

Modelo Genérico de Uma Rede Inteligente Utilizando o Matlab

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GENERIC MODEL OF A SMART GRID USING MATLAB

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“Each joy in my life and each breath in my lungs attests to your overwhelming grace”

Joel Quartuccio

Acknowledgments

First and foremost, I would like to express my deep gratitude to my mother and family for educating me, they are responsible for who I am today. They have always supported me and believed in me, making this entire process possible.

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Resumo

Uma Rede Inteligente (RI) é uma versão modernizada da rede elétrica tradicional que utiliza tecnologia avançada para melhorar a eficiência, confiabilidade e sustentabilidade do sistema de energia. O conceito de uma SG consiste em integrar vários componentes, tais como infraestrutura avançada de medição, fontes de energia distribuídas, redes de comunicação e fontes de energia renováveis, para criar uma rede inteligente e autocorretora.

A necessidade da RI surge da crescente demanda por eletricidade, da integração de fontes de energia renováveis e do crescente número de fontes de energia distribuídas. As alterações climáticas e a necessidade de reduzir as emissões de gases de efeito estufa aumentaram a pressão para a transição para um sistema de energia mais sustentável, e é aqui que entra a tecnologia da rede inteligente. A RI permite a monitorização e o controlo em tempo real do fluxo de eletricidade, permitindo a integração de fontes de energia renováveis, como energia solar e eólica, e a gestão da demanda. Isso ajuda a reduzir a dependência de combustíveis fósseis, a diminuir as emissões de carbono e a promover o uso de energia limpa. Além disso, a RI permite uma eficiência energética melhorada e a integração de veículos elétricos e outras fontes de energia distribuídas, o que pode reduzir ainda mais as emissões de carbono. Também facilita uma comunicação e envolvimento melhores entre os provedores de serviços e os clientes, o que leva a decisões de uso de energia mais informadas.

Em resumo, a Rede Inteligente é uma etapa necessária na transição para um sistema de energia mais sustentável, eficiente e resistente. A mesma permite a monitorização e controlo em tempo real do fluxo de eletricidade, integração de fontes de energia renováveis e fontes de energia distribuídas, comunicação melhorada entre provedores de serviço e clientes e contribui para enfrentar as mudanças climáticas, reduzindo a dependência de combustíveis fósseis e promovendo a energia limpa.

Palavras-Chave

Demanda, Fontes de Energia Distribuída, Fontes de Energia Renovável, Rede Elétrica, Rede Inteligente.

Abstract

A Smart Grid (SG) is a modernized version of the traditional electrical grid that utilizes advanced technology to improve the efficiency, reliability, and sustainability of the power system. The concept of SG is to integrate various components such as advanced metering infrastructure, Distributed Energy Resources (DER), communication networks and renewable energy resources, to create an intelligent and self-healing grid.

The need for SG arises from the increasing demand for electricity, the integration of renewable energy sources, and the growing number of DER. Climate change and the need to reduce greenhouse gas emissions have increased the pressure to transition to a more sustainable energy system, which is where smart grid technology comes into play. SG allows for real-time monitoring and control of the flow of electricity, enabling the integration of renewable energy sources, such as solar and wind power, and the management of demand. This helps to reduce dependence on fossil fuels, decrease carbon emissions and promote the use of clean energy. In addition, SG enables improved energy efficiency and the integration of electric vehicles and other DER, which can further reduce carbon emissions. It also facilitates better communication and engagement between utilities and customers, which leads to more informed energy use decisions.

In summary, Smart Grid is a necessary step in the transition towards a more sustainable, efficient and resilient energy system. It enables real-time monitoring and control of the flow of electricity, integration of renewable energy sources and DER, improved communication between utilities and customers, and contributes to tackle climate change by reducing dependency on fossil fuels and promoting clean energy.

Keywords

Demand, Distributed Energy Resources, Electrical Grid, Renewable Energy Sources, Smart Grid.

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Acronyms List

AC	–	Alternating Current
ADA	–	Advanced Distribution Automation
AMI	–	Advanced Metering Infrastructure
BESS	–	Battery Energy Storage Systems
CAES	–	Compressed Air
CCS	–	Controlled Current Source
CT	–	Current Transformer
CVPP	–	Commercial VPP
DC	–	Direct Current
DG	–	Distributed Generation
DMS	–	Distribution Management Systems
DR	–	Demand and Response
DS	–	Distributed Storage
EMI	–	Electromagnetic Interference
EMS	–	Energy Management Systems
DER	–	Distributed Energy Resource
DOE	–	United States Department of Energy
FACTS	–	Flexible AC Transmission Systems
FERC	–	Federal Energy Regulatory Commission
FES	–	Flywheels

FREEDM	–	Future Renewable Electric Energy Delivery and Managment
GUI	–	Graphical User Interface
HAN	–	Home Area Networks
HVDC	–	High Voltage DC
LAN	–	Local Area Network
MBD	–	Model Based Design
NAS	–	Sodium Sulphur
PHEV	–	Plug-in Hybrid Electric Vehicles
PHS	–	Pumped Hydro
PLC	–	Power Line Communication
PV	–	Photovoltaic
PT	–	Potential transformer
V2G	–	Vehicle-to-Grid
VPP	–	Virtual Power Plants
RFI	–	Radio Frequency Interference
SCADA	–	Supervisory Control and Data Acquisition
SG	–	Smart Grid
SMES	–	Superconducting Magnetic Energy Storage
SOC	–	State of Charge
TEPCO	–	Tokyo Electric Power Company
THD	–	Total Harmonic Distortion

TVPP – Technical VPP

UC – Ultra-capacitor

1. INTRODUCTION

Smart grids (SG) are an intelligent, modernized version of the traditional electrical grid. These grids are designed to improve the efficiency, reliability, and sustainability of the power system by incorporating advanced technologies such as automation, communication, and control systems. These technologies allow for real-time monitoring and management of the grid, which enables the integration of renewable energy sources, DER, and electric vehicles. Additionally, SG also enable dynamic pricing and demand response, which can help reduce costs and carbon emissions.

The implementation of SG is essential for meeting the growing demands for electricity and addressing the challenges posed by climate change. It can also help to improve the security and resilience of the power system, as well as support economic growth and job creation. Moreover, the integration of different DER, such as wind turbines, solar panels, and electric vehicles, into the power grid can be facilitated by SG, thus contributing to the growth of renewable energy in the energy mix.

The SG uses technologies that modernize the power system including Advanced Metering Infrastructure (AMI), Distribution Management Systems (DMS), Energy Management Systems (EMS), and Advanced Distribution Automation (ADA). AMI provides real-time data on energy consumption and enables dynamic pricing, while DMS and EMS are used

to optimize the distribution of electricity and manage the integration of DER. ADA is used to improve the reliability and resiliency of the grid by automating the distribution system.

The development and implementation of SG is a complex and multi-disciplinary task that involves various stakeholders such as utilities, regulators, consumers, and technology providers. It also requires significant investments in infrastructure and technology, as well as the development of new business models and regulatory frameworks. Therefore, the results of this simulation will provide valuable insights for policymakers, regulators, and industry experts to make informed decisions.

The aim of this thesis is to explore various aspects of SG, including the technical, economic, and regulatory challenges that need to be addressed in order to successfully implement them. We will also investigate the potential benefits of SG for the power system, consumers, and the environment, as well as the various technologies and solutions that are currently being developed and deployed in order to modernize the grid.

1.1. CONTEXT

This thesis project stems from the recognition that the current electrical grid is outdated and lacks the capabilities to effectively handle the integration of decentralized energy production, smart metering, and advanced management techniques. The increasing adoption of renewable energy sources, such as solar and wind power, as well as the growth in DER, such as electric vehicles and energy storage systems, has placed new demands on the grid. The existing power grid lacks the capability to manage these demands and requires an upgrade to effectively integrate and manage these emerging technologies.

In order to address this issue, this thesis project proposes the creation of a simulation that models a real-world power system and evaluates its viability. The simulation will take into account various factors such as the integration of renewable energy sources, the management of DER, and the implementation of advanced metering and control systems. By modelling a realistic power system, it will allow in-depth analysis of the potential impacts on the modernized grid in factors such as efficiency, reliability, and sustainability.

The simulation will also be used to compare the modernized power system with the current grid. This comparison allow an evaluation of the potential benefits on the modernized grid, such as increased renewable energy integration, improved energy efficiency, and reduced carbon dioxide issuances. It will also help identify any challenges or limitations that need to be addressed in order to successfully implement the modernized grid.

Overall, this thesis project aims to contribute to the understanding of the potential benefits and challenges of modernizing the electrical grid. By creating a simulation model of a real-world power system and evaluating its viability, it allows to analyze the potential impacts and compare it to the current grid and provide valuable insights for the development of a modernized grid.

1.2. GOALS

In this thesis, an effort was made to gain a comprehensive understanding of the concept of a SG through the use of simulation. To this end, the following objectives were established:

- An investigation into the concept of the SG
- Analysis of the operations and technologies of SG
- A study of MATLAB/Simulink
- The implementation and study of a SG simulation in MATLAB/Simulink
- An evaluation of the efficiency of the simulation model through various scenarios
- The creation of a comprehensive thesis report.

1.3. DOCUMENT STRUCTURE

The thesis is comprised of six chapters, with supplementary chapters to be appended at a later stage. The initial section of the thesis deals with the contextualization of the problem and the examination of state-of-the-art concepts. In the first chapter, the problem is presented in detail and the primary objectives are succinctly defined. The second chapter comprises a comprehensive study of the state of the art in the field of SG and their effect on the electrical grid. The third chapter delves into the critical technologies associated with SG. The fourth chapter conducts a meticulous analysis of the SG infrastructure. The fifth chapter addresses the challenges that would be encountered in the implementation

of a SG. The sixth chapter concludes the thesis. Finally, the final phase of the dissertation will encompass additional chapters on simulation, scenario analysis, and data analysis.

2. SMART GRID

There have been no substantial modifications to the electric system in the recent few decades. This system is completely outdated since its structure uses technology from 40 years ago but also because the energy consumption has increased dramatically in the last decades and, renewable energies have a high penetration in the global production. The electric power system was developed to provide unidirectional flow to end consumers, hence it is not prepared to accommodate renewable energy. With that in mind comes the need for a new, more flexible and responsive technology.

