generation and demand forecasting to define electricity prices in short term or long term, consequently leading to smart consumption forecasting techniques according to the given information.

6.3 Distributed generation control

In a previous section, we discussed issues surrounding the nature of renewable power plants because of intermittency and voltage-frequency fluctuations. To counteract these problems SG technology uses devices suitable for remotely controlling production and dealing with power issues. While SCADA and smart meter technology involvement in this is discussed above, we take a look at devices upgrading electricity production and maintaining operation in voltage inconstancy.

- **Maximum Power Point Tracking (MPPT)** : Developed charge controllers used in PV panels that can convert solar energy to electricity with better efficiency, harvesting up to 30% more energy than traditional pulse width modulation (PWM) controllers. Its effectiveness lies in the addition of a DC/DC converter that regulates voltage in the PV system. Using smart battery life algorithms, SoC is regulated and battery life is prolonged. Lastly, MPPT display real-time or saved results in phone apps, constantly informing the using of his unit's performance.

- **Fault Ride Through (FRT)**: A feature of mainly WT generators, but also used in PV and ESS. It consists of Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT). LVRT is about maintaining grid connection in the event of a voltage drop, basically working as a large-scale uninterruptible power supply device, that is used to offer automated electricity backup. On the contrary, HVRT helps the power plant remain connected in sudden voltage increase.

6.4 Demand Side Management and Demand Response

One of the key aspects of DSM techniques are the Demand Response programs. Demand response programs are initiatives created to control the demand for electricity during times when the power grid is under a lot of strain or when electricity costs are at their highest. In order to balance the supply and demand of electricity and maintain grid stability, these programs encourage users to use less electricity during these important periods. Demand response's fundamental tenet is that customers can modify their consumption habits in response to indications or incentive programs from the utility or grid operator. Customers can relieve system strain, prevent power outages, and lessen the need for extra power generation by voluntarily lowering or adjusting their electricity usage, particularly during high demand hours. This can also be accomplished by automated smart devices that can be connected to certain appliances. Demand response initiatives are crucial not only for controlling power demand, strengthening grid stability, and fostering a more sustainable and effective electrical system, but also for lowering greenhouse gas emissions by decreasing the reliance on fossil fuel-based power generation during peak hours. Some of the DR techniques are Time of Use (TOU) rates, Critical Peak Pricing (CPP), Load Curtailment Programs (LCP), Peak Time Rebate (PTR) programs, Demand Biding Programs (DBP) etc.

- **TOU rates**: The cost of power is determined on the time of day under these rates. Customers pay higher prices at times of high demand and reduced rates during times of low demand. The system will experience less stress if users shift their energy use to off-peak times and benefit from lower pricing.

- **Critical Peak Pricing**: In these schemes, rates are markedly increased for consumers during specified critical peak times, which are times of particularly high grid demand. Participants are advised to use less electricity during these peak events after receiving early notice of them from energy providers.

- **Direct Load Control (DLC)**: DLC handles the operation of mainly household appliances via a control switch that is handled by electricity providers. While being very convenient for households, DLC is not suitable for the industrial sector. Some small-scale businesses could also benefit from such programs. Electricity providers announce the amount of electricity that has to be curtailed and users place their bids. If the bid is accepted and the user meets the contract's demands, he will be awarded, but if he misses the target he receives a penalty.

- **Load Curtailment Programs**: These programs are basically the same as DLC plans but deal with multiple loads rather than only household appliances in DLC. Commercial and industrial consumers who can lower their electricity demand by changing their production processes or operations frequently employ these programs. These consumers get monetary rewards or other advantages for agreeing to reduce their energy use at times of peak demand, but if the terms of the agreement are not met, a fine is given to the user.

- **Peak Time Rebate**: These programs offer consumers financial incentives or bill adjustments for cutting back on their electricity usage at times of high demand. Typically, participants are informed in advance of impending peak occasions and compensated according to how much they reduce their electricity usage.

- **Demand Biding Programs**: Customers may choose to bid on their capacity to reduce electricity consumption in real-time electricity markets in such demand response systems. Grid operators can ask these customers to cut back on their usage and pay them appropriately when they do so. As a result, electricity prices drop and the grid is more stable during peak demand periods. Demand biding techniques associate with short-term, user-driven actions that can be far more enjoyable and profitable for both users and energy providers.

- **Emergency Demand Response Programs**: They have many similarities with DBP, but are mainly linked to some electricity meltdowns, power outages etc. In these situations, users can decide to voluntarily alter their current energy consumption at this period, in order to get a compensation.

When talking about DR programs the three main sectors that these schemes are implemented should be taken into account.

- **Commercial Sector**: In the commercial sector, demand response initiatives frequently target companies, offices, stores, and other commercial facilities. These initiatives encourage businesses to use less electricity during times of high demand or during emergencies. By modifying the settings for their lighting systems, air condition systems, and other electrical equipment, commercial entities can correspond to demand response tactics, for instance, during peak hours, they might temporarily raise temperature setpoints, turn down the lights, or use less non-essential equipment. Commercial consumers can reduce stress on the electrical system, stabilize the grid, and save money by taking part in demand response programs by gaining financial incentives in exchange for their readiness to reduce their energy usage.

- **Residential Sector**: Demand response programs in the residential sector encourage individual homes to cut back on their use of power during times of high demand. Smart meters and home automation systems, which enable homeowners to monitor and manage their energy use, are frequently used to implement these programs. Initiatives for reducing residential consumption sometimes utilize TOU or CPP schemes. It is advised for consumers to carry out their energy-intensive tasks at off-peak times when electricity prices are lower, such as running large appliances or recharging electric vehicles. Residential participants can control their energy expenditures and help to maintain the stability of the system by voluntarily changing their energy usage habits.

- **Industrial Sector**: Due to its high electricity consumption, the industrial sector is essential to demand response. Large energy consumers including factories, data centers, and industrial facilities are the focus of demand response systems in the industrial sector. These consumers frequently have the choice to modify their energy consumption by streamlining production procedures, improving workflow, and improving equipment performance. Industrial demand response schemes typically provide financial rewards for reducing or shifting loads during periods of high demand. By temporarily lowering output levels, altering work schedules, or employing backup power sources, participants can lower their electricity demand. They assist in maintaining grid stability and balancing the supply and demand of electricity by doing this, and they may be compensated or pay less for their involvement.

Further investigation is needed for smart meters and smart communication systems surrounding Demand Response programs. Smart Meters play crucial role in promoting these schemes and making it possible for customers and grid operators to monitor and communicate energy consumption data effectively, facilitating the interchange of information in real-time. They are computerized devices that measure and record electricity consumption at regular intervals, usually hourly. Smart meters allow for two-way communication between the consumer and the utility or grid operator, in contrast to standard meters. They deliver precise and timely information on energy utilization, enabling more accurate monitoring and management of electricity usage. Smart meters enable users to monitor their patterns of energy use and spot potential plans for energy savings tactics. Additionally, dynamic pricing mechanisms like TOU rates or CPP, which are essential to many demand response systems, are made possible by smart meters. The meters responsible for this are called Interval Meters which are TOU meters measuring electricity consumption in hourly increments. They are used to inform users about these pricing plans, allowing them to modify their energy consumption in response to real-time pricing signals. Smart meters also give grid operators useful data on power quality, load profiles, and electricity demand. Operators can use this data to pinpoint peak demand periods, foresee grid stress, and efficiently control the supply-demand balance during emergency situations. By creating a communication infrastructure for the flow of data between consumers, grid operators, and other sectors, Smart Communication Systems support the operation of smart meters. The real-time information flow required for the execution of demand response programs is made possible by these technologies. The network of communication protocols and technologies known as AMI links smart meters to the utility's back-end operations. It makes it possible for consumption statistics, meter readings, and price information to be securely and reliably transmitted between the utility and customer premises. These networks can be implemented utilizing a variety of communication technologies, including cellular, radio frequency, and powerline carrier networks. AMI networks make it easier to gather information on energy use, read meters from a distance, and communicate in real-time for demand response applications. Smart meters and other smart equipment, such as thermostats and appliances, can communicate with each other and with the consumer's premises thanks to HANs, which also enable the interchange of information and the receipt of commands. Consumers may monitor and manage their energy use, get demand response alerts, and take part in load-reduction efforts thanks to HANs, while the service provider's systems and the smart meters are connected using WAN technologies. Cellular networks, powerline communications, and specialized wireless networks that provide the safe transfer of data over greater distances are included in this. Smart communication systems can also be categorized in the manner of consumer's participation. On the one hand, Home Energy Management Systems (HEMS) are advanced communication systems that make it possible for households to keep an eye on, manage, and optimize their energy usage. To provide real-time energy usage data, energy management capabilities, and demand response participation possibilities, these systems incorporate smart meters, smart thermostats, smart appliances, and other connected devices. Customers can manually modify their energy use with HEMS in response to price signals or demand response events. On the other hand, Demand Response Automation Server (DRAS) and Open Automated Demand Response (OpenADR) are automated techniques mainly handled by energy providers. DRAS programs harvest information and commands from the grid operator and deliver them to multiple end-use systems or appliances inside a building or facility. By coordinating and managing energy-consuming machinery like heating, ventilation, and air conditioning systems, lighting, and manufacturing equipment, DRAS guarantees prompt and automatic reactions to demand response events.

OpenADR systems offer a framework for communication between utilities, aggregators, and end-user customers. Using OpenADR, utilities can transmit signals or events to consumers' energy management systems, enabling them to automatically change their energy usage in accordance with specified criteria using automated demand response.

6.4.1 Demand side management simulations

Many papers deal with DSM techniques, which is the most important aspect of the smart grid. These programs are used to manage electricity consumption pattern for consumers, meanwhile reducing peak demand, exploiting available power from RES and achieve the best power efficiency. In general, there are six techniques for DSM programs, peak clipping, load shifting, valley filling, load building, strategic conservation and flexible load. Peak clipping refers to the curtailment of the load in peak hours, in load shifting the peak demand load is moved to off peak hours, valley filling is about increasing the load in off peak hours, load building refers to increasing the overall load demand to improve consumer's quality of life, conservation aims for a more efficient way of energy exploitation while decreasing the demand and flexible load is about some appliances that can be monitored to modify their energy consumption according to signals from the grid meanwhile not causing disruption in the grid.

Two of the proposed models include a load shifting technique presented in [57] and [58]. Sinha et al. created an algorithm that shifts the consumption of some devices to off peak hours according to time-of-day tariffs and appliance priority. Using the forecasted load of different households per hour the algorithm shifts the consumption to periods when the cost of kWh is small thus reducing electricity cost and smoothing out the daily demand. Hakimi et al. proposed an algorith where the moment when the discrepancy between load and RE generated power is most evident is the time when the controllable loads are shifted. The load shifting of the washing machine, the dishwasher and the heating/cooling system counterbalances the intermittent nature of the solar and wind energy used in this paper. The outcomes demonstrate that implementing this strategy will boost consumption flexibility and RES penetration in smart grids. Demand Response programs' importance may increase in the future when bidirectional energy trading becomes the norm in Smart Grids. Bidirectional energy trading is made possible, in part, by the widespread use of distributed energy resources and the installation of smart metering systems in future Smart Grid, which necessitates the careful design of control mechanisms for both the bidirectional energy scheduling and the associated financial incentive optimization procedures. Wu et al. [47] investigated the energy trading process in a hybrid system where a utility company and a Local Trading Center (LTC) work together for the benefit of all participants. Energy sellers and buyers work together with the LTC in two ways the nonprofit-oriented LTC, which seeks to assist only consumers and sellers, and the profit-oriented LTC, which targets at increasing its own profit as much as possible, while offering the necessary benefits to sellers and buyers. This work focuses on investigating the benefits of buyers and sellers in accordance with the appropriate pricing of the LTC and its related demand response management system.