The SG is the new electrical power system that offers a viable answer to these difficulties. The SG, unlike traditional grids, will produce, transport, and distribute electricity in a two-way flow of electrical power and information from facilities to consumers and vice versa.

Despite the constant increase in popularity of SG, its definition remains debatable to this day. The concept of what constitutes an SG change from author to author, but the effect of an SG in the power systems and the world in general are the same as explained by every author.

Despite not having a unique definition for SG, there are some reputable entities that gave it a concept. For example, the United States Department of Energy (DOE) defines it as

“An automated, widely distributed energy delivery network, the SG will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near instantaneous balance of supply and demand at the device level”.

A SG is an upgrade to a traditional distribution network and a two-way communication network for information, sensing, and monitoring of energy consumption through the use of smart devices. In contrast to the traditional SG, which has all of its power production sources and consumer entities linked via a network, a common SG contains several power generations sources and consumer entities [1].

There are some characteristics that can assist to identify an SG, these traits are present in the majority of SG applications and are essential for distinguishing it from the traditional grid:

- **Two-way communication:** Integrate information and communication technologies into every part of the electrical generation, delivery, and consumption allowing users and operators to regulate energy usage, giving them additional options. This integration permits to reduce the environmental impact, improve electricity markets, increase dependability and service, reduce costs with increasing efficiency;
- **Automatically-repair:** The use of distribution grid sensors and with integrated intelligent technologies allows the power station to analyze grid condition in real-time and respond to any issue, and even anticipate the system disturbance, faster and more efficiently. The SG has the ability to mitigate or even prevent service outages or losses in quality;
- **Automation and control strategies:** The SG makes use of digital information, distribution automation, and other control methodologies to allow the deployment and integration of DER, renewable energy generation, automated systems, energy storage systems, and peak shaving technologies;
- **Decentralized production:** With the use of enhanced communication and metering technologies the customers are allowed to take part on the energy system, with all the benefits associated with it, such as diminishing losses and

emissions. An SG integrates technologies that enable users to control their home appliances, enabling for more effective energy management. In other words, SG establishes real-time communication between the grid and the customers, allowing a cooperative connection to be established while eliminating the need for a more robust infrastructure and power plant. This helps to ensure the proper operation of electricity markets, which are having difficulty integrating renewable energy in general and micro producers in particular;

- **Environmental attacks resistance:** The real-time data from the grid enables operators to regulate electrical flux by redirecting it to alternate routes that provide service in the impacted areas;
- **Accommodation for all generation and storage options:** An efficient connectivity between all kinds of energy production (distributed production) and storage allows residential customers to inject energy into the grid or even cut usage during specific hours of the day to meet the needs of the grid Demand and Response (DR). This aspect helps create a more dependable system, lowers electricity prices, and increases the number of options for customers. This convergence of technologies enables improved management of the electricity market, which has historically struggled to adapt to and accommodate rapid changes in production;
- **Enhanced efficiency:** SG reduces grid operating and maintenance costs by optimizing energy flows, which decrease energy waste and maximize the utilization of low-cost resources. The SG harmonizes the transport grid's local flux distribution and inter-regional flux, decreasing grid congestion and strangling spots.

The features listed above represent a notion for a more dependable, smart, manageable, distributed, and protected grid. The SG is a broad and vague term with a poorly defined structure. Even though its structure isn't defined, its purpose and goals are firmly defined.

To understand how these improvements will be performed, it is necessary to first grasp how SG operates, as well as the devices and the mechanisms it employs. The SG is addressed from a technological standpoint in this thesis into three subsystems: infrastructure, management, and protection.

In order to understand the differences between SG and the conventional grid, Table 1 summarizes the main characteristics of each.

Table 1: Main differences between conventional grid and SG

Conventional Grid	SG
Centralized Production	Distributed Power Generation
No Energy Storage	Energy Storage
One-Way Communication	Two-Way Communication (bi-directional)
Electromechanical Control	Digital Control
Manual Restoration	Self-Healing
Outages and Blackouts	Islanding and Adaptive
Reactive Approach	Proactive Approach
Utility has total control	Increased Customer Participation
Reduced to Non-existent Real-Time Monitoring	Vast Real Time Monitoring
Slow Reaction Time	Exceptional Reaction Time

2.1. DIRECT IMPACTS OF A SG

SG are a key technology for the optimization of energy consumption and the integration of renewable energy sources. With the increasing demand for better power quality, increased renewable energy integration and the need for peak demand reduction, the implementation of SGs has become imperative. The current electric power grid infrastructure is outdated and unable to meet the growing demands of the modern power system. SGs provide an array of benefits including increased efficiency, improved reliability, and enhanced security. This thesis aims to explore the current state of the art in SG technology and to identify potential future research directions in the field of SGs.

2.1.1. POWER QUALITY

Power quality is a critical aspect of the electric power system, particularly in the context of SGs. It encompasses any deviation from a perfect sinusoidal waveform, including Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) noise, transients, surges, sags, brownouts, blackouts, and other distortions to the waveform. Harmonic distortions, which are caused by non-linear loads, digital devices, and other advanced power electronic equipment, are a particularly significant power quality issue. The EMI and RFI terms appeared due to higher penetration of non-linear loads and power electronic devices that affect negatively the grids quality, these distortions can lead to overheating of transformers, malfunctioning of equipment, and even damage to digital electronic control systems in operation, which can result in increased costs for utilities and end-users.

In a SG system, AMI and DER can be used to monitor and control power quality issues in real-time. Smart meters, for example, can be used to determine the Total Harmonic Distortion (THD) of the supply voltage, allowing utilities to identify the source of harmonic distortions and take appropriate remedial measures. This can be done by using advanced filtering and harmonic mitigation techniques to reduce harmonic distortions and improve the power factor.

Additionally, the use of advanced power electronic converters and energy storage systems can also help to improve power quality [2].

The use of advanced technologies like advanced power electronic converters, energy storage systems, and microgrids can be used to enhance power quality and support the integration of renewable energy.

2.1.2. ENHANCED RENEWABLE ENERGY INTEGRATION

As concerns towards climate change grow it increases renewable energy penetration in order to reduce carbonic emission and environmental impacts thus it is crucial to a proper renewable energy integration in the electrical grid. At present, the penetration of renewable energy generation is relatively low and can be handled by the current electric grid relatively well. However, as the penetration of renewable energy sources increases, significant improvements and modifications will be required to accommodate and integrate the variable and stochastic nature of these sources [3].

As the penetration of renewable energy sources increases, the electrical grid will require more fast-start and fast-ramping resources to make up for generation shortfalls when these resources are not operating at their expected output levels. Considerable research is being conducted in this field, and proposed systems such as the Future Renewable Electric Energy Delivery and Management (FREEDM) have been developed to address many of these issues. The FREEDM system is displayed in the Figure 1 [4].

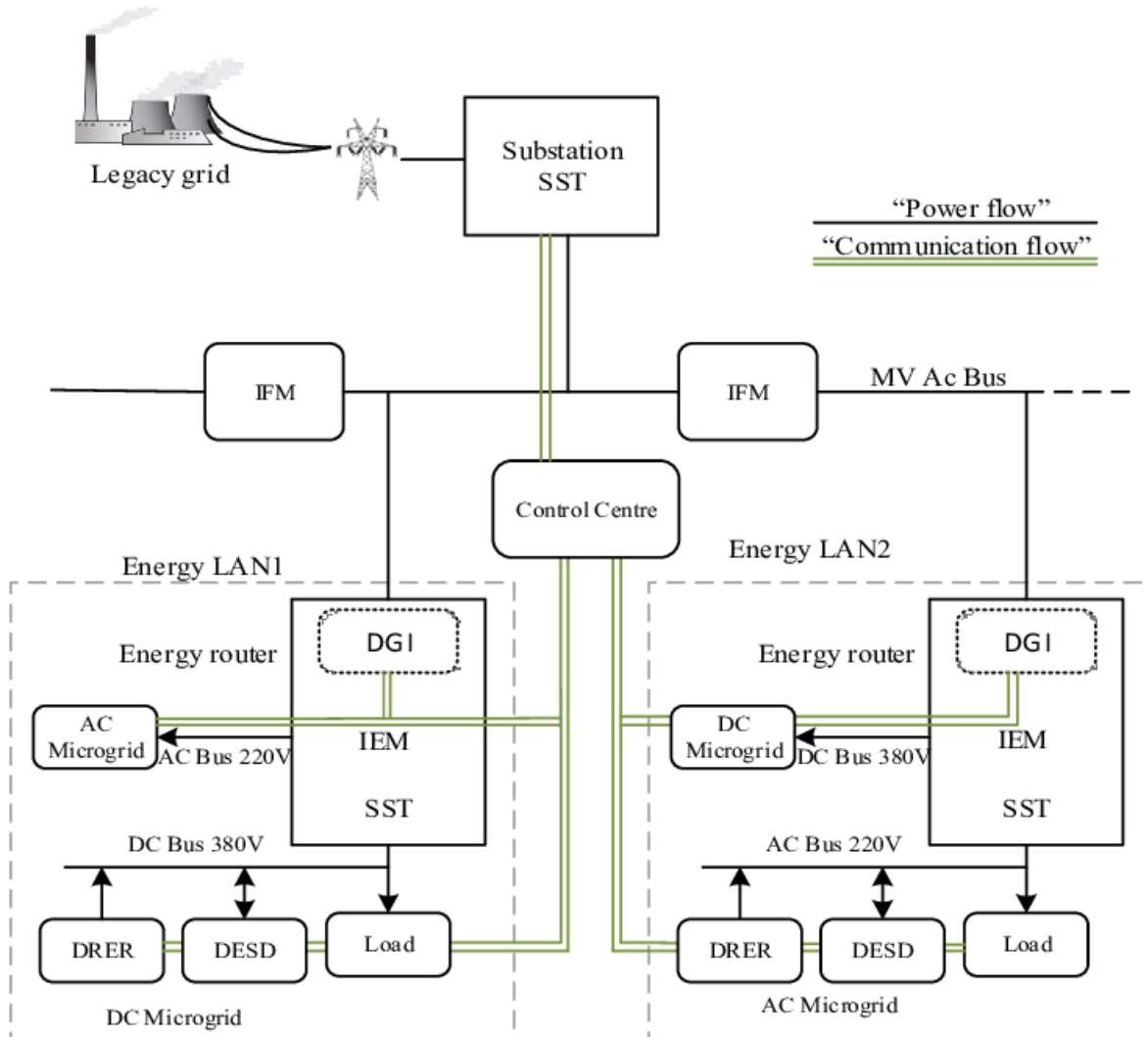


Figure 1: Electric grid showing key elements of the FREEDM system [5]

The goal of these systems is to create an efficient electric power grid that integrates highly stochastic, distributed, and scalable alternative generation sources and energy storage with existing power systems. This will facilitate a green and sustainable energy-based society, mitigate the growing energy crisis, and reduce the impact of carbon emissions on the environment.

The introduction of SG will not only help to reduce greenhouse gas emissions but also encourage increased integration of renewable sources and energy storage assets with the electric power grid. SG can handle the variable nature of renewable energy sources by using AMI and DER to monitor.

2.1.3. TECHNOLOGY IMPROVEMENTS

The current electric grid is severely lacking in automation, particularly on the distribution side. While real-time load monitoring is used in the current system, it lacks the ability to integrate information from a wide array of sources and equipment, resulting in reduced situational awareness. Additionally, with the increase in energy efficiency programs, there is a significant shortfall in the ability to understand and act on the acquired data. The Figure 2 illustrates the technological evolution of the SG, which moves towards increasingly active distribution networks with stochastic generation, energy storage, and controllable and observable load. This shift will change the way electric power networks are planned and operated.

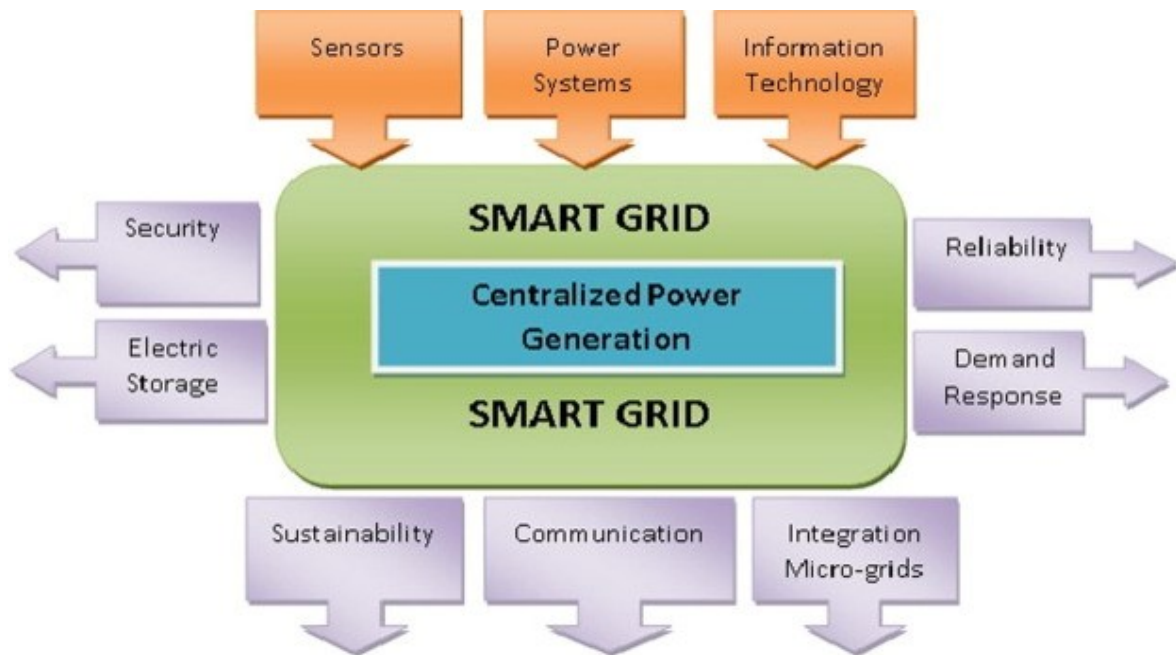


Figure 2: Overview of SG technological improvements [6]

The integration of advanced technologies such as AMI, DER, and automated control systems will enable the real-time monitoring and control of power flows, reducing the need for manual intervention and increasing the efficiency of the grid. This will also

improve the ability to integrate renewable energy sources, such as solar and wind, into the grid and enhance the overall flexibility and resilience of the grid [7].

Furthermore, the implementation of a SG will also improve the ability to respond to changes in demand and supply, enabling the grid to operate more efficiently and reducing the risk of power outages. Additionally, the integration of advanced analytics and machine learning algorithms will enable the grid to better predict and respond to changes in demand, improving the overall reliability of the grid.

2.1.4. PEAK DEMAND REDUCTION

As previously discussed, electricity is the epitome of the just-in-time process, as it must be consumed the moment it is generated. Peak demand occurs during times of greatest need for electricity, and prices are at their highest. Due to a lack of anticipation of the time and nature of peak demand at a certain time, utility operators are forced to operate peaking plants for longer than necessary to meet demand and maintain availability of power. These generating units that meet peak demand are generally expensive to operate, as the fuel used in these plants is bought on the volatile spot market and, in many cases, are fossil fuels that contribute extensively to greenhouse gas emissions.

The introduction of SG, advanced metering infrastructure, demand response, and increased customer participation can lead to significant reductions in peak demand. Such a SG implementation would help utilities drive down costs and, in some cases, even eliminate the use of these plants, thus saving the planet from carbon emissions. SG technologies such as demand-side management and dynamic pricing can enable utilities to better anticipate and respond to changes in demand, leading to more efficient use of resources and a reduction in the need for peaking plants. Furthermore, the integration of renewable energy sources into the grid can also help to reduce peak demand by providing a more stable and predictable source of power [8].

Additionally, the use of energy storage systems, such as batteries and Flywheels (FES), can also help to reduce peak demand by allowing utilities to store energy during off-peak hours and release it during peak demand periods. This can help to smooth out the fluctuations in demand and reduce the need for peaking plants.

SG technologies can also enable utilities to implement demand-side management programs, which incentivize customers to reduce their consumption during peak demand periods. This can be achieved through various mechanisms such as time-of-use pricing, where customers are charged different rates depending on the time of day, or through direct load control programs, where customers agree to have their energy consumption remotely controlled by the utility during peak demand periods.

The implementation of a SG can also improve the integration of DER such as rooftop solar, electric vehicles, and energy storage systems. By connecting these DER to the grid, utilities can better predict and respond to changes in demand, enabling them to better manage the grid and reduce the need for peaking plants. Furthermore, the integration of DER can also reduce the dependence on fossil fuels, which in turn can help to reduce greenhouse gas emissions and mitigate the impacts of climate change [9].

In conclusion, the implementation of a SG can help to reduce peak demand and the need for peaking plants by enabling utilities to better predict and respond to changes in demand, and by improving the integration of renewable energy sources, energy storage systems and DER into the grid. This can help to reduce costs, improve the reliability of the grid, and mitigate the impact of climate change. Additionally, by providing consumers with more control over their energy usage and costs, SGs can also promote energy efficiency and conservation, further reducing peak demand and the need for peaking plants. Overall, SG can play a crucial role in improving the sustainability and resilience of the electric power system.

2.2. SMART GRID TECHNOLOGIES

SG technology is a rapidly evolving field that offers a wide range of benefits for the electric power industry. At its core, a SG is an advanced version of the traditional electric power grid that is able to intelligently integrate and manage the various components of the grid, including generation, transmission, distribution, and consumption. By leveraging advanced communication technologies, advanced metering infrastructure, and advanced analytics, SGs are able to improve the efficiency, reliability, and security of the electric power system, while also reducing costs and promoting the integration of renewable energy sources. This chapter explores the various technologies that make up a SG, including advanced metering infrastructure, demand response, Distributed Generation

(DG), energy storage, and advanced analytics. It also examines the potential benefits and challenges of implementing a SG and explore the ongoing research and development efforts in this field.

2.2.1. ADVANCED METERING INFRASTRUCTURE

The integration of SG technologies, particularly in the realm of distribution automation, has become increasingly important in recent years. The term "smart grid" has traditionally been associated with AMI, and while the implementation of such technology is a crucial component, it represents only one aspect of a comprehensive SG system. An advanced Energy Management System (EMS) paired with smart metering at the end-user level can offer a range of opportunities for energy reduction and peak demand management. Additionally, the implementation of Home Area Networks (HAN) can further strengthen demand-side programs. The advanced functionality of AMI can facilitate additional capabilities such as real-time pricing and time-of-use pricing, peak demand shaving, demand profiling, remote condition monitoring of sensitive equipment, load monitoring, and outage detection and islanding [10].

AMI structure is explained in Figure 3Figure 2 and is divided in 3 sections:

1. Sensing in AMI:

- **Human Management (Customer Interaction):** This aspect of sensing can be likened to the utility customers' behavior and interactions with their utility meters. Just as sensors detect human activities, AMI meters detect customer utility usage patterns.
- **Environment (Utility Grid):** The environment here represents the utility grid, including the physical infrastructure for electricity, water, or gas distribution. Sensors in the form of advanced meters collect data on the consumption within this environment.

2. Reasoning in AMI:

- **Activity Recognition (Data Analysis):** Activity recognition in the context of AMI can be compared to the analysis of the data collected by the meters. It involves identifying and understanding customer

consumption patterns, just as activity recognition identifies human actions based on sensor data.

- **Learning (Pattern Recognition):** Learning in AMI corresponds to recognizing recurring patterns in utility consumption data over time. This learning process is similar to understanding and learning from human behavior patterns.
- **Knowledge (Data Repository):** Knowledge in the AMI structure is akin to the accumulation and storage of historical utility consumption data. It represents the knowledge gained from analyzing past patterns.
- **Decision (Utility Management):** Decision-making in AMI involves using the knowledge gained to make informed choices about utility distribution and management, similar to how decisions are made based on recognized human activities.

3. Action in AMI:

- **Action (Utility Response):** Actions in AMI can be seen as the utility's response to the insights and decisions derived from data analysis. For example, the utility might adjust distribution strategies, perform maintenance, or implement rate changes based on the information gathered.
- **Environment (Utility Grid):** The actions taken by the utility, such as optimizing grid operations or implementing demand response programs, influence the utility grid, altering how resources are distributed and consumed.