Pairing Demand Response programs with RES is an issue concerning the paper in [59]. Ali et al investigate the different methods of using DSM programs and not only present their benefits but also propose their method of a smart Demand Response program. The techniques mentioned in this paper are Ant Colony Optimization (ACO) and Teaching-Learning Based Optimization (TLBO). Ali et al. suggest a new methodology pairing the two optimization techniques mentioned above. ACO is a meta-heuristic algorithm that states that when ants gather their food, they return to their colony in the quickest possible route. As long as DR is concerned, household appliances represent the ants and the 24 hours of the day represent the routes, in a way that each appliance will have to use the best route in order to reduce cost, Peak-to-Average Ratio (PAR) and carbon emissions. These elements are taken into account and the algorithm figures out the best possible solution. TLBO has two structural components teacher and students, and operates in two stages, teacher and learner phases. In teacher stage, all individuals gather information from the teacher, who is selected as the best choice among all the people. However, in the learner stage all individuals share information-knowledge among each other and this happens because if a new individual owns better knowledge than the teacher, he replaces him. This continues until the best possible solution is given and likewise the suitable hour for the appliances' operation is examined and updated through TLBO. The authors create a new approach using both ACO and TLBO in a hybrid scheme and by implementing solar and wind energy, battery storage systems and V2G present the benefits in PAR, cost and CO2 reduction. The study shows that this combined design brings better results in PAR and cost mitigation and equal or less results in CO2 reduction than those mentioned earlier. PAR Designing a Smart Grid Mangement System is the main goal for the next paper [60]. Ricalde et al. propose a small scale SG for public building use. The proposed microgrid integrates as main energy sources wind turbines and photovoltaic arrays with an installed capacity of 6 kW but with external sources in the form of hybrid or electrical vehicles that can provide or consume energy from the microgrid. A management system is introduced in order to control the loads and ensure balance between generated and demanded energy. Weather and load data for a whole year have been used to do this, 10% of the total system capacity is used for this implementation. 16kWh of battery capacity, 3.2kW wind turbine and 2.8kW of PV panels are used by the microgrid as well as EVs working with V2G technology. A Multiagent system (MAS), a computerized system created from multiple interacting intelligent agents that address challenges that are tough for a monolithic framework to solve, is using a communication system to turn on and off electrical loads in the building. This aims to cost reduction and energy balance. Wind and solar power forecasting is made by a neural network using Kalman Filter, an algorithm that estimates and predicts the state of a dynamic system, and offers the estimated power production to the MAMS to control for the best energy distribution possible concerning demand and EUR/kWh throughout the day. Overall, MAMS play a vital role in optimizing and managing the smart grid and distributed energy resources. It is used for DR and load management coordinating the agents, ensuring the flow of information between them, balancing supply-demand and maximizing the RES potential from distribution and storage meanwhile ensuring grid stability. Last but not least, forecasted data are used in [61]. Zarei et al. proposed an AC optimal power flow model in regard to Demand Response. RES units, demand prediction with deep learning, and the algorithm will work together to achieve peak reduction, voltage fluctuations minimization and cost reduction. Improving the voltage profile and power quality and improving the load factor of the power grid are the additional benefits of DR programs and are presented in this paper. The voltage level can alternate from generation and consumption fluctuations and power losses, thus jeopardizing the stability of the grid, so it is crucial to maintain the same voltage values of the system.

6.5 Fault types and critical clearing time

System's symmetry is another crucial part of electric power systems, concerning the concept of balanced distribution of voltage and current in the three phases throughout the system. A symmetrical system is based on efficient power transfer with less losses, stable operation without voltage fluctuations, reduced harmonic distortions and machinery durability. Faults are divided to symmetrical and unsymmetrical based on the number of the phases involved. Symmetrical, or balanced, faults are those that involve all three phases of the system whereas unsymmetrical, or unbalanced, refer to one or two phases of the system. The most common balanced fault is the three-phase fault and as far as unbalanced faults are concerned Single Line-to-Ground (SLG), Double Line-to-Ground (DLG) and Line-to-Line (LL) faults are mainly studied.

6.5.1 Short circuit faults

This is the most critical fault type, caused when two independent parts of the grid connecting to each other, mainly caused by environmental factors or equipment failure. Short circuit faults are characterized by excessive power flow, voltage dips, power outages due to the respond of safety devices in these faults, severe damage in power machinery and serious threats for the population from electric shock, fires and explosions [62]. To counteract these faults power grid is equipped with protective relays that send signals to circuit breakers to separate the defective part of the grid from the rest and reclosing devices to automatically close the circuit, surge protectors that restore voltage levels, grounding system to prevent electric shock, and fuses. There are four main examples of short circuit faults:

- **Line-to-Line fault:** two conductors of different phase come into contact with each other resulting in current surge and voltage dips that can cause irreversible damage in electrical equipment.

- **Single Line-to-Ground fault:** a conductor touches ground or a grounded object, usually because of high winds or lighting strikes that cause tree branches touching power lines, and results in abrupt increase in current.

- **Double Line-to-Ground fault:** it is basically the same as Line-to-Ground fault but require two phase conductors that come into contact with the ground simultaneously.

- **Three-phase (3Φ) fault :** happens when all three phase conductors are short circuited together either directly or with the ground, causing maximum flow of current and dangerous voltage dips.

6.5.2 Open circuit faults

Open circuit faults develop when there is a discontinuity in the electrical system, which interrupts the passage of electricity. These flaws can impair the reliability of the grid again leading to hazardous consequences in equipment and people, and cause power outages. These problems can be mitigated with the traditional safety devices mentioned above and contemporary real-time monitoring devices. One, two or three phase conductors can be disconnected or impaired resulting in single line open fault, double line open fault or three line open fault respectively. Their influence in the grid is proportional to the number of phase conductors that are disconnected in load, safety and system stability, starting from an imbalance in the system with single line fault, and leading to full power loss with a three line fault.

6.5.3 Critical Fault Clearing Time

The process of clearing the faults is carried through the analysis of Critical Clearing Angle (CCA) and Critical Clearing Time (CCT). The CCT is a pivotal concept in power system stability analysis, specifically in the context of transient stability. It represents the maximum duration for which a power system can sustain a fault before the system becomes unstable. If the fault is cleared within this time, the system can maintain synchronism and return to a stable operating condition. Determining the CCT is essential for the design and setting of protection systems, ensuring the reliability and resilience of power networks. During pre-fault conditions, load flow analysis is performed to establish the steady-state operating conditions of the power system and the initial rotor angles and power flows are calculated. Consequently, the user introduces a fault at a specified location and simulates its impact on the system, and monitors the system's response, particularly the rotor angles of the synchronous generators. After that, by clearing the fault, user observes whether the system regains stability gradually increasing the fault duration,usually with a time step of 50 milliseconds, in simulations. The maximum duration for which the system remains stable upon fault clearance is the CCT. The swing equation describes the dynamic behavior of a synchronous generator rotor:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \tag{6.1}$$

where:

- M is the inertia constant,

- δ is the rotor angle,
- P_m is the mechanical power input,
- P_e is the electrical power output.

The electrical power output P_e of a synchronous generator can be expressed as:

$$P_e = \frac{EV}{X}\sin(\delta) \tag{6.2}$$

where:

- E is the internal voltage of the generator,
- V is the terminal voltage,
- X is the reactance of the transmission line,
- δ is the rotor angle.

The Equal Area Criterion, seen in Figure 6.2 is used to determine stability. For a system to remain stable, the areas A_1 and A_2 must be equal:

$$A_1 = \int_{\delta_0}^{\delta_{cr}} (P_m - P_e)\, d\delta \tag{6.3}$$

and

$$A_2 = \int_{\delta_{cr}}^{\delta_{max}} (P_e - P_m)\, d\delta \tag{6.4}$$

where:

- δ_0 is the initial rotor angle,
- δ_{cr} is the critical clearing angle,
- δ_{max} is the maximum rotor angle during the transient.

The CCA is the rotor angle δ_{cr} at which the areas A_1 and A_2 are equal. To find the CCA, solve the following equation:

$$\int_{\delta_0}^{\delta_{cr}} (P_m - P_m\sin(\delta))\, d\delta = \int_{\delta_{cr}}^{\delta_{max}} (P_m\sin(\delta) - P_m)\, d\delta \tag{6.5}$$

Simplifying, this becomes:

$$\int_{\delta_0}^{\delta_{cr}} (1 - \sin(\delta))\, d\delta = \int_{\delta_{cr}}^{\delta_{max}} (\sin(\delta) - 1)\, d\delta \tag{6.6}$$

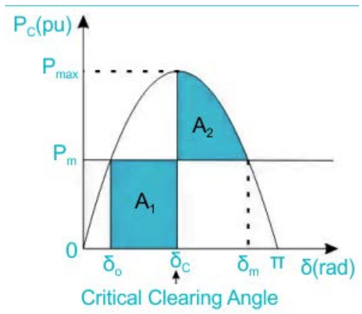

Figure 6.2: Equal area criterion

Since P_m is a constant and can be factored out, the equation reduces to:

$$[\delta + \cos(\delta)]_{\delta_0}^{\delta_{cr}} = [\delta + \cos(\delta)]_{\delta_{cr}}^{\delta_{max}} \tag{6.7}$$

Expanding this:

$$(\delta_{cr} + \cos(\delta_{cr})) - (\delta_0 + \cos(\delta_0)) = (\delta_{max} + \cos(\delta_{max})) - (\delta_{cr} + \cos(\delta_{cr})) \tag{6.8}$$

Simplifying, we get:

$$2\delta_{cr} + 2\cos(\delta_{cr}) = \delta_{max} + \cos(\delta_{max}) + \delta_0 + \cos(\delta_0) \tag{6.9}$$

Therefore, the Critical Clearing Angle δ_{cr} must satisfy this equation. Typically, δ_{max} and δ_0 are known or can be estimated from pre-fault and post-fault conditions.

To find the CCT, integrate the swing equation over time. During the fault, the electrical power P_e might drop to zero, so the equation simplifies to:

$$M\frac{d^2\delta}{dt^2} = P_m \tag{6.10}$$

Integrate once to get the first derivative:

$$M\frac{d\delta}{dt} = P_m t + C_1 \tag{6.11}$$

Assuming the initial angular velocity $\omega_0 = 0$ at $t = 0$, $C_1 = 0$:

$$M\frac{d\delta}{dt} = P_m t \tag{6.12}$$

Integrate again to find δ:

$$M\delta = \frac{P_m t^2}{2} + C_2 \tag{6.13}$$

Assuming the initial angle δ_0 at $t = 0$, $C_2 = M\delta_0$:

$$M(\delta - \delta_0) = \frac{P_m t^2}{2} \tag{6.14}$$

Solving for t, the critical clearing time t_{cr} is:

$$t_{cr} = \sqrt{\frac{2M(\delta_{cr} - \delta_0)}{P_m}} \tag{6.15}$$

6.6 Symmetrical Components

In power systems analysis, symmetrical components are a method used to simplify the analysis of unbalanced three-phase systems and demonstrates that we can display any set of N unbalanced phasors as N number of systems with N number of symmetrical sets of balanced phasors. These components are known as positive, negative, and zero sequence components and are displayed in Figure 6.3.

- **Positive Sequence**: 120 degrees apart, following the original phase order (A-B-C).
- **Negative Sequence**: 120 degrees apart, in reverse phase order (A-C-B).
- **Zero Sequence**: All phases are in phase (0 degrees relative difference), following the original phase order (A-B-C).