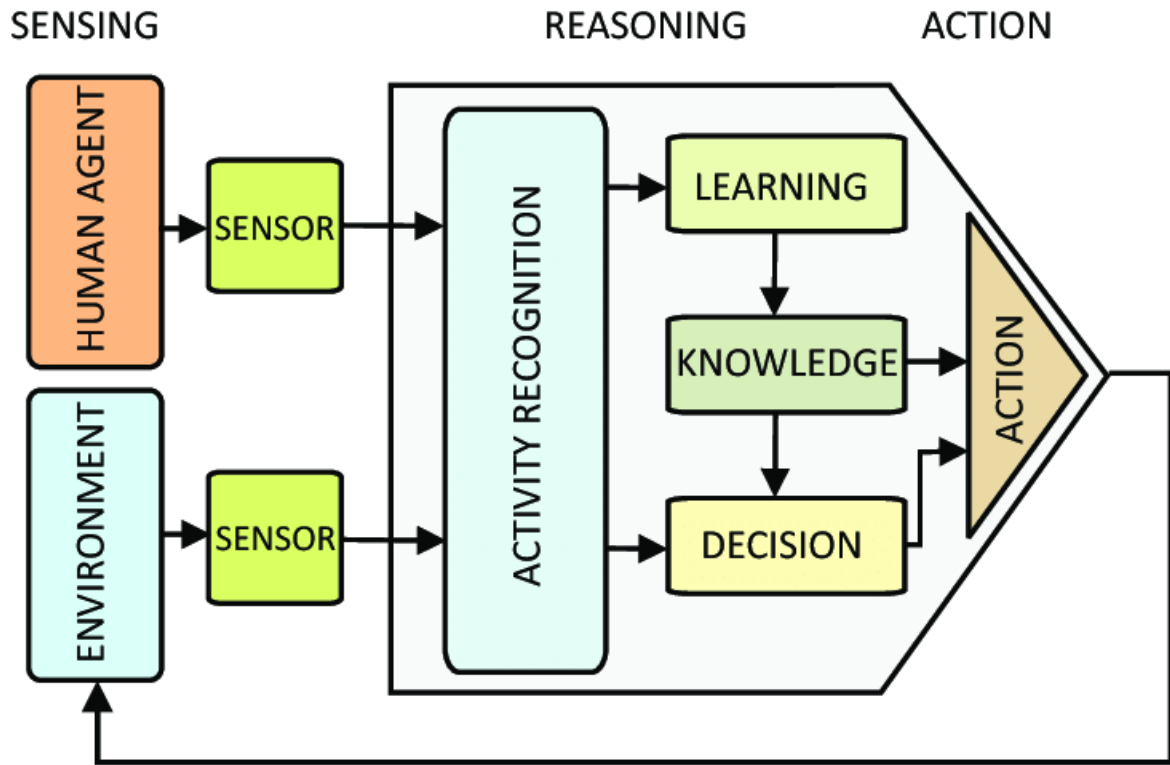


Figure 3: AMI structure [11]

The integration of smart meters and other advanced digital electronic devices, connected through a two-way communication network, has the potential to generate a significant amount of data. This data must be organized and made accessible to various stakeholders within the utility organization, in order to effectively utilize it for energy management and optimization. The use of dynamic pricing models and load shedding techniques, enabled by enhanced two-way communication technology, can effectively and efficiently manage load distribution and reduce peak demand. It is crucial that the control center continuously synchronizes pricing signals with the utility side database to ensure accuracy of consumer billing data and effective conservation efforts. Additionally, features such as data recording, power monitoring, and tamper protection can provide valuable long-term benefits [12].

The use of smart meters and other remote digital electronic devices in the SG system allows for the collection and analysis of vast amounts of data, including energy consumption patterns, pricing signals, and load distribution. This data can be used to improve energy efficiency and reduce peak demand through dynamic pricing models and load shedding techniques. However, it is important that the data is organized and accessible to various users within the utility organization in order to effectively utilize it.

The two-way communication technology used in SG systems allows for real-time monitoring and control of the grid, enabling the detection of outages and other issues in a timely manner. This can help improve the reliability and security of the power grid. Furthermore, features such as data recording and tamper protection can aid in identifying and preventing fraud and other malicious activities.

As part of SG, DMS have been developed to improve the ability of distribution utilities to detect, locate, and respond to network disturbances. DMS can be used to control the distribution network in real-time and to optimize the use of DER such as DG, energy storage and demand-side management. DMS can also be used to identify and mitigate power quality issues and to manage voltage levels on the distribution network [13].

It is important to note that the integration of advanced technologies in the SG such as DMS, AMI, and others, requires a robust communication infrastructure. This infrastructure must be secure, reliable, and able to handle large amounts of data. Additionally, the integration of these technologies requires a significant investment in both hardware and software, as well as training and support for utility employees.

2.2.2. DEMAND AND RESPONSE

The integration of Demand and Response (DR) technology into the SG paradigm is crucial for maintaining a balanced market power supply and designing effective market strategies. DR refers to the policies and business practices where customers adjust their energy consumption during peak demand periods in response to pricing signals or other incentives. In recent years, interest in DR has grown among regulators and government entities due to its potential economic and societal benefits.

The implementation of technologies such as smart meters, time-of-use pricing, and load control devices for end-users is critical for increasing customer participation and achieving tangible results for both utilities and consumers in terms of economic benefits. For instance, building management offices can utilize the energy prediction capabilities of smart meters to implement peak shaving programs by temporarily shutting off certain equipment during high-demand periods, thereby reducing energy consumption and costs.

Overall, as consumers gain more awareness and understanding of SG technology and DR programs, they will be able to benefit financially and in terms of convenience, while also contributing to a reduction in greenhouse gas emissions. An example of this can be seen in California's DR program where utilities offer incentives to customers who reduce their energy usage during peak hours [14].

DR is already being implemented in some electrical systems, for example, in the United States, the Federal Energy Regulatory Commission (FERC) has made significant efforts to promote DR programs through Order 745, which requires grid operators to compensate DR resources at the same rate as traditional generation resources. Additionally, many states have implemented DR programs to help manage peak demand and reduce the need for expensive peaker plants. Furthermore, with the integration of advanced metering infrastructure and other SG technologies, it has become easier for utilities to communicate with customers, monitor their usage and provide real-time pricing signals to encourage demand response. One recent example of this is the launch of the “Green Button” initiative, which enables customers to access their energy usage data in a standard format and allows them to better manage their energy consumption, by using third-party apps that help them understand their energy usage, set goals and control their energy costs.

2.2.3. OPTIMAL ASSET UTILIZATION AND OPERATING EFFICIENCY

The SG utilizes advanced technologies that allow for the collection and analysis of real-time data, including grid operating parameters and the state of health of equipment. This information is used to monitor equipment condition, detect degradation in performance, optimize operations, and develop a condition-based maintenance strategy based on the type of fault. By analyzing failure and maintenance characteristics, the SG can predict the lifespan of equipment during its life cycle, ultimately increasing the operating efficiency of the overall grid and reducing the costs of operations and maintenance. This allows for proactive maintenance and the ability to predict and prevent equipment failures, ultimately reducing downtime and increasing the overall efficiency of the grid. Additionally, the use of advanced analytics and data management tools allows for the identification of inefficiencies and opportunities for optimization in the grid operations. One example of this is the use of real-time data from SG sensors and devices to optimize the scheduling and dispatch of energy resources. This helps to maximize the utilization

of renewable energy sources, reduce dependence on fossil fuels, and ultimately decrease the environmental impact of the power grid [15].

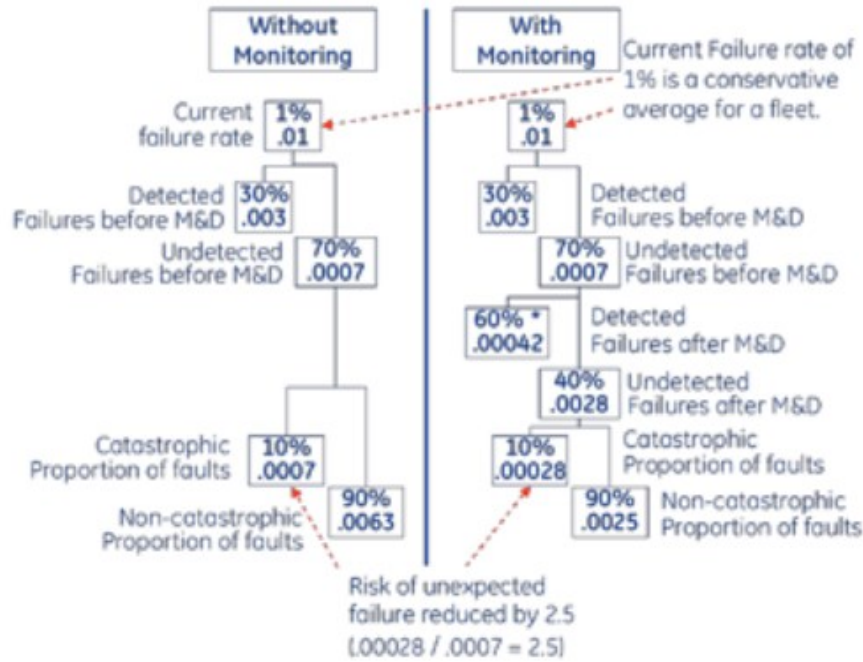


Figure 4:Transformer reliability comparison [16]

The implementation of condition monitoring in the SG can significantly reduce the risk of transformer failure. As illustrated in Figure 4, the risk of failure without monitoring is approximately 0.7%, whereas with the implementation of condition monitoring, the risk is reduced to 0.028%. This represents a 2.5 times reduction in the risk of catastrophic failures, and can result in significant savings in annual maintenance costs. With this implementations SG can contribute to a overall more safe, reliable and more cost-effective system.

2.3. INFRASTRUCTURE SYSTEM

The infrastructure system includes SG's energy, management, and communication infrastructures. In other words, this system is linked to all the physical components that withstand the SG.

As previously noted, SG must facilitate two-way information and electric flows. In the case of information, this two-way transit is usual, but in the case of electricity, it is not.

When we look at the present electric system, we can see that electricity is only transferred in one direction: from power plants to customers.

In SG ecosystems, users can produce electricity from renewable sources such as wind turbines or solar panels and feed it into the grid. Furthermore, electric cars will be able to be used for Vehicle-to-Grid (V2G) when demand for electricity is high.

The prospect of a backward flow of power necessitates additional infrastructures, including protective mechanisms that are not yet accessible nor installed in the grid.

2.3.1. ENERGY INFRASTRUCTURES

The energy infrastructure is exceedingly complex due to the tremendous energy demand that must be met, as well as the necessity for immediate response, distance to which the energy needs to travel, and the safety of all users. Power generation and, transmission, distribution are all part of the energy infrastructure.

Despite global attempts to shift power production toward renewable energy, a significant share of electricity is still produced with steam turbines using fossil fuels. In most circumstances, a steam turbine has a rotating electrical generator that revolves utilizing a steam turbine. Steam can be produced by burning coal, oil, natural gas, or nuclear fuel.

The power leaves the generator and travels to a transmission substation at the power plant, where it is raised in voltage using step-up transformers. This greater voltage allows for less electricity losses in transmission network making transmission viable for long distances. The voltage must be scaled down to distribution networks before it can be used in residential facilities or companies. This procedure occurs in a tiny power substation, which is made up of transformers, a bus that distributes electricity in different directions, circuit breakers, and switches. This substation's power enters the distribution system. When power is delivered to the service area, the voltage is dropped again so that it may be utilized in houses and facilities [17], [18].

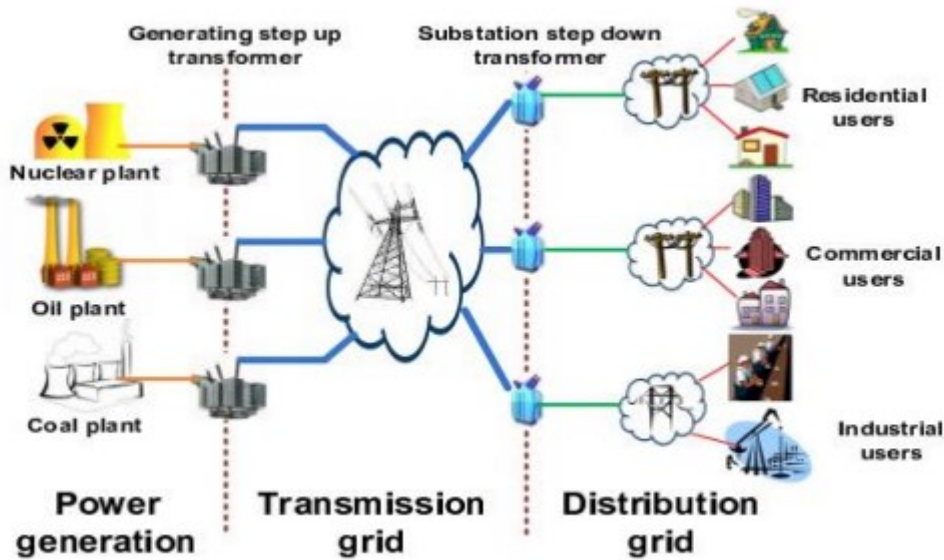


Figure 5: Traditional power grid[19]

The typical grid is described in Figure 5, the power generation, transmission, distribution, and consumption are the four components of the conventional grid. The SG may also be classified into these infrastructural categories, although all these labels are more ambiguous, taking the commercial user as an example, they might be both a consumer and a producer. The SG's adaptability, responsiveness, and bidirectional flux leads in to more fluid infrastructure categories [20].

2.3.2. POWER GENERATION

The modern power generating structure dates back to 1830, when British scientist Michael Faraday realized that the motion of a loop of wire or a disc of copper between the poles of a magnet does create electricity. Until recently, society relied on this technique with the help of fossil fuels to generate energy.

However, due to environmental and economic issues associated with fossil fuel burning, the usage of renewable sources is expanding.

There are two principles linked to electricity generating in SG. The first element is DG, which uses DER systems to generate power. This is only feasible because SG allows for the bidirectional flow of power and information. Another crucial idea is Virtual Power Plants (VPP), which controls a huge number of remote generators [21].

The DG is essentially a small-scale power producing system. It is a collection of small-scale electric power generation units located at or near a customer. Some experts argue that DG is referring to electricity generation at the point of consumption. This enables for the decrease of transmission and distribution costs, complexity, interdependencies, and inefficiencies.

The fast development of the world population and technological improvements have resulted in an exponential increase in energy consumption. In general, fossil fuels are not sustainable and have serious environmental and public health repercussions. All of these economic, health, and environmental issues make renewable energy a more enticing option. Renewable energy now has a significant influence on overall electricity generation worldwide, and it is predicted to surpass fossil fuel output [22].

As seen in Figure 6, many methods can be employed for small-scale power generation.

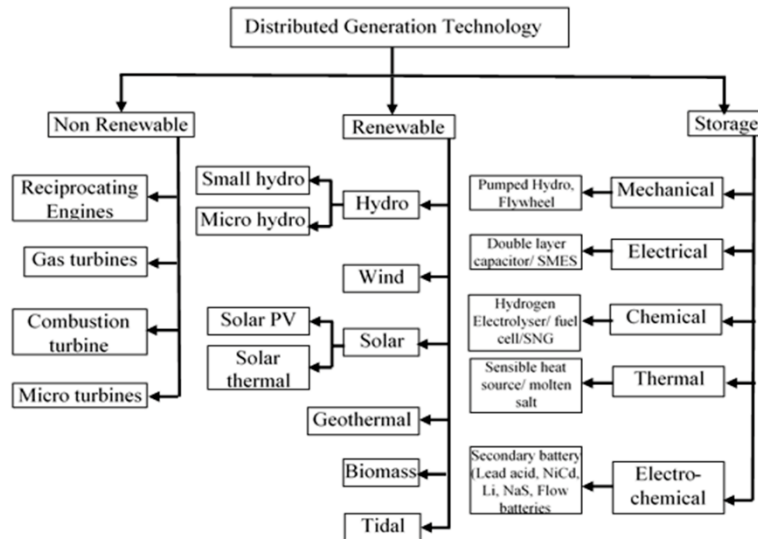


Figure 6: Distributed technologies [23]

With such a huge number of DER, numerous challenges must be solved, like as the intermittent nature of renewable sources, which are weather dependent, their fluctuating output is referred as non-dispatchable. Furthermore, because of differing ownerships, DER units operating in isolation limit their potential to supply local demands but not the overall grid.

VPP can address all of these challenges by controlling all of the DG generating sources and aggregating them into a cluster of dispersed generator units, controlled loads, and storage systems that function as a unique power plant that is extremely adaptable and responsive.

VPP has an energy management system that controls the power flows coming from the generators in a two-way communication. The VPP must receive information about the present condition of the energy produced in real-time, but it may also transmit signals to control and operate objects. This function enables the VPP to achieve several goals such as lowering generation costs, lowering emissions, and increasing profits giving it multiple optimization capabilities to different scenarios. In Figure 7 is illustrated the typical components comprising a Virtual Power Plant (VPP) [24].

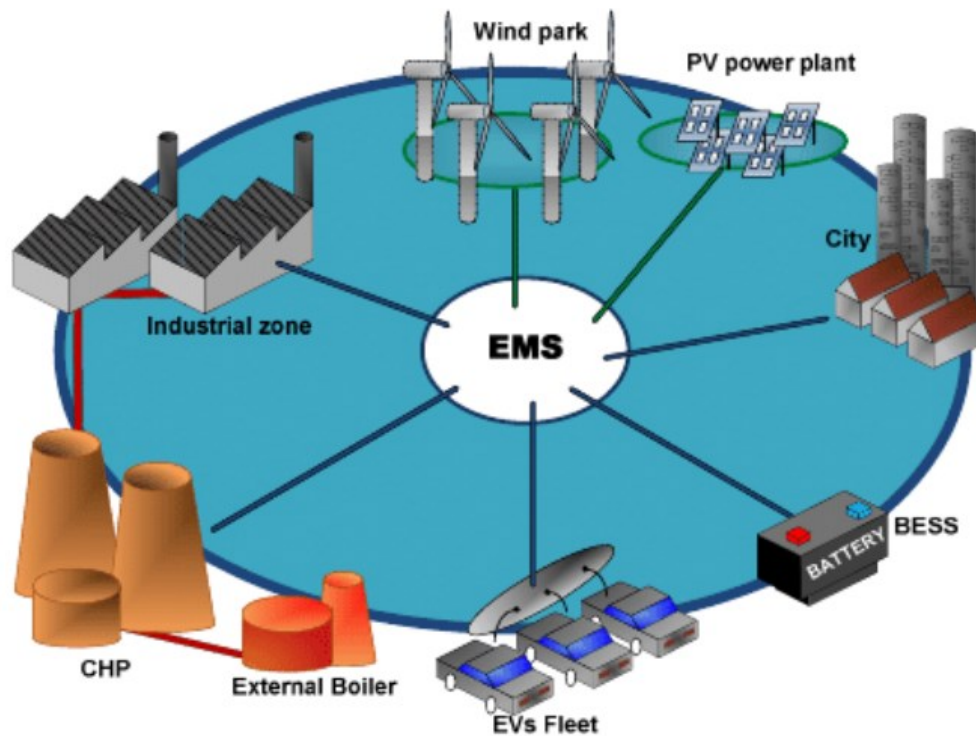


Figure 7: Virtual Power Plant structure [25]

The VPP possesses the capability to seamlessly incorporate a variety of DER into its framework, both from a technological and commercial/market perspective.

VPP are categorized into Technical VPP (TVPP) and Commercial VPP (CVPP). The TVPP is responsible for ensuring that the power system is operated in an optimized and

secure manner, taking into account physical constraints and the potential services offered by the VPP. On the other hand, the CVPP views DER as commercial entities and optimizes the economic utilization of the VPP portfolio for the open electricity market by considering the price and amount of energy that the DERs can deliver. While the primary purpose of the CVPP is to schedule and optimize DER utilization considering energy offers and needs, the TVPP manages the operational employment of specific DERs in a technical manner.