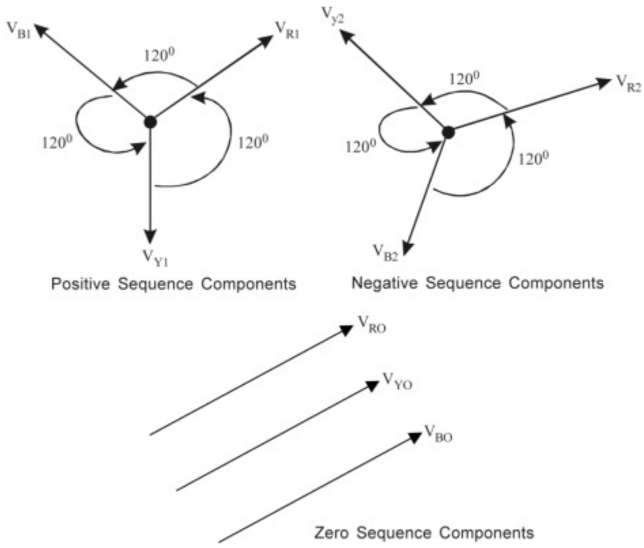

Figure 6.3: Symmetrical Components

Given three-phase voltages V_a, V_b, V_c, the symmetrical components are calculated as:

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$
$$V_1 = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$V_2 = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

Where $a = e^{j120^\circ} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$.

6.6.1 Phase Voltages from Symmetrical Components

$$V_a = V_0 + V_1 + V_2$$
$$V_b = V_0 + a^2V_1 + aV_2$$
$$V_c = V_0 + aV_1 + a^2V_2$$

6.6.2 Symmetrical Components of Currents

Given three-phase currents I_a, I_b, I_c, the symmetrical components are calculated as:

$$I_0 = \frac{1}{3}(I_a + I_b + I_c)$$
$$I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c)$$
$$I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c)$$

6.6.3 Phase Currents from Symmetrical Components

$$I_a = I_0 + I_1 + I_2$$
$$I_b = I_0 + a^2I_1 + aI_2$$
$$I_c = I_0 + aI_1 + a^2I_2$$

$$a = e^{j120^\circ} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$
$$a^2 = e^{j240^\circ} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$
$$a^3 = 1$$
$$1 + a + a^2 = 0$$

6.6.4 Symmetrical Components of Currents

For currents, the symmetrical components I_{a0}, I_{a1}, I_{a2} represent the zero-sequence, positive-sequence, and negative-sequence components respectively:

- **Zero Sequence Current $\mathbf{I_{a0}}$**

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$$

- **Positive Sequence Current $\mathbf{I_{a1}}$**

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$

- **Negative Sequence Current $\mathbf{I_{a2}}$**

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + aI_c)$$

To summarize, here are the equations for phase voltages and phase currents:

- **Phase Voltages**

$$V_a = V_0 + V_1 + V_2$$
$$V_b = V_0 + a^2 V_1 + aV_2$$
$$V_c = V_0 + aV_1 + a^2 V_2$$

- **Phase Currents**

$$I_a = I_0 + I_1 + I_2$$
$$I_b = I_0 + a^2 I_1 + aI_2$$
$$I_c = I_0 + aI_1 + a^2 I_2$$

6.7 Types of power system stability

Power system stability is the study of its dynamics during disruptions and refers to a system's ability to revert to normal or stable operation after being subjected to some type of disturbance. Power system instability is characterized by loss of synchronism, which occurs when synchronous equipment go out of phase due to a disturbance. Three types of stability are important: steady state, transient, and dynamic stability.

6.7.1 Steady state stability

Steady state stability is the study of subtle and gradual alterations or changes in the functionality of a system. The load is gradually increased, with the goal of determining the machine's maximum loading capacity before losing synchronism. The maximum power that can be delivered to the receiving end of the system without impacting synchronism is known as the Steady State Stability limit. The first step in determining steady state stability is to perform power flow analysis. involving solving the load flow equations to determine the voltage magnitude and angle at each bus in the network. The transferred power is determined by voltages at each point of the system, transmission line reactance, and phase angle difference between sending and receiving ends. When the phase angle difference exceeds 90 degrees, the steady state stability limit and estimated power represent the greatest amount of power that may be transferred before instability occurs. To improve steady-state stability, voltage-regulating FACTS devices, power system stabilizers, and additional infrastructure, such as transmission lines, generators, should be installed.

6.7.2 Dynamic stability

Dynamic stability refers to how a system responds to minor perturbations, which can cause oscillations. Dynamically stable systems have oscillations that do not exceed a particular threshold and disperse rapidly. If oscillations increase in amplitude, the system becomes unstable. Instability is typically caused by interconnected control systems. Refers to a power system's ability to remain stable and return to a steady operational condition after suffering major disturbances for a short time. These disturbances include large, unexpected events like faults, line trips, generator outages, or large load changes. Dynamic stability is critical for guaranteeing the ongoing and reliable functioning of power systems, as it addresses the system's behavior over a longer period of time, from seconds to minutes, following the initial disruption, including the effects of control systems and protection devices. The most typical method for analyzing dynamic stability is Time-Domain Simulation, which simulates the power system's response to disturbances across time using sophisticated models of generators, loads, transmission lines, and control systems. It may also use Frequency Response that examines the system's response to small-signal perturbations in the frequency domain and helps to create control systems that improve dynamic performance, and Eigenvalue analysis, a mathematical approach used to study the stability of power systems by examining the linearized system equations.

6.7.3 Transient stability

Transient stability analysis is critical for determining the power system's ability to remain stable and resume normal operation after a disturbance or fault. This research focuses on the system's responsiveness in the short term, often from milliseconds to a few seconds after a problem. Different forms of faults have varying effects on the transient stability of the power system. It's used to see how generators and other system components react to disturbances. Whether the system can maintain synchronism, the generators remain in phase with one another, determine the degree of damage and duration of faults that the system can tolerate, establish techniques and protective schemes to improve system stability, and implement control actions to mitigate the impact of faults [63]. Aspects that affect transient stability are inertia level, the response to critical fault clearing time and the use of control devices. After setting the characteristics of the system, a disturbance is set, usually a fault or generator trip and the results in rotor angles, voltage and power are presented in correlation with time. Different results can be shown if the CCT is not taken into consideration. The differences in system stability in clearing the fault before and after CCT are evident· if the issue is not resolved within the CCT, synchronous generators may lose synchronization with one another. This means that the generators' rotor angles will diverge greatly without settling, frequently crossing the 180-degree line.A stable response will show rotor angles recovering to equilibrium following a disturbance. Moreover, a stable voltage response will show a brief dip followed by a return to normal levels whereas an unstable voltage response will exhibit persistently low voltage or chaotic swings that fail to return to stable values. Last but not least, same as in voltage, a stable power response will exhibit a brief spike in power followed by a return to steady-state values, but an unstable power response exhibits persistent oscillations, with power levels failing to stabilize [64].

6.7.4 Flexible Alternating Current Transmission Systems devices

FACTS devices are a class of smart technologies that improve the controllability, stability, and power transfer capacity of AC transmission networks. This is accomplished through real-time control of several electrical characteristics such as voltage, impedance, and phase angle. FACTS devices are essential in modern power systems for addressing challenges such as congestion, stability, and power quality.They mainly use power electronic components such as thyristors, Gate Turn-Off Thyristors (GTO), and Insulated Gate Bipolar Transistors (IGBT) to provide fast and precise power regulation.

- **Shunt Compensation Devices:** connected in parallel with the transmission line and are primarily used for voltage control and reactive power compensation.

    1. **Static VAR Compensator (SVC):** Using Thyristor-Controlled Reactors and thyristor-switched capacitors it provides fast-acting reactive power compensation to adhere to voltage fluctuations maintaining stability.

    2. **Static Synchronous Compensator (STATCOM):** It provides better dynamic study compared to SVC, using voltage source converters, providing both inductive and capacitive compensation, and voltage regulation. It is usually operated with IGBT or GTO based converters, which can offer fast switching speeds in a large variety of applications, or precise control on turn-off applications respectively.

    3. **Thyristor-Controlled Reactor (TCR):** It regulates the amount of reactive power that the reactor absorbs through modifying the values of the connected thyristor's firing angle, the angle at which the thyristor is triggered. When the angle is 0 degrees the thyristor absorbs the maximum reactive power, whereas when the angle is delayed it absorbs less reactive power.

- **Series Compensation Devices:** connected in series with the transmission line and are mainly used to control power flow and improve the transmission capacity.

1. **Thyristor-Controlled Series Capacitor:** Using a series capacitor bank it modifies the series capacitance to control the transmission line's impedance and enhance the power transfer capability.
2. **Static Synchronous Series Compensator (SSSC):** A voltage source converter is used to provide a controllable voltage that in turn improves power flow and transient stability.
3. **Dynamic Voltage Restorer (DVR):** This time the voltage source converter is connected in series with the load and protects it from voltage disruptions. It is usually connected in series with critical loads that need to maintain voltage stability during disturbances.

- **Combined Shunt and Series Compensation Devices:** using the benefits of both shunt and series devices they offer an extensive regulation of the power system.

  1. **Unified Power Flow Controller (UPFC):** controls lines' voltage, impedance and phase angle levels through a series and a shunt voltage converter connected to a DC link.
  2. **Interline Power Flow Controller (IPFC):** has the same operation as UPFC devices, but it can control multiple transmission line with multiple connected converters.

By regulating voltage control, FACTS make sure that voltage levels adhere to certain bounds, preventing voltage swells and sags thus maintaining steady voltage levels, in order to avoid over- or undervoltage situations, safeguard delicate equipment and keep it operating effectively, and provide quick reactive power assistance to maintain voltage stability in the context of transient events and disruptions. Regarding Power flow control, they enhance transmission capacity by enabling more power to be transmitted across existing lines by modifying impedance and regulating the phase angle, as well as directing power flow through desired routes to balance loads and prevent overloading the transmission lines. As far as stability improvement is concerned, regulating transient stability, by enhancing the system's ability to withstand and recover from short-term disturbances like faults and sudden load changes, and steady-state stability by sustaining balance under regular operating circumstances is of outmost importance. Enabling almost immediate control over reactive power, voltage, and power flow, which is essential for emergency situations and abrupt load fluctuations, enhances the dynamic response of the system. Moreover, they are renowned for their ability to monitor systems in real time and modify parameters to maintain peak performance. Power quality improvement is also addressed with the minimization of the waveform distortion to reduce harmonics and avoid electrical equipment damage and overheating and guaranteeing flawless operation by balancing loads and dispersing them more equally throughout the network. Congestion control in power networks is the process of ensuring that electricity is efficiently delivered across the grid without overpowering any component of the network. Overloaded transmission lines can cause instability, outages, and higher operating expenses. Overloaded transmission lines can be caused by a variety of factors, including higher demand and unequal generator distribution, RES integration, or poor maintenance. FACTS devices play an important role in congestion management by improving power flow regulation, increasing system stability, and making better use of existing transmission infrastructure. Efficient congestion management reduces the need for costly infrastructure upgrades and operational costs associated with congestion, provides grid operators with the tools to manage power flows dynamically, adapting to changing conditions and demands, and allows for more reliable and cost-effective electricity markets, benefiting both producers and customers. Last but not least, FACTS devices such as STATCOM and SVC provide dynamic reactive power assistance, ensuring voltage levels remain stable despite intermittency of renewable energy. Also, FACTS devices help to maintain grid frequency by controlling power flows and adjusting for abrupt fluctuations in generation. Devices like Thyristor-Controlled Series Capacitor improve the power transfer capabilities of transmission lines, allowing more renewable energy to be carried over long distances without requiring new infrastructure and overcoming the obstacle of large distances between RES units and big cities, while UPFC and SSSC can guide power flows along specific channels, making better use of existing transmission lines and minimizing congestion.

6.8 Transient stability analysis simulation

For this diploma thesis, the IEEE 14 bus system is used as a reference and case study, to show the results of the integration of renewable energy to the grid regarding losses, voltage profile and transient stability stability. For this, PSS/E power system simulation and modeling software will be used to analyze the grid's components in different cases. The IEEE 14 bus system is shown in Figure 6.4. The following scenarios will be studied in this section:

- **Scenario 1:** IEEE 14 bus system with conventional generators
- **Scenario 2:** IEEE 14 bus system with wind generator
- **Scenario 3:** IEEE 14 bus system with wind generators and FACTS devices

6.8.1 Scenario 1: IEEE 14 bus system with conventional generators

In this scenario the classic IEEE 14 bus system is presented. It consists of 14 buses, 5 generators and 11 loads. After performing the Newton-Raphson solution from the PSS/E Graphical User Interface (GUI), the results about voltage profile and system's losses can be harvested from the application's reports. The active and reactive power losses in the network are 16,40 MW and 63,48 MVar respectively. Meanwhile the voltage profile of the system consists of a maximum voltage of 1,033 pu and a minimum voltage of 0,96053 pu, which indicates a 7,54% divergence. After that, a 3-phase bus fault is implemented in Bus 2 in order to inspect the grid's stability after clearing the fault before CCT. The CCT for the fault in Bus 2 is 0,385 seconds, so we choose to clear the fault at tcl=0,38 s. The graphs showing the grid's response to the bus fault regarding bus voltages, relative rotor angleand produced power are presented below. As we can see, from the graphs of active power in Figure 6.5, reactive power in Figure 6.6, voltage in Figure 6.7, relative rotor angles in Figure 6.8 and bus frequency in Figure 6.9, the results show oscillations during the fault that dump out in post-fault times revealing that the system is stable after the initial disturbance.

6.8.2 Scenario 2: IEEE 14 bus system with wind generator

For the second scenario a wind generator replaces the 100% of the conventional generator production in bus 2 and produces the 14.28% of the total power. The wind generator model used for the simulation is a type 4 wind turbine also known as full-converter wind turbines, are among the most advanced and commonly utilized types in modern wind generating systems as they provide numerous benefits in terms of efficiency, control, and grid compatibility. The power flow diagram of this scenario can be seen in Figure 6.10. For the dynamic profile of the wind turbine two blocks are used, one for the generator profile and one for the electrical profile. The parameters of the blocks, as well as the parameters for generators, voltage, loads and lines of IEEE 14 bus system, can be seen in Table A.1, Table A.2, Table A.3 and Table A.4 in Appendix A.

After checking system's reports the updated system's losses are 16.12 MW of active power losses and 62.36 MVAR of reactive power losses. There is a slight reduction in both active power and reactive power losses, which is the intention for maximizing the grid's efficiency. The simulation runs for 1 second and at that time a 3-phase fault is set in Bus 2. The fault is cleared at t_{cl} = 0,38 s and the simulation runs for 10 seconds in total. After plotting the voltage, frequency, relative rotor angles, active power and reactive power in Figure 6.11, Figure 6.12, Figure 6.13, Figure 6.14, Figure 6.15 respectively, during the transient stability analysis, it is observed that the values return to their initial state with a smoother oscillation and the system regains its stability faster.

6.8.3 Scenario 3: IEEE 14 bus system with wind generators and FACTS devices

For the last scenario two wind generators replace the 100% of production by the conventional generators in buses 2 and 6, and FACTS devices are used in several buses in order to get the most preferable result. It can be observed that changing the location and the quantity of FACTS devices leads to fluctuations in the voltage profile of the grid. For this scenario the four cases that are considered are:

- **Case A:** the classic 14 bus system with conventional generators and without FACTS devices.
- **Case B:** Two wind generators producing 28.57% of the total power and FACTS devices in buses 3, 5 and 10.
- **Case C:** Two wind generators producing 28.57% of the total power and FACTS devices in buses 3, 12 and 13.
- **Case D:** Two wind generators producing 28.57% of the total power and FACTS devices in buses 3, 5 and 12.

The power flow diagrams of Case B, Case C and Case D are shown in Figure 6.16, Figure 6.17 and Figure 6.18 respectively.

The results of the voltages in p.u. are presented in Table 6.1. It is observed that in case C, voltage at bus 8 is above the maximum normal operation voltage (1,05 pu) and is closer to maximum emergency operation voltage (1,10 pu). As a result, Case C is not the optimal choice. Moreover, the voltage divergence percentage is reduced when using wind generators and FACTS, in Case B it falls to 6,91%, and in Case D it falls to 6,64%, whereas whith the conventional generators and no FACTS devices the percentage is 7,54 %. Taking into consideration that Case D is the preferable choice, the effect of RES and FACTS devices in the transient stability analysis are notable. After running the simulation for 1 s, the 3φ fault is implemented in bus 2 and the CCT is 0,415 s, so the fault is cleared at t_{cl} = 1,41 s and the simulation continues to run until 10 s. The system returns to its stable condition faster, Figure 6.19 and Figure 6.20 show the instantaneous response of the voltage and frequency of every bus respectively, while Figure 6.21, Figure 6.22 and Figure 6.23 show the response of relative rotor angles, active power and reactive power of the system, after the fault clearing. Finally, the system's losses are reduced significantly resulting in a 26.21 % reduction in active power losses and 28.13% reduction in reactive power losses.

Table 6.1: Voltage profile in p.u. of various cases depending on the location of FACTS devices

Buses	Case A	Case B	Case C	Case D
Bus 1	1,03	1,03089	1,03	1,03
Bus 2	1,00345	1,01465	1,01856	1,01477
Bus 3	0,983	1,00909	1,01	1,01
Bus 4	0,97984	0,99550	1,01229	0,99761
Bus 5	0,98441	0,99833	1,01771	1,00000
Bus 6	0,98961	0,99591	1,09721	1,00703
Bus 7	0,99208	1,00124	1,03575	1,00550
Bus 8	1,033	1,04179	1,07508	1,04592
Bus 9	0,97477	0,98003	1,02495	0,98536
Bus 10	0,9694	0,97443	1,03019	0,98072
Bus 11	0,9757	0,98085	1,05969	0,98941
Bus 12	0,97464	0,98228	1	1
Bus 13	0,97007	0,97782	1,04357	0,99047
Bus 14	0,96053	0,97469	1,01557	0,98356

To address the system's stability for another type of disturbance, for this scenario, Case D will be tested under SLG fault. The sequence data for generators and lines can be found in Figure A.5 and Figure A.6. The SLG fault is applied in bus 3 at t = 1 s, and using the same process of fault clearing, the calculated CCT is 0,585 s, so the fault is cleared at t_{cl} = 1,58 s. Consequently, the graph of relative rotor angles in Figure 6.24 show that generators sustain their synchronism. Figure 6.25 and Figure 6.26 show the system's response regarding active power and reactive power respectively, whereas Figure 6.27 and Figure 6.28 demonstrate the stability of bus voltages and frequencies.

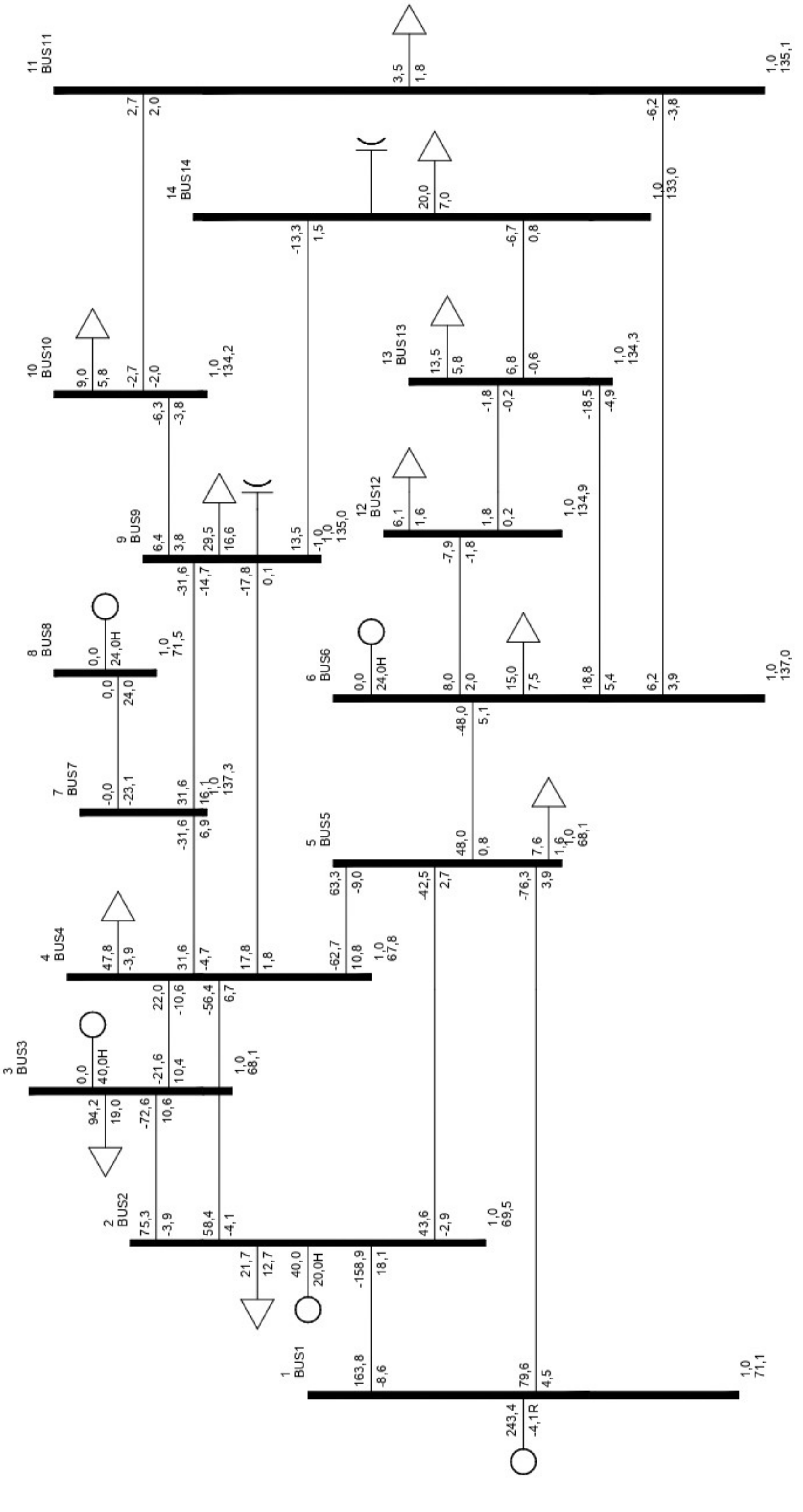

Figure 6.4: IEEE 14 bus system

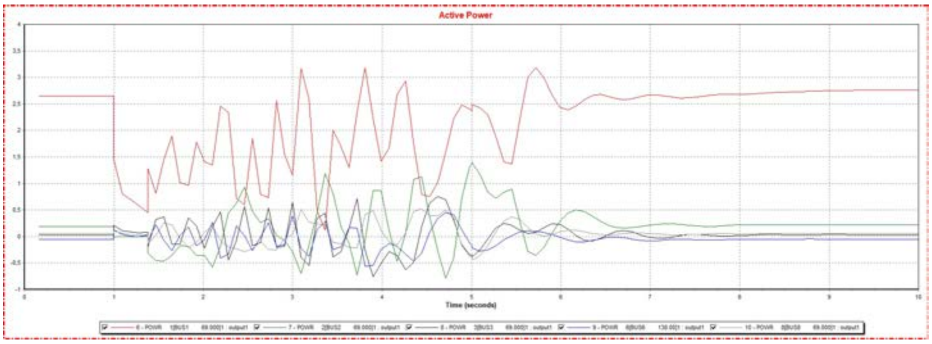

Figure 6.5: Scenario 1: Active power of generators after 3-phase fault in bus 2

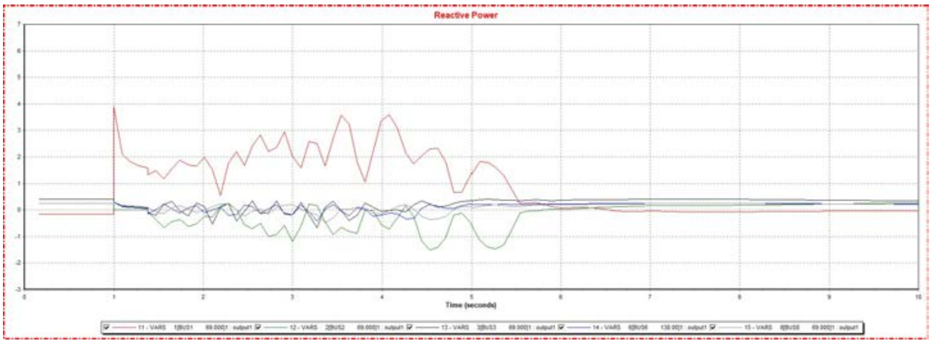

Figure 6.6: Scenario 1: Reactive power of generators after 3-phase fault in bus 2