2.3.3. TRANSMISSION GRID

In recent years, there has been a growing interest in the development of more efficient and safe transmission lines within the electrical grid. The current transmission lines, while functional, have several limitations that make them less reliable and more prone to failure. As such, significant research has been conducted to develop new technologies and methodologies that can improve the efficiency and safety of transmission lines.

One of the key areas of research has been in the development of new materials and construction techniques that can increase the overall strength and durability of transmission lines. This includes the use of advanced composites, such as carbon fiber reinforced plastics, which have significantly higher strength-to-weight ratios than traditional materials like steel. Additionally, new construction techniques such as automated welding and advanced coatings have been developed to improve the overall integrity of transmission lines [26].

Another area of research has focused on the development of new monitoring and control systems for transmission lines. These systems allow for real-time monitoring of the state of the transmission lines, which can help to detect and prevent potential failures before they occur. Additionally, advanced control systems can be used to optimize the flow of electricity through the transmission lines, increasing overall efficiency and reducing energy losses.

In conclusion, significant progress has been made in the development of more efficient and safe transmission lines. The use of advanced materials, construction techniques, and monitoring and control systems has the potential to greatly improve the overall reliability and performance of the transmission grid. Further research is needed to fully realize the

potential of these technologies and to continue to push the boundaries of what is possible in transmission line design.

The smart transmission grid is composed of three main parts: control centers, the transmission network, and substations. The concept behind the smart control centers is to augment the existing control centers with new functions such as monitoring, analytical capabilities, and controllability. Traditionally, monitoring is done through estimators that rely on data collected via Supervisory Control and Data Acquisition (SCADA) and Remote Terminal Units (RTU). However, in a SG, this information is collected by state measurement modules, which are more efficient. These devices will be studied in more detail in the information subsystem. The results from state measurement are combined with Geographical Information Systems (GIS) for visual display on control center screens in real-time, allowing for better system management and control [27].

In the context of SG, long-distance transmission is achieved through the utilization of high-capacity AC and DC facilities. These new transmission lines, which can have up to 6 or 12 phases, improve transmission efficiency while reducing electromagnetic fields.

The reliability and flexibility of these transmission lines are further enhanced through the use of Flexible AC Transmission Systems (FACTS) and High Voltage DC (HVDC) devices. These technologies have been shown to effectively alleviate transmission congestion. HVDC lines, in particular, have become increasingly popular due to their ability to provide a controllable and economic alternative to long-distance AC lines [28].

In addition to these technological advancements, the smart transmission network is composed of solid-state components such as transformers, circuit breakers, and other devices that offer improved reliability and longer life spans. The smart substations, in particular, must provide monitoring, operation, control, protection, and maintenance capabilities for the equipment installed within them.

From an operational standpoint, these substations must be digitized in order to improve efficiency and reduce maintenance costs. The operator should be autonomous but coordinated with other substations through a communication network. The traditional electromechanical Current Transformer (CT) and Potential Transformer (PT) will be replaced by optical CT and PT which allow wide bandwidth, high accuracy of measurement, and low maintenance costs. Each substation has its own Local Area

Network (LAN) and a communication network via router to connect all the substations, allowing for a comprehensive and integrated monitoring of the transmission grid [29].

The Figure 8 illustrates the interconnection of the transmission network within a SG system.

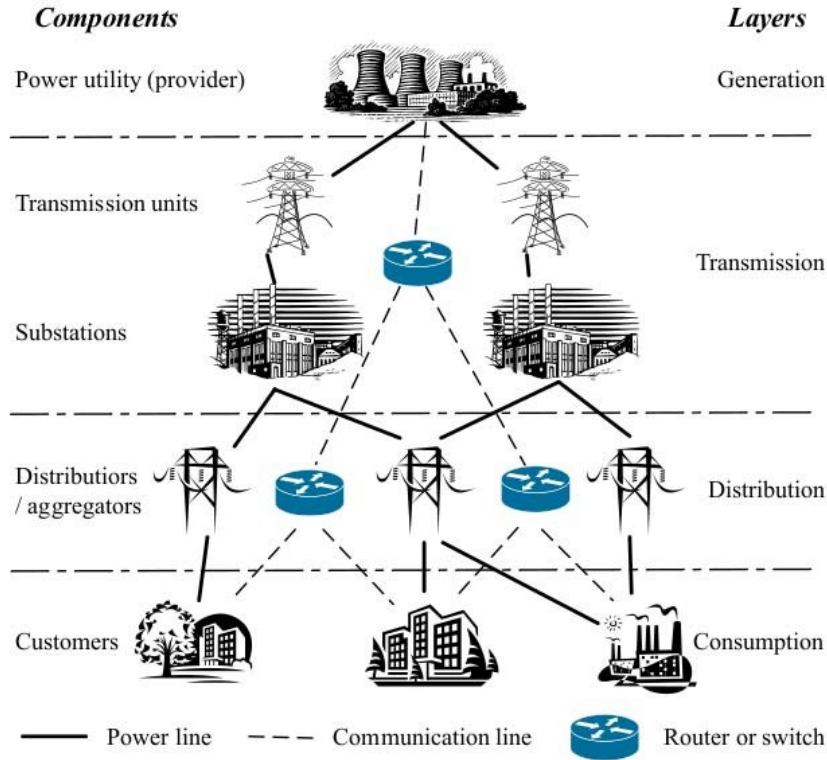


Figure 8: Transmission connection in a SG [30]

2.3.4. DISTRIBUTION GRID

The proliferation of distributed power generation has been on the rise in recent years, and this trend is expected to continue with the increasing penetration of renewable energy sources into the grid. As a result, the traditional model of household consumers will be replaced by a paradigm in which individuals are both consumers and producers of energy. While this presents numerous advantages, it also poses significant challenges related to balancing energy production and demand. To address this issue, the implementation of in-home distribution systems that facilitate the reduction of energy consumption and the alignment of production with demand at the household level will be necessary. Two specific systems that can be utilized in this context.

One potential solution to the challenges posed by distributed power generation is the implementation of a circuit switching system based on alternating current (AC) power distribution. The aim of this system is to concurrently deliver electricity via a single in-home power distribution network, incorporating both renewable energy sources and commercially sourced power. Given that the quality of energy produced by renewable sources is often inferior to that of commercially sourced power, this system employs batteries to compensate for fluctuations. Additionally, convertors and inverters are used to match the quality of commercial power. However, for certain devices that incorporate batteries, it may be acceptable to connect the load directly to the source, depending on the requirements.

To achieve optimal source-and-load matching, it is necessary to have accurate knowledge of the quality and quantity of generated power. To overcome this challenge, the system employs Power Line Communication (PLC) technology. The system comprises two components: an information terminal and an AC power router. Each component is equipped with a PLC modem and a microprocessor with a Linux operating system. The information terminal gathers data from sources and loads, and the CPU decides the most suitable source for a given load and communicates this information to the router [31].

Another distribution system that can address this challenges is a packet dispatching system in Direct Current (DC) distribution, which utilizes power packets and transmits them through IP-based networks [32].

This system is composed of multiple sources and loads, each one with an individual address, as well as a mixer, a router, and a single distribution line connecting the mixer and the router, as depicted in the Figure 9, below. The supplied power from the sources is divided into several units of payload, which are attached with a header and a footer to form a power packet. The header comprises a start signal that marks the beginning of the packet, the load and sender addresses. The footer includes the end signal. The amount of energy per packet is regulated by adjusting the length of the payload. A power request to a specific address is issued when the payload is empty.

The function of the mixer is to gather the payloads and send them to the distribution line. The router receives the packets, the controller sorts them according to the addresses on the headers and sends them to the corresponding loads. Additionally, the system can be

integrated with advanced control algorithms to optimize the power allocation and balance the energy demand and supply in real-time. Furthermore, the system can be equipped with communication interfaces to enable remote monitoring and control of the distribution network [33].

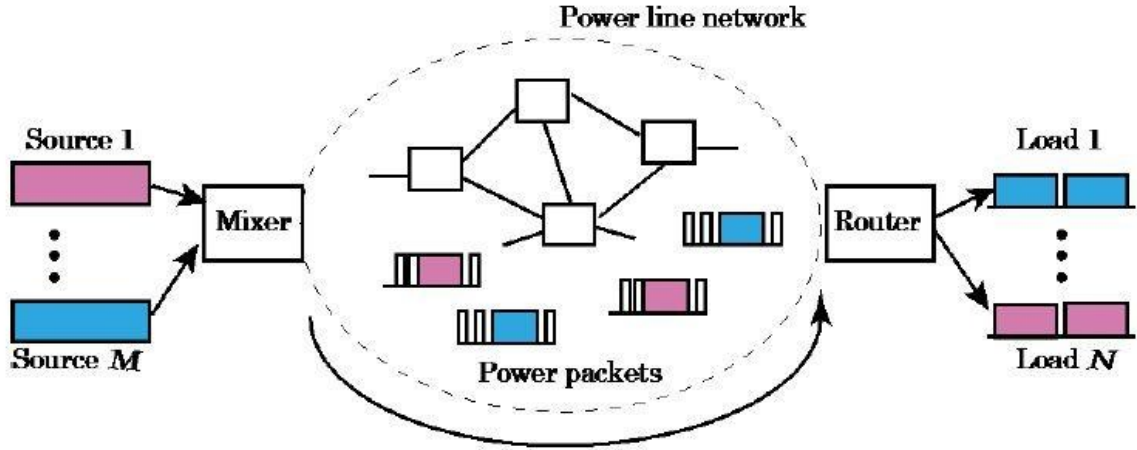


Figure 9: Packet dispatching System [34]

2.3.5. MICROGRID

One of the key components of the SG is the concept of the microgrid, which is being advanced through the deployment of Distributed Generation (DG) technologies. A microgrid is a collection of electricity generation, energy storage, and loads that is connected to a traditional centralized grid, also known as a macro grid. Microgrids can be considered as an extension of the distribution grid, located downstream of the distribution substation, and comprised of DER, various types of electricity and/or heat consumers.

The DER units within a microgrid encompass both DG and Distributed Storage (DS) systems, which have varying characteristics and capacities depending on the loads and energy usage within the system. DER units can be divided into two groups based on their interaction with the microgrid; they can be connected through rotating machines or through electronic converters to provide a connection medium with the system. The control and operation strategies for the two groups of DG and DS are vastly different from one another. As a result, the control strategies and dynamic behavior of a microgrid are vastly different from those of a conventional power system, particularly in islander mode.