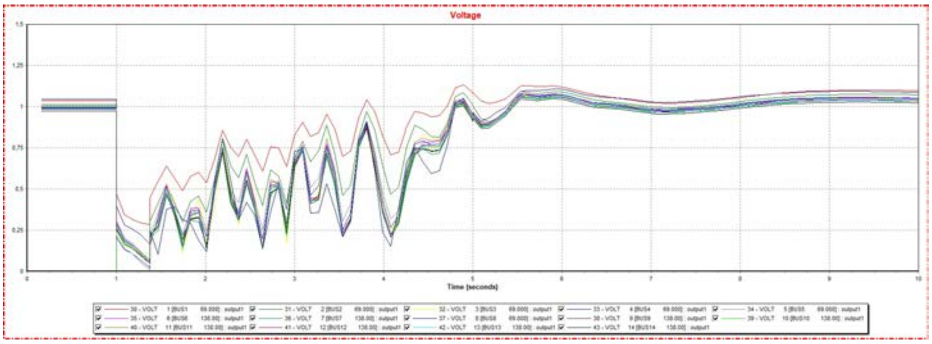

Figure 6.7: Scenario 1: Bus voltage after 3-phase fault in bus 2

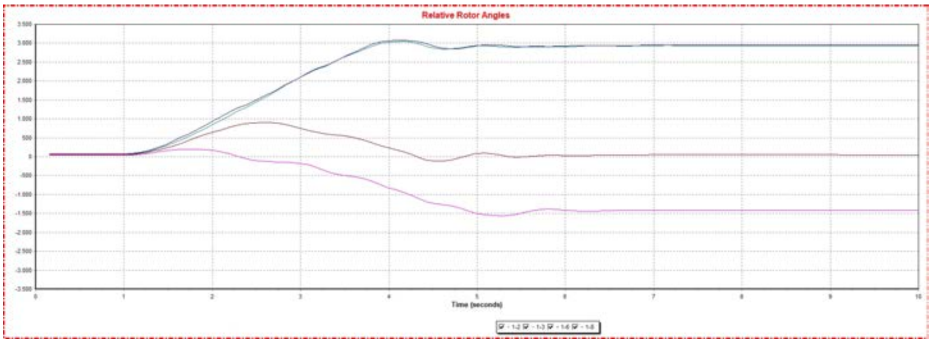

Figure 6.8: Scenario 1: Relative rotor angles after 3-phase fault in bus 2

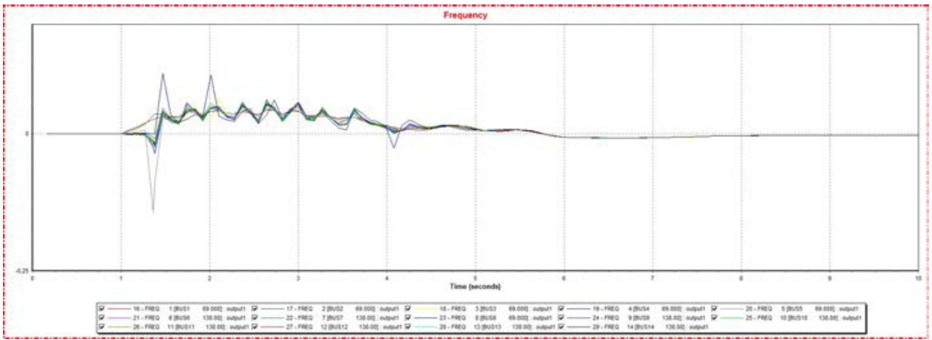

Figure 6.9: Scenario 1: Bus frequency after 3-phase fault in bus 2

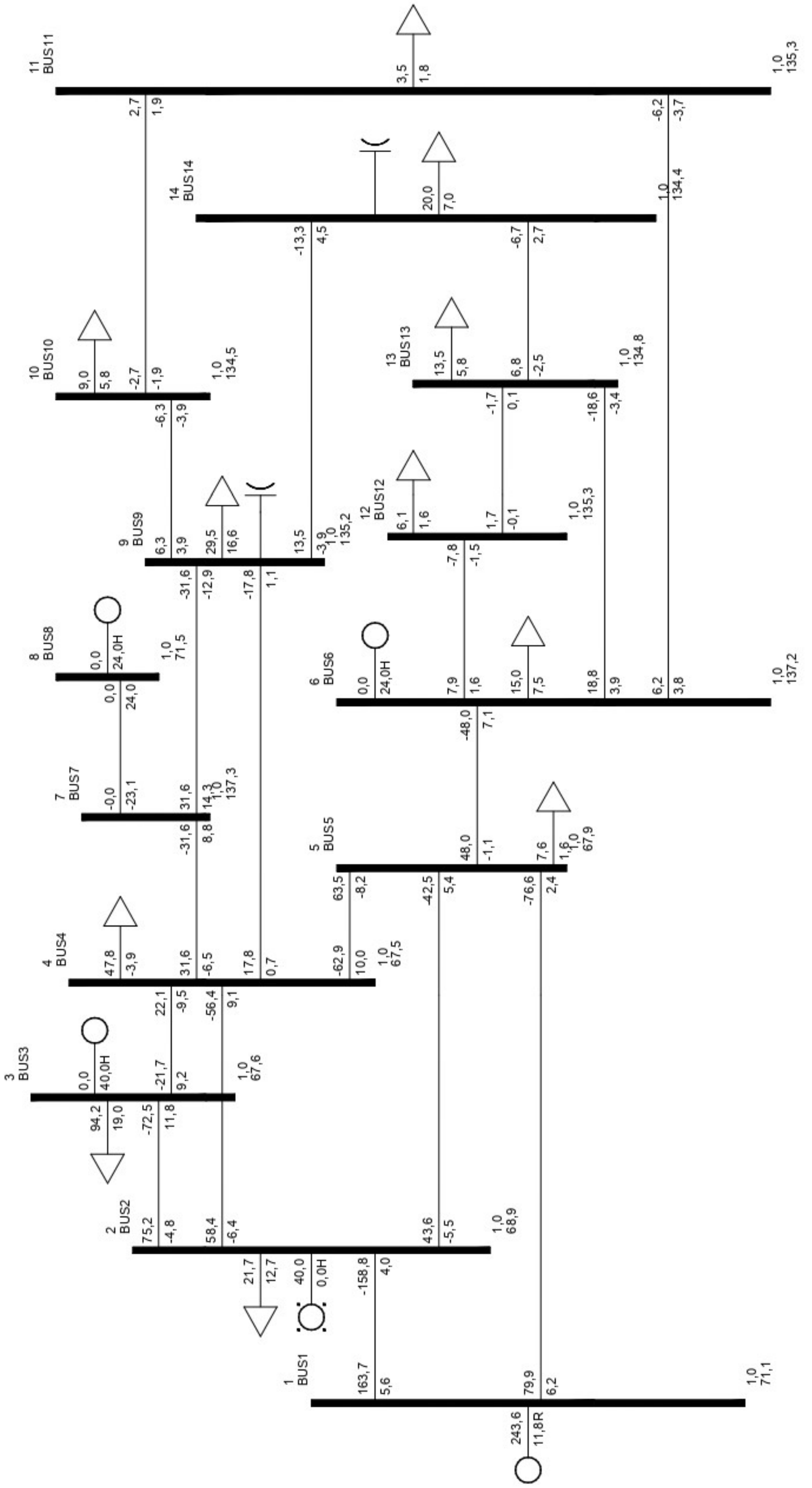

Figure 6.10: Scenario 2 power flow diagram

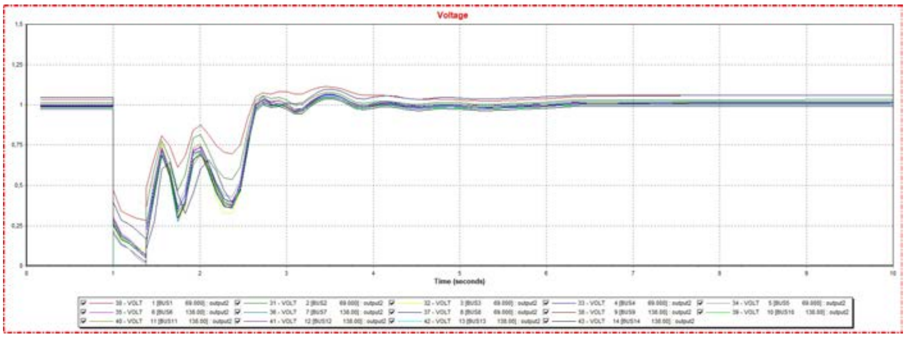

Figure 6.11: Scenario 2: Bus voltage after 3-phase fault in bus 2

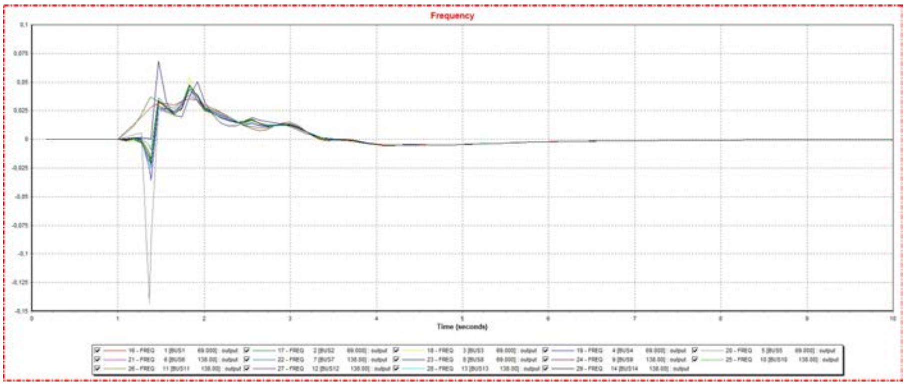

Figure 6.12: Scenario 2: Bus frequency after 3-phase fault in bus 2

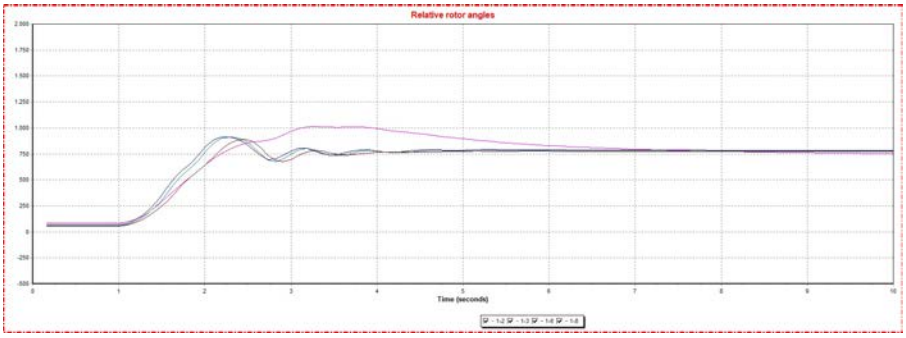

Figure 6.13: Scenario 2: Relative rotor angles after 3-phase fault in bus 2

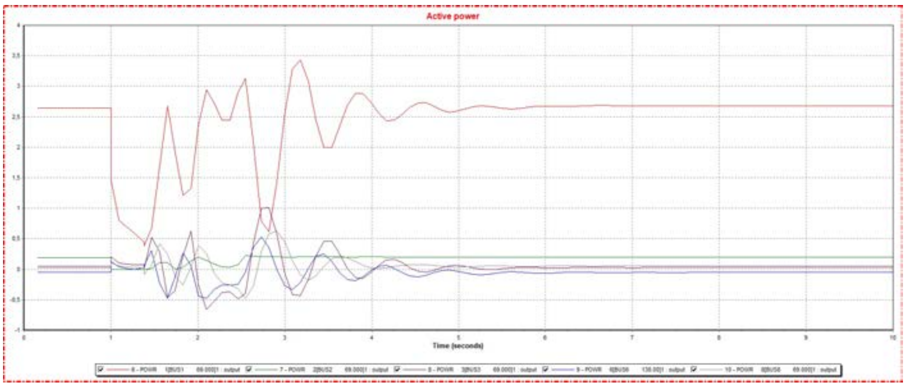

Figure 6.14: Scenario 2: Active power of generators after 3-phase fault in bus 2

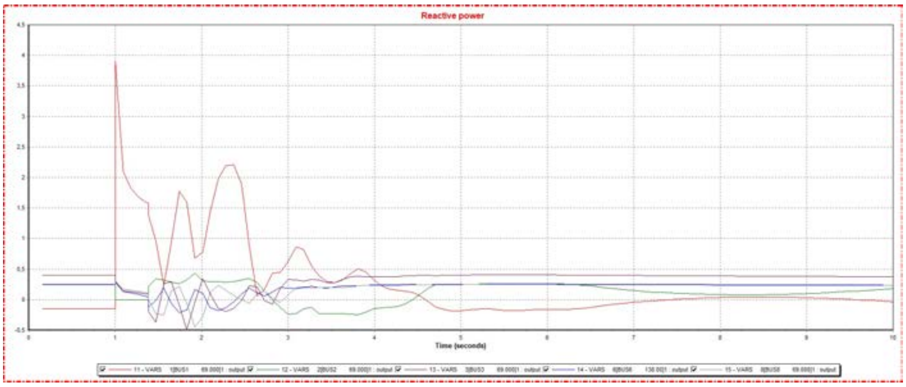

Figure 6.15: Scenario 2: Reactive power of generators after 3-phase fault in bus 2