Additionally, the control strategies and energy management of a microgrid are highly dependent on the type of DER, load requirements, and expected operation scenarios, as opposed to pre-defined and well-established strategies in grid-connected mode. Advanced control algorithms and energy management strategies, such as demand response and DER management systems, are necessary to optimize the power allocation and balance the energy demand and supply in real-time. Furthermore, the system can be equipped with communication interfaces to enable remote monitoring and control of the distribution network. The Figure 10 illustrates the components and general architecture of a microgrid [35].

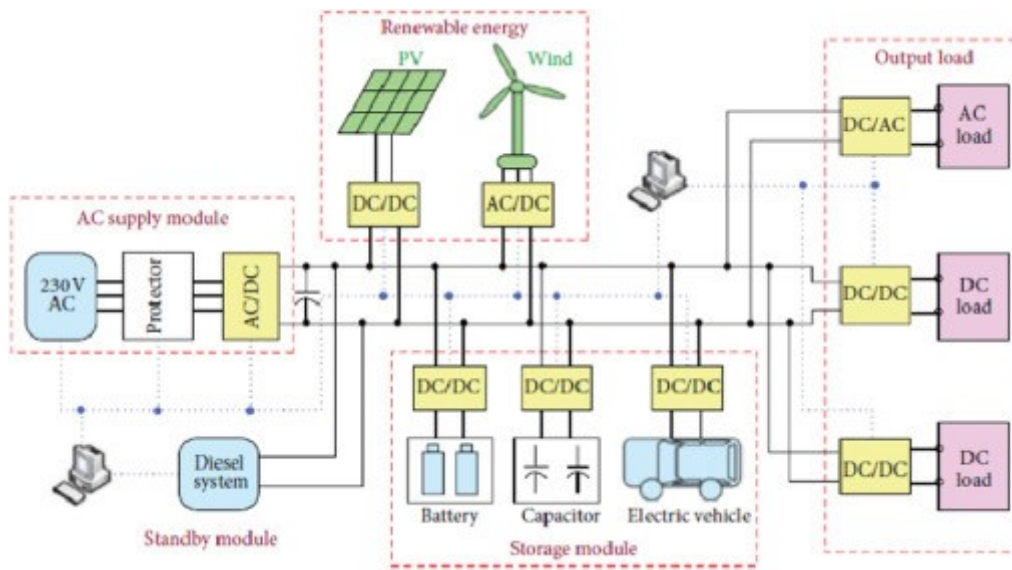


Figure 10: Microgrid architecture [36]

2.3.6. RENEWABLE ENERGY SOURCES

In developed countries, a key strategy to increase the share of renewable energy in the power sector is to undertake updates and modernizations to the existing infrastructure. This modernization process is technically feasible and can provide new solutions to accommodate the unique characteristics of different types of renewable generation, such as variability, DG, and high initial costs.

SG have the capability to integrate these characteristics of renewable generation and effectively manage the variability in power production. As it is well-known, some renewable energy sources such as wind and solar power are dependent on external conditions, like weather, to generate electricity. Therefore, it is essential that the power system has the ability to absorb this variability and adapt to changes in power production.

Additionally, renewable generation technologies typically have a higher investment cost than traditional generation technologies. Despite being cost-effective in some situations, particularly in developing countries, there is a lack of sufficient investment in renewable energy. Therefore, it is important to explore and implement policies and financial mechanisms that can encourage private and public investment in renewable energy projects.

The SG can effectively address the challenges of variability, (DG), and capital requirements, while also providing additional benefits to facilitate the transition to renewable energy sources. To address variability, the SG can integrate a wide range of renewable resources through advanced communication and control techniques. For example, a Photovoltaic (PV) system and a set of industrial and commercial users on an interruptible rate can be tied together with SG technology. If the PV system experiences a drop in production due to passing clouds, the SG can automatically stop service to the interruptible rate consumers without penalty. When the clouds pass and the PV system resumes production, the service can be resumed.

With regards to DG, the SG can play a crucial role in promoting and integrating this type of generation into the power system, as highlighted in this work. The SG can enable utilities to manage and incorporate many small and/or individual DG plants into the electric system, which can help reduce costs and improve system efficiency [37].

Finally, SG can also help address capital requirements and encourage private investment in DG. Historically, electric utilities have been responsible for investing in power plants to produce electricity, but with the increasing prevalence of DG, any person or organization can invest in energy generation systems. The SG allows for this, enabling utilities to manage and incorporate many small and/or individual DG plants into the electric system.

In a more radical vision, the SG can be compared to the Internet, where governments once had the responsibility to provide the grid, but now the private sector provides that service. In this vision, with almost all generation distributed, consumers could be able to make direct market, bilateral deals with producers, and the utility's role would be relegated to distribution only.

2.3.7. ENERGY STORAGE

Energy storage has become a crucial need in the power industry, as increasing cases of blackouts, low power quality, and fluctuating frequency due to the rise in renewable energy generation have highlighted the need for reliable and efficient energy storage solutions. Economic energy storage is highly desirable for peak shaving and power quality improvements. Energy storage devices enable the power system network to integrate renewable sources with the power system by converting them into a smoother and dispatchable format, provide ride-through capability when DG fails to supply the required energy, and manage the amount of power required to supply during peak power demand by storing it during off-peak hours.

Different types of storage systems such as Battery Energy Storage Systems (BESS), FES, Compressed Air (CAES), Pumped Hydro (PHS), ultra-capacitors (UC), superconducting magnetic energy storage (SMES), and hydrogen storage store energy in different forms such as electrochemical, kinetic, pressure, potential, electrostatic, electromagnetic, chemical, and thermal. Lead-acid batteries are still used on a large scale due to their low cost and ruggedness, but they are losing popularity because of weight and power density issues. Sodium sulfur (NAS) battery systems, which are already in use at the grid level by Tokyo Electric Power Company (TEPCO) since the 1980s, are gaining much popularity due to their high power and energy densities, temperature stability, low cost, and good safety [38].

Such storage technologies can complement the current power plants for peak shaving, emergency power supply, uninterrupted power supply, and can be integrated later with various renewable energy generation resources. Furthermore, the value of energy storage technologies must be assessed with consideration to costs of installation in the short term, maintenance costs, and revenue or savings provided by the energy storage in the medium term, and finally the potential long-term benefits to the overall electricity infrastructure.

Energy storage is necessary to give more flexibility to the grid, to maximize the renewable energy utilization and will also allow for more installed capacity of renewable sources since in many cases it is not economically or technically feasible because of the demand in some periods, but with storage systems this stops being a problem. To achieve a greater inertia system in a SG with predominant renewable energy penetration, batteries will be needed.

2.4. SG CHALLENGES

SG are a key technology for the integration of renewable energy sources and the optimization of energy transmission, distribution, and consumption. However, the deployment and operation of SG also pose several technical, economic, and regulatory challenges. These include issues such as integrating RES and DG into the grid, upgrading and modernizing an aging infrastructure, managing and storing large amounts of data, meeting the needs of different stakeholders including utilities governments and consumers, ensuring the stability and reliability of the grid, protecting the privacy and security of communication networks, and designing pricing and incentive mechanisms that encourage consumer participation. This topic aims to review the current state of the art in addressing these challenges and to identify potential future research directions in the field of SG.

2.4.1. TECHNICAL CHALLENGES

One of the major technical challenges facing the deployment and operation of SG is the integration of planning and real-time analysis. This requires the development of sophisticated algorithms and models to balance the conflicting objectives of maximizing the utilization of renewable energy sources while maintaining the stability and reliability of the grid. Additionally, the large system models required for this analysis can be computationally intensive and may require significant computing resources.

Another significant challenge facing SG is the handling of large amounts of data generated by AMI devices. This data must be collected, stored, and analysed in real-time to support decision-making and control of the grid. Furthermore, there is a need for the development of AMI-based decision-making algorithms that can effectively utilize this data to optimize the operation of the grid [39].

SG systems also require the ability to perform time series simulation to evaluate the impact of different scenarios on the grid. This includes the integration and protection of DG sources, as well as the integration of energy storage technologies that can provide cheap, reliable, and sustainable energy.

Apart from the aforementioned technical challenges, effective interoperability of SG devices also requires the development of robust standards. With increased investments in

the SG sector, a number of SG technologies are already being implemented in the electric power grid. However, in the absence of universal standards, these technologies face the danger of becoming prematurely obsolete or their security being compromised.

Moreover, increased dependence on DG, demand-side resources, and distribution system applications significantly increase the system's exposure to cyber vulnerability. Therefore, a robust security architecture needs to be built on existing communication and technology infrastructures to enable the implementation of SG at various levels in the electric power system. Furthermore, a robust framework for conformity testing and certification of SG devices and systems need to be established to ensure interoperability and cyber security [40].

2.4.2. BUSINESS AND FINANCIAL CHALLENGES

Establishing a robust business case for the deployment of SG is crucial for the successful implementation of these systems in the real world. A business case, in its most general terms, provides the basic rationale for investment in projects for business change. In the SG arena, entities that are primarily responsible for building business cases include network operators, electricity retailers, and newly emerging players such as generation and demand aggregators.

One of the biggest business challenges facing the utility industry is the high initial capital cost associated with the deployment of a full-fledged SG. Justifying this cost with site-proven benefits is crucial for the success of SG projects. Furthermore, consumers may be sceptical about the cost benefits of such an investment, as they may appear small compared to the investment required [41].

At the macro policy level, the power industry must meet the requirements of a resource-saving and environmentally friendly society, adapt to climate change, and conform to sustainable environmental standards. Additionally, sharing the cost of common infrastructure across the benefits derived from various applications will provide a more realistic cost-benefit ratio for each application in an integrated system for full roll-out beyond the pilot stage [42].

With so much investment put into SG scenarios, it is important for utilities to recover their investment costs. While SG are primarily associated with cost savings at the consumer end, it is also vital to note that on a broader perspective, SG can lead to potential savings by increasing the reliability of the electric power grid. For example, the implementation of wide-area measurement systems (WAMS) and phasor measurement units (PMUs) could have avoided the 2003 great northeast blackout, which resulted in approximately \$10 billion in economic damages in the U.S.