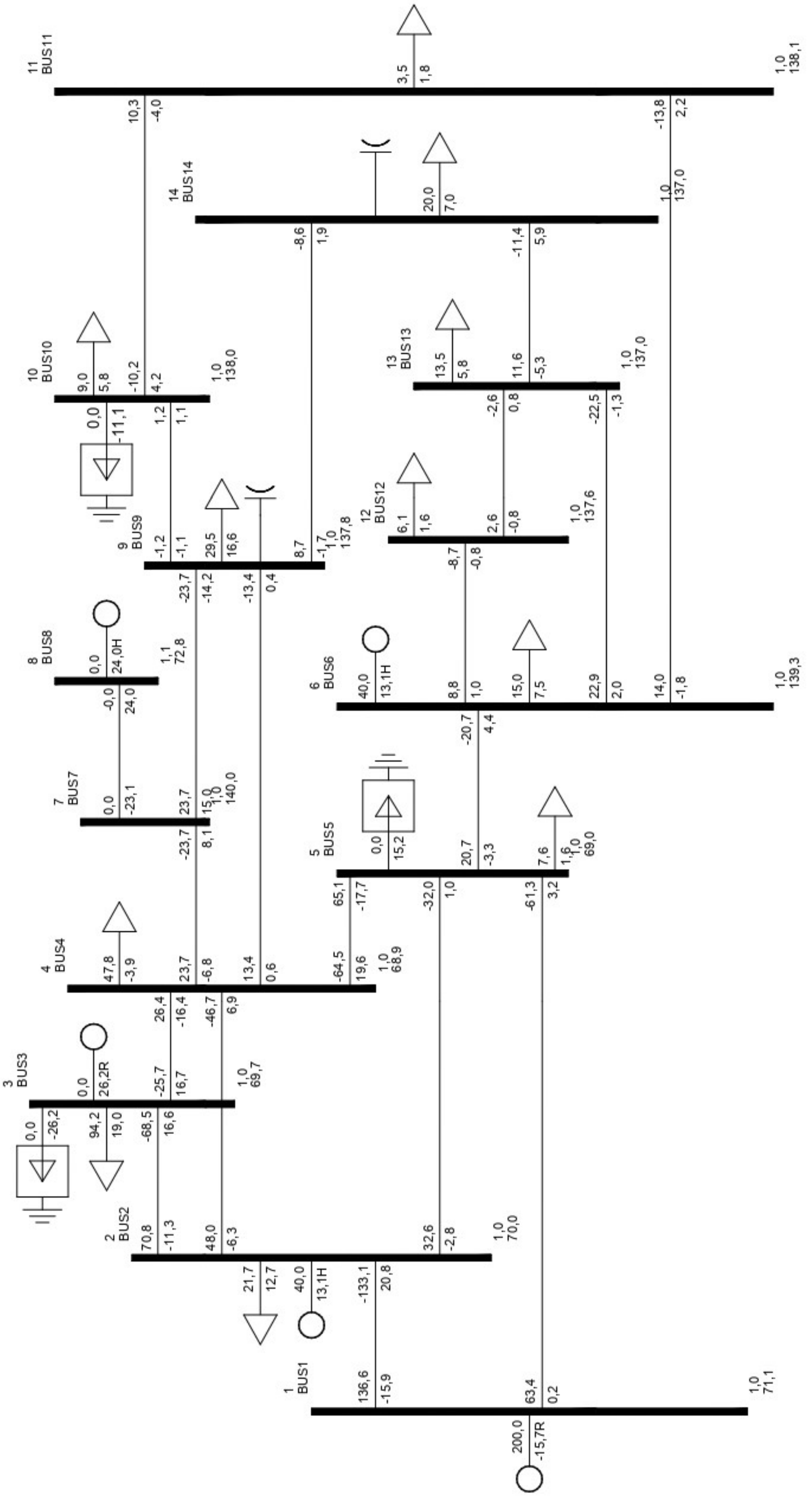

Figure 6.16: Scenario 3 - Case B power flow diagram

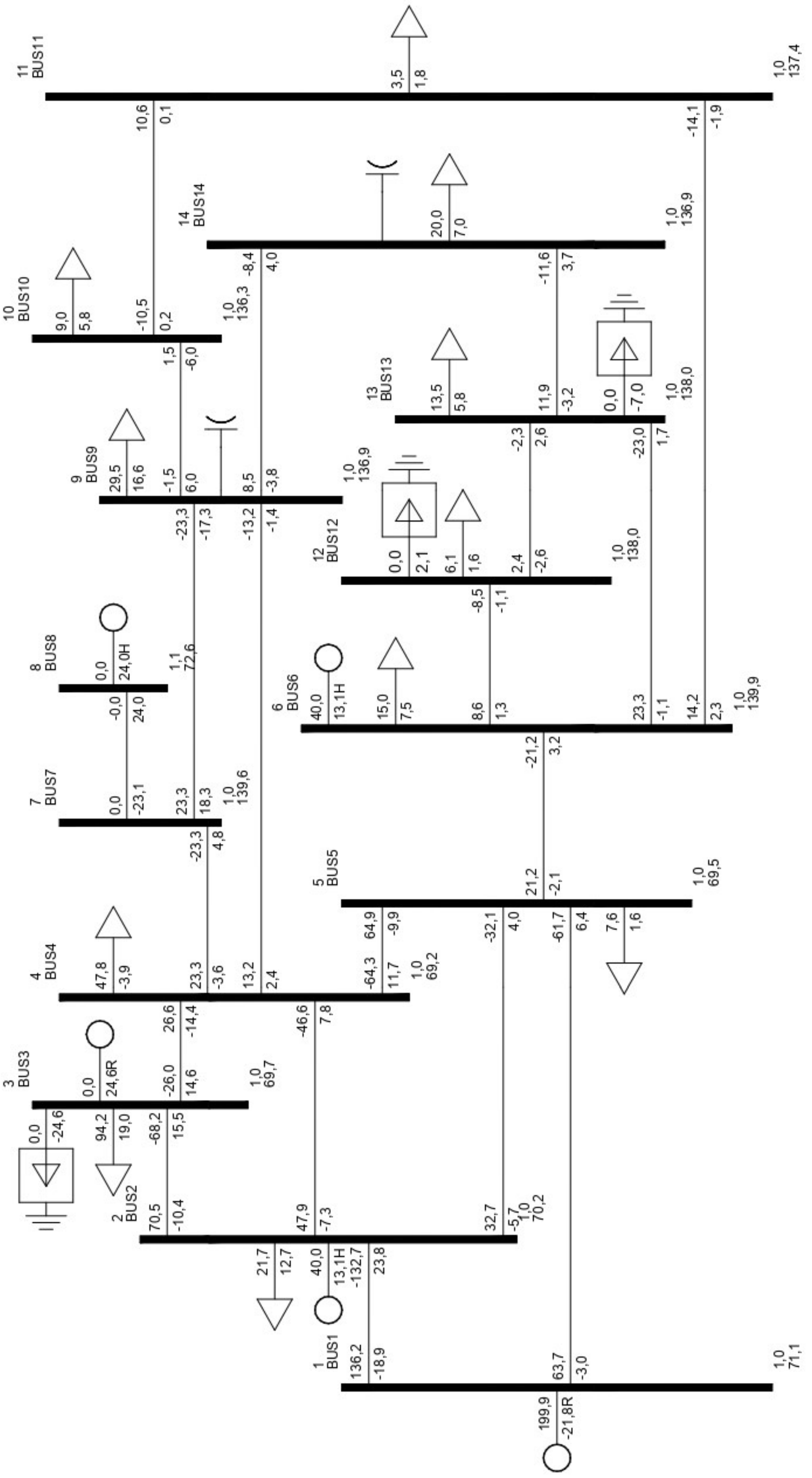

Figure 6.17: Scenario 3 - Case C power flow diagram

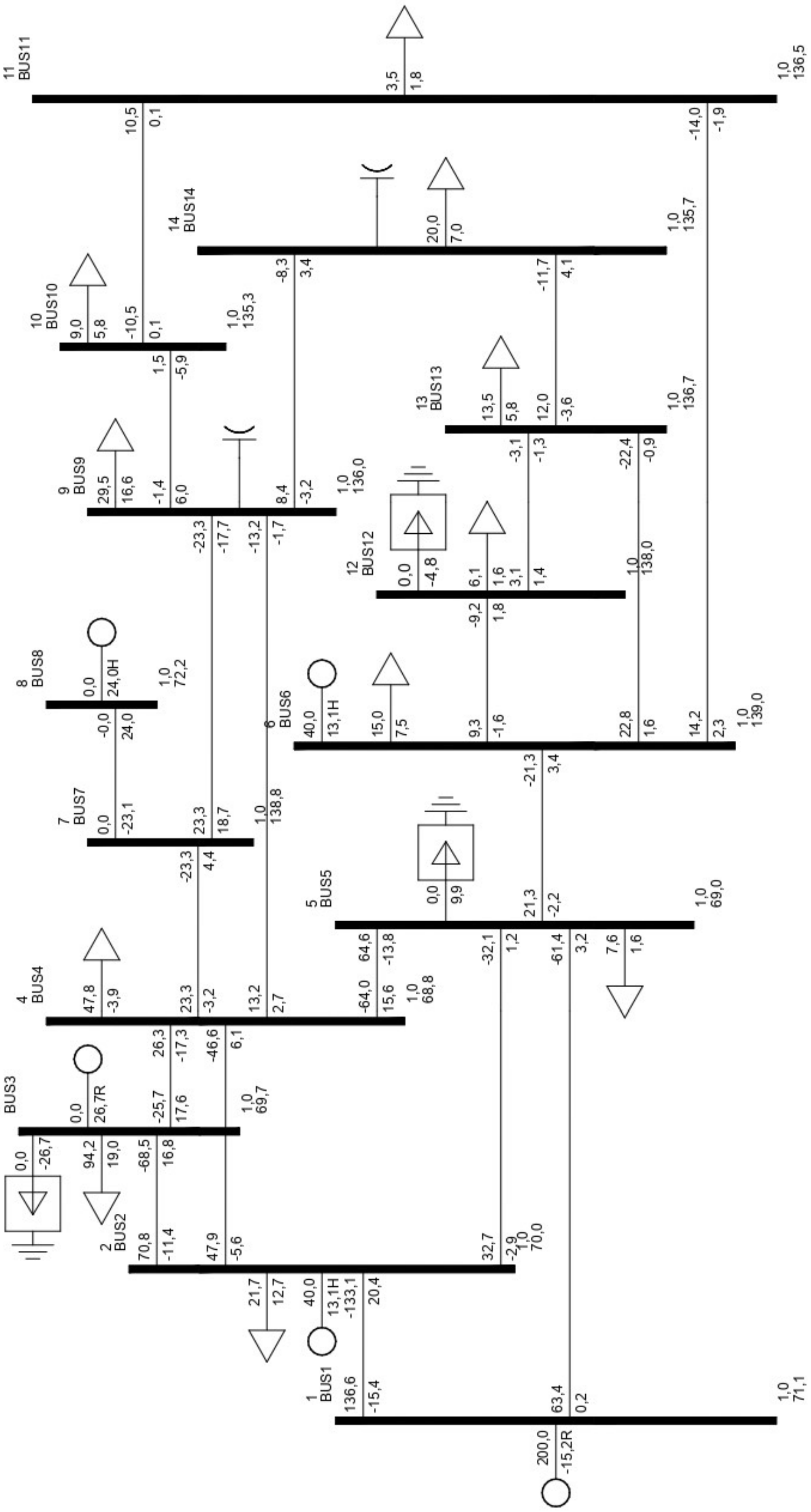

Figure 6.18: Scenario 3 - Case D power flow diagram

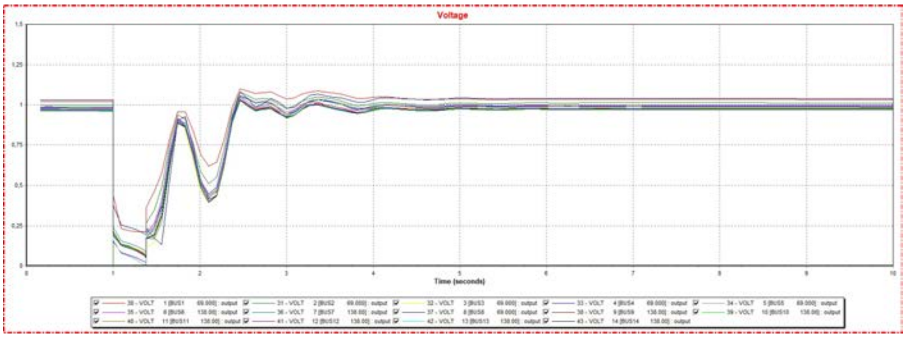

Figure 6.19: Scenario 3 - Case D: Bus voltage after 3-phase fault in bus 2

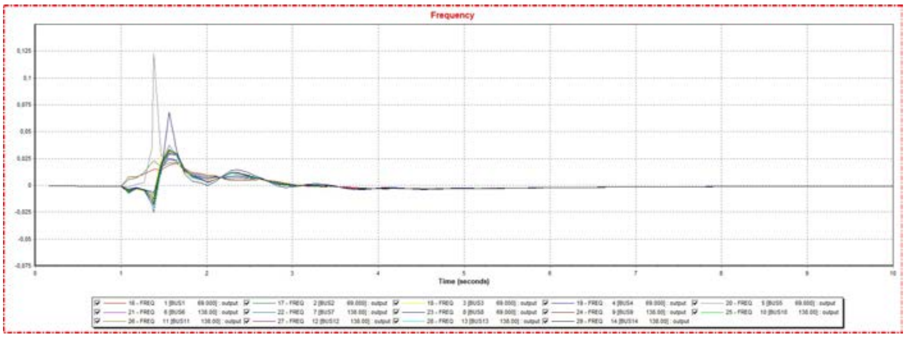

Figure 6.20: Scenario 3 - Case D: Bus frequency after 3-phase fault in bus 2

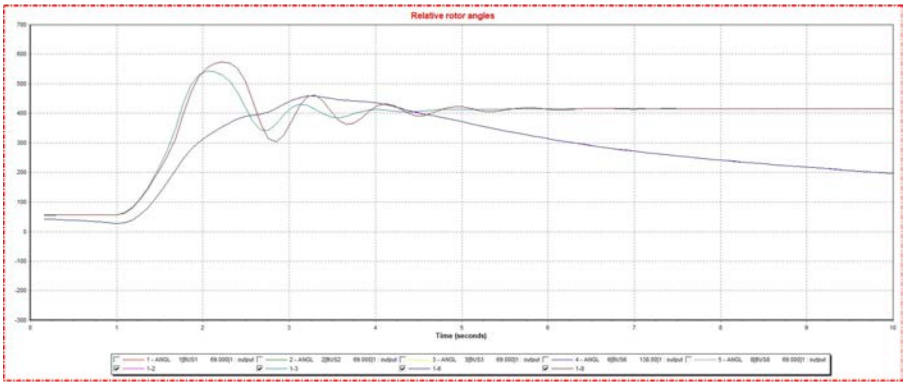

Figure 6.21: Scenario 3 - Case D: Relative rotor angles after 3-phase fault in bus 2

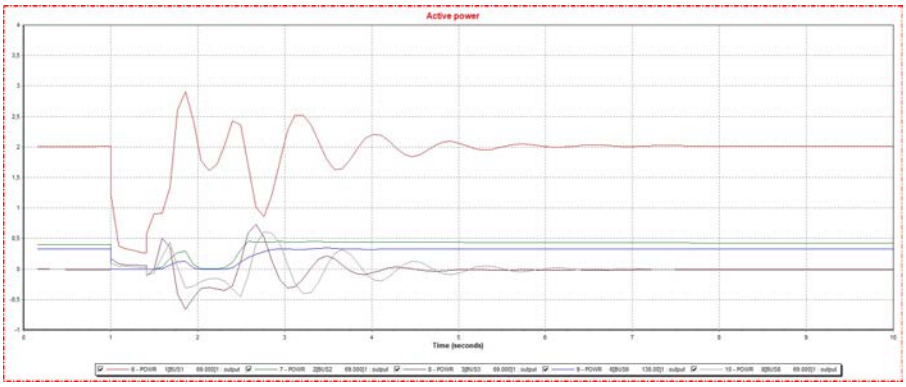

Figure 6.22: Scenario 3 - Case D: Active power of generators after 3-phase fault in bus 2

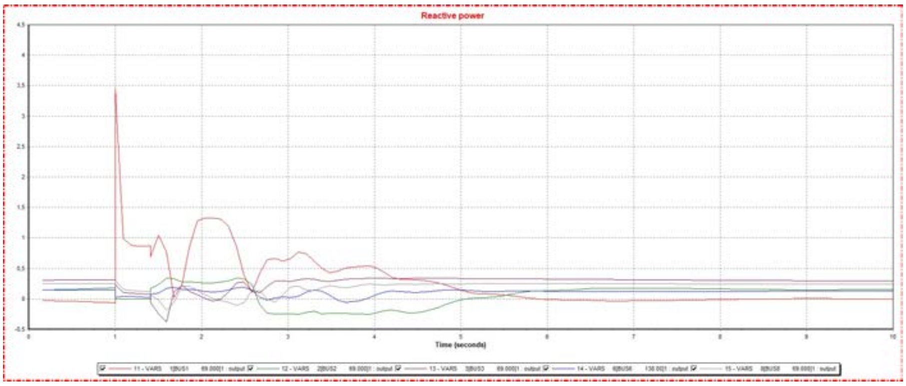

Figure 6.23: Scenario 3 - Case D: Reactive power of generators after 3-phase fault in bus 2

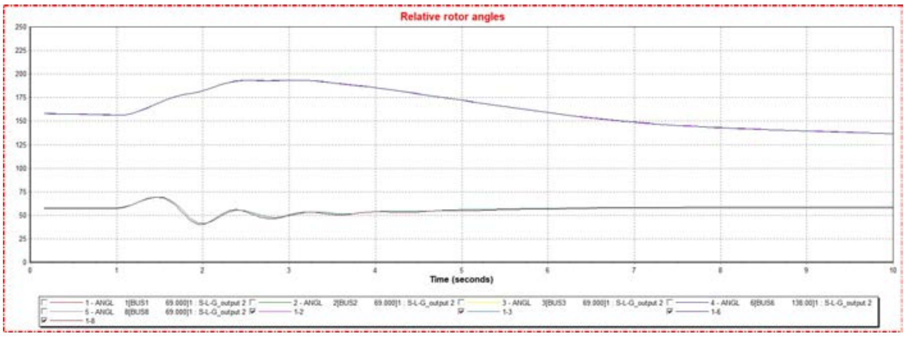

Figure 6.24: Scenario 3 - Case D: Relative rotor angles after SLG fault in bus 3

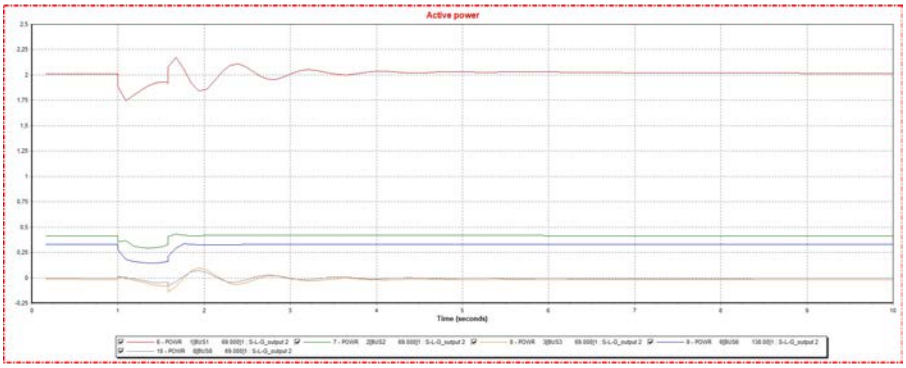

Figure 6.25: Scenario 3 - Case D: Active power of generators after SLG fault in bus 3

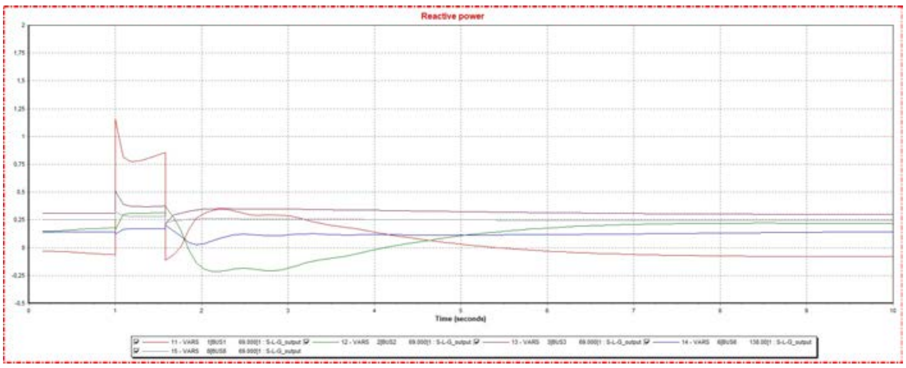

Figure 6.26: Scenario 3 - Case D: Reactive power of generators after SLG fault in bus 3

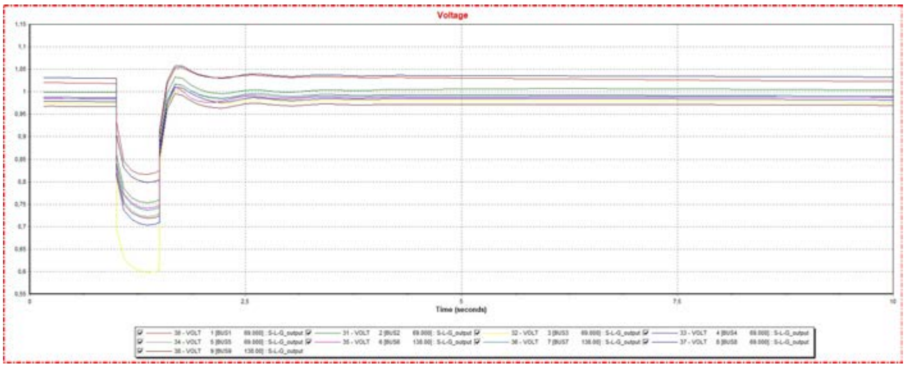

Figure 6.27: Scenario 3 - Case D: Bus voltage after SLG fault in bus 3

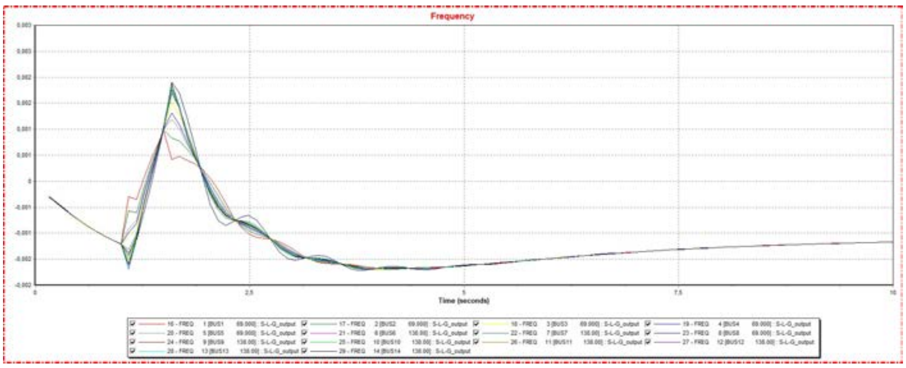

Figure 6.28: Scenario 3 - Case D: Bus frequency after SLG fault in bus 3

Chapter 7

Conclusion

In the course of this diploma thesis the many-sided subjects of renewables and smart grids were discussed. In the last section, a conclusion is reached in which the chapters analyzed above are reviewed and plans for future study and implementation are suggested.

7.1 Synopsis and results

Initially, smart grid components were presented and evaluated. Customers, markets, operation, service providers, generation, transmission and distribution are the 7 domains of the NIST model, and their cooperation is the key of success in smart grid technology. After scrutinizing these domains and consider their offer in the process of energy production, distribution and consumption, the subject of renewable energy sources is presented. EU stats show the great need of renewables adoption and governments show more and more interest in facing the serious problem of climate change. Specifically, the various types of solar PV panels and wind turbines, and the advantages-benefits RES offer in economic, technical, environmental and other sectors are displayed. V2G technology is another issue that draws people's attention and is widely introduced in Chapter 3. The serious matter of obstacles in the adoption of RES and Smart Grids is demonstrated in the next part of this dissertation. Instability of the energy and location of RES units, privacy, lack of subsidization, regulatory framework and infrastructure, and battery deterioration of EVs are some of the cases that draw the attention of this thesis. Meanwhile, suggestions such as setting the right feed-in tariffs, regulations and special funding for renewables according to each country's GDP, improving units, distribution and transmission lines, getting people to learn about planet pollution and the positive effects of the new technology that emerge, equipping cities with domestic wind turbines, solar panels and creating virtual neighborhoods, imposing user's safety through security regulations and lastly proposing battery maintenance models, can prove useful in the direction of overcoming these obstacles. Finally, a simulation of integrating RES in the grid using smart FACTS devices, shows the benefits of this study regarding voltage profile, transmission losses and system's stability taking into consideration voltage, frequency and other elements of the system. Two types of faults were used in several versions of the IEEE 14 bus system, for example a 3-phase fault on bus 2 of the IEEE 14 bus system with two wind generators and three FACTS devices is used to determine the amelioration of the system's response after clearing the fault. The results show that, this case regains its stability faster and with fewer oscillations than the classic IEEE 14 bus system, as it can be observed by the graphs in Chapter 6. The location of FACTS devices is also another concern of this study, mainly because the voltage values of the buses differ from one case to another. By practising 3 cases, the best one is selected by calculating the least divergence in the values. Furthermore, in the selected case, SLG fault is implemented in bus 3 and after the fault clearing, the system shows instant reaction and maintains its stability fast and effectively. Overall, the instant response in the transient stability analysis, the reduction of active power losses and reactive power losses, and the improvement of the voltage profile of the buses, illustrate that using RES and FACTS devices in the simulation, can provide many benefits in the system and solve problems that trouble the traditional grid.

7.2 Future work

Future work requires better promotion from governments and energy providers, improving the components of the current grid, setting a not only affordable but efficient energy plan for every citizen. The proposed simulation can be put to test in scenarios with more buses, or even in real-time conditions with existing grid infrastructure, but the most important measure will be the increase of RES integrated in the system. Without it, and with the rapid environmental strain, soon enough earth and its habitants will come across with even greater consequences such as the rise of sea level, prolonged drought and wildfire periods, escalation in both duration and incidence of storms, and the continuous increase of temperature. Modernising the existing framework in transmission, communication, control and security, regarding electrical grids, will offer major advantages in making the most of energy production from solar, wind and other forms of renewable energy. As a result, the necessity for maximum exploitation of green energy, is of the outmost importance, and integrating RES in smart grids paves the way for securing a more sustainable future.

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APPENDICES

Appendix A

IEEE 14 bus system parameters

Table A.1: Type 4 Wind Turbine Generator and Electrical parameters

Generator Parameters	WT4G1	Electrical Parameters	WT4E1
$TIQCmd$	0,02	$T_f v$	0.15
$TIPCmd$	0,02	KPV	18.0
$VLVPL1$	0,40	KIV	5.00
$VLVPL2$	0,90	Kpp	0,05
$GLVPL$	1,11	KIP	0,10
$VHVRCR$	1,20	Kf	0,00
$CURHVRCR$	2,00	Tf	0,08
$RIp_L VPL$	2,00	QMX	0,47
$T_L VPL$	0,02	QMN	-0,47
		$IPmax$	1,10
		TRV	0,00
		$dPMX$	0,50
		$dPMN$	-0,50
		$T_P ower$	0,05
		KQI	0,10
		$VMINCL$	0,90
		$VMAXCL$	1,10
		KVI	120
		Tv	0,05
		Tp	0,05
		$ImaxTD$	1,70
		$Iphl$	1,11
		$Iqhl$	1,11

Table A.2: Generator data of IEEE 14 bus system

At bus	P_{gen} (MW)	Q_{gen} (MVAR)	M_{base} (MVA)	X_{source} (p.u.)
1	243,4187	-4,0820	320	0,23
2	40	20	55	0,28
3	0	40	50	0,34
6	0	24	30	0,28
8	0	24	30	0,34

Table A.3: Voltage and load data of IEEE 14 bus system

Bus	Voltage (p.u.)	Angle (deg)	P_{load} (MW)	Q_{load} (MVAR)
1	1,06	0	0	0
2	1,045	0	21,7	12,7
3	1,01	0	94,2	19
4	1	0	47,8	-3,9
5	1	0	7,6	1,6
6	1,07	0	15	7,5
7	1	0	0	0
8	1.09	0	0	0
9	1	0	29,5	16,6
10	1	0	9	5,8
11	1	0	3,5	1,8
12	1	0	6,1	1,6
13	1	0	13,5	5,8
14	1	0	20	7

Table A.4: Line data of IEEE 14 bus system

From bus	To bus	R (p.u.)	X (p.u.)	B (p.u.)
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0438
2	3	0.04699	0.19797	0.0374
2	4	0.05811	0.17632	0.0492
2	5	0.05695	0.17388	0.0340
3	4	0.06701	0.17103	0.0346
4	5	0.01335	0.04211	0.0128
4	7	0	0.20912	0
4	9	0	0.55618	0
5	6	0	0.25202	0
6	11	0.94980	0.19890	0
6	12	0.12291	0.25581	0
6	13	0.06615	0.13027	0
7	8	0	0.17615	0
7	9	0	0.11001	0
9	10	0.03181	0.08450	0
9	14	0.12711	0.27038	0
10	11	0.08205	0.19207	0
12	13	0.22092	0.19988	0
13	14	0.17093	0.34802	0

Table A.5: Generator sequence data of IEEE 14 bus system

	Positive	Positive	Negative	Negative	Zero	Zero
At bus	R (p.u.)	X (p.u.)	R (p.u.)	X (p.u.)	R (p.u.)	X (p.u.)
1	0,001	0,007	0,001	0,007	0,001	0,007
2	0,002	0,011	0,002	0,011	0,002	0,011
3	0,007	0,13	0,007	0,13	0,007	0,13
6	0,002	0,162	0,002	0,162	0,002	0,162
8	0,001	0,095	0,001	0,095	0,001	0,095

Table A.6: Zero Sequence Impedance Data for IEEE 14-Bus System

From Bus	To Bus	R_0	X_0
1	2	0.05814	0.17751
1	5	0.16209	0.66912
2	3	0.14097	0.59391
2	4	0.17433	0.52896
2	5	0.17085	0.52164
3	4	0.20103	0.51309
4	5	0.04005	0.12633
4	7	0.0	0.62736
4	9	0.0	1.66854
5	6	0.0	0.75606
6	11	0.28494	0.59670
6	12	0.36873	0.76743
6	13	0.19845	0.39081
7	8	0.0	0.52845
7	9	0.0	0.33003
9	10	0.09543	0.25350
9	14	0.38133	0.81114
10	11	0.24615	0.57621
12	13	0.66276	0.59964
13	14	0.51279	1.04406