Lastly, addressing consumer concerns regarding plug-in hybrid electric vehicles (PHEV) in terms of pricing, cost benefits, technical specifications, and reliability is crucial for the success of SG projects. PHEV will play an important role in future SG networks, but they are currently very expensive and considered a luxury rather than a way to save money and reduce carbon emissions. Additionally, the cost of converting a hybrid vehicle to a PHEV is high, and there is very little infrastructure in the form of charging stations to support this new technology. Furthermore, PHEV have not yet gained universal acceptance as a contributor to reduced greenhouse gas emissions, since the fossil fuel base load plants are the ones powering these vehicles. All these issues in the PHEV sector need to be resolved to achieve universal acceptance of its technology and thus economic and environmental benefits [43].

2.4.3. REGULATION CHALLENGES

The cost factor and the regulatory framework for the recovery of investments are among the biggest challenges facing the SG movement. With investments for SG deployment in the form of advanced metering infrastructure estimated to be around \$27 billion and the Brattle Group's estimation of around \$1.5 trillion to update the grid by 2030, it is clear that these costs are a significant consideration. While the SG is seen as a collection of technologies that enable a new way of operating power systems, utilities and regulators often view it as a collection of new kinds of transmission and distribution investments, each yielding unfamiliar new products and service streams.

Utilities, regulators, and other stakeholders will have to evaluate these investments by measuring their value to customers, their impact on utility rates, and how customers and generators who use the new capabilities are charged for their use. Today, with increased

expectations from the SG, regulatory agencies face a monumental task of ensuring that investments made in this sector do not prove futile [44].

Furthermore, with a limited talent pool in this sector and increasing demand for human resources, regulators need to take on this challenge with determination and perseverance to transform the current grid into a SG. It is essential for the regulators to have a clear understanding of the benefits of SG technology and to make sure that the costs of implementation are justified by the benefits they bring. Additionally, it is crucial to develop a regulatory framework that supports the recovery of investments and encourages innovation in the SG sector [45].

2.5. CONCLUSIONS

In recent years, the implementation of SG technology has emerged as a critical aspect of the energy sector, offering numerous benefits in terms of improved reliability, efficiency, and sustainability. The SG represents a significant advancement in the way energy is distributed and consumed, and it has the potential to revolutionize the energy landscape.

The core components of the SG include advanced monitoring and control systems, which allow for real-time data collection and analysis, as well as the integration of renewable energy sources, such as wind and solar power. The result of these advancements is an energy system that is more resilient, flexible, and efficient. Additionally, the SG enables greater energy security by providing advanced warning systems in the case of potential disruptions, as well as enabling the rapid restoration of service in the event of an outage.

Despite the numerous benefits of the SG, there are also challenges to be addressed. One of the most significant of these is the need for significant investment in infrastructure and technology, which can be a barrier to implementation, particularly in developing countries. There is also the challenge of data privacy and security, as the SG involves the collection and transmission of large amounts of sensitive information.

In conclusion, the SG represents a critical opportunity for the energy sector to improve the reliability, efficiency, and sustainability of the energy system. The integration of advanced technology and renewable energy sources offers numerous benefits that are critical to the future of the energy landscape. With continued investment and research, the SG has the potential to play a pivotal role in shaping the energy future, and it is

essential that we remain focused on overcoming the challenges and realizing its full potential.

3. SIMULATION MODEL

In this chapter, the simulation model for the smart grid using MATLAB Simulink is presented and discussed in detail. The development of the simulation model is a crucial aspect of this thesis, as it forms the foundation for studying the behaviour and performance of the smart grid system. This chapter begins by providing an overview of the simulation model, followed by a detailed explanation of the chosen software and environment for the simulation. Additionally, the methodology employed for constructing the simulation model will be elaborated upon.

3.1. MODEL OVERVIEW

The simulation model serves as a virtual representation of the SG, enabling to emulate its dynamic behaviour, interactions, and responses to various stimulus. This section offers an outline of the simulation model's key components, objectives, and scope, providing a comprehensive understanding of what the model aims to achieve.

3.1.1. SELECTION OF SOFTWARE AND SIMULATION ENVIRONMENT

As outlined in Chapter 2 with a comprehensive literature review, the SG constitutes an intricate network of interconnected entities operating. To model this multi-agent system, the selection of a suitable simulation environment is crucial. It's imperative to consider

the project's time constraints. Comparative analyses were conducted to explore the strengths and limitations of various agent-based modelling software options, including AnyLogic [46], Mosaik [47], and others were reviewed [48]. Additionally, works such as R.J. Allan's Survey of Agent-Based Modelling and Simulation Tool [49] and M. Pipattanasomporn et al.'s research on Multi-agent systems in a distributed smart grid: design and implementation [50] were examined. The feasibility of employing the Model-Based Design (MBD) approach was also scrutinized.

MBD, a technique for facing complex network challenges, involves visually addressing issues related to mathematical model creation, complex control systems, signal processing, and communication networks. Through this approach, an executable specification can be derived from the underlying model, facilitating the simulation of real system behaviour. Notably, MBD is a favoured methodology in the design of embedded software in the power industry.

Given the array of simulation options and the project's ambitious scope of creating a robust and user-friendly framework within a tight timeframe, the decision was made to adopt the Simulink [51] environment developed by MathWorks. Simulink provides a block diagram environment tailored to support multi-domain simulations and MBD. It encompasses a Graphical User Interface (GUI), solvers, and customizable block libraries suitable for modelling and simulating dynamic systems such as the SG [52]. The integration of Simulink with MATLAB® enables seamless incorporation of MATLAB algorithms into models, while facilitating the export of simulation results to MATLAB for further analysis, including potential micro-grid optimization.

MathWorks' Simulink, known for its model-based approach, is extensively employed in power industry research. Noteworthy studies such as "Feasibility Analysis of the Positioning of Superconducting Fault Current Limiters for the Smart Grid Application Using Simulink and SimPowerSystem" by U.A. Khan et al. [53] and "Intelligent Energy Management System Simulator for PHEV at Municipal Parking Deck in a Smart Grid Environment" by P. Kulshrestha et al. [54] have employed Simulink and particularly the SimPowerSystems™ toolbox for analysis. A report by A. Bergmann on the Benefits and Drawbacks of Model-Based Design [55] highlights Simulink's key advantages, including:

- A GUI facilitating user understanding and documentation, thereby reducing documentation costs [55].
- A library of pre-implemented mathematical models available through extensive blocks [52], [54], [55].
- Hierarchical structure and automatic bug detection for rapid in-system debugging [55].
- Availability of Simscape Electrical™ (formerly SimPowerSystems) with component libraries for modelling and simulating electrical power systems [56].

Nevertheless, two primary drawbacks are associated with Simulink's use. Firstly, the platform's independence requires downloading device-specific libraries for future projects aimed at optimizing code execution time, potentially complicating porting to another target. Secondly, limitations arise from the functions implemented in Simulink model blocks. If specific functionalities absent from the library are needed for future research, proprietary blocks in C-code must be coded. It is noteworthy that the work elaborated did not necessitate proprietary block creation, as the required blocks were all present in the Simscape Electrical library [55].

Moreover, the intricate nature of SG, with its complex algorithms governing diverse hardware domains, controllers, and monitoring software, necessitates careful consideration of its layered components [57]. Given the complexity and expense of real-world implementation and testing, simulation emerges as a powerful methodology for modelling SG. Software simulation serves as a pivotal research tool, enabling experimentation and testing on a modelled system before real-world deployment. In the context of the Smart Grid's heterogeneous domains such as electronics, markets, distribution, and generation, various specialized tools contribute to domain-specific research. The potential for co-simulation, wherein multiple simulators are coupled to simulate different subsystems, offers a comprehensive understanding of the entire system's functioning.

One of simulation's key benefits is the flexibility it provides for studying power systems under diverse conditions and scenarios. Researchers can control simulation time, potentially accelerating it compared to real-world systems, thereby reducing the time

required for technology development [58]. This flexibility grants simulations with a distinct advantage over studies reliant on real-world deployments.

3.1.2. METHOD

In the context of Simulink, the selection of a suitable method for solving the system model is essential. Simulink offers three distinct methods, each catering to specific modelling and analysis needs:

- **Continuous Method:** This approach employs a variable-step solver, such as ODE15s [59], for solving the system model. It deals with continuous-time dynamics and is suitable for systems where precise time-domain behaviour needs to be captured.
- **Discrete Method:** In the discrete method, the electrical system is discretized, and solutions are determined at fixed time steps [60]. This approach is well-suited for systems where time granularity is more important than continuous-time dynamics.
- **Phasor Solution:** The phasor solution method is primarily utilized to study electromechanical oscillations of power systems [61]. For this model, the phasor solution was adopted to build the simulation presented in section 3.1.4. This decision aligns with the thesis focus on the quasi-steady behaviour of the system rather than transients, which are essential for network stability studies [118]. In phasor mode, system components like loads and transformers are designed with high bandwidth to swiftly transition between conditions. This approach disregards transient responses, with the steady-state response effectively representing a load-flow analysis [62], [63].

A load-flow study, also known as a power-flow analysis, involves numerically analysing power flow within an interconnected network. It entails determining the complex voltages and currents at different network nodes [64]. With this information, various active, reactive, and apparent powers flowing through the system can be calculated [61], [64].

Simulink's phasor mode, implemented through the Powergui block [59], computes voltages and currents as phasors. Phasors are complex numbers representing sinusoidal functions with invariant amplitude, angular frequency, and initial phase angle [64]. These

functions correspond to sinusoidal voltages and currents at a specific frequency, characteristic of Alternating Current (AC) generation. Phasors can be represented in cartesian coordinates (real and imaginary parts) or polar coordinates (amplitude and phase) [61]. The phasor solution method entails solving a reduced set of algebraic equations, avoiding the need for specific solvers, and considerably reducing simulation times [61], [64]. The main limitation of this approach is that it calculates the system's solution at a single frequency. For this research, the frequency was set at 50Hz, the targeted operating frequency of this specific grid but can be easily converted into a 60 Hz grid. While real-world frequencies may fluctuate between stability thresholds this model does not account for these minor variations in voltages, currents, and power flow.

In broader terms, simulation serves as an imitation of real-world systems. This technique replaces a real system with a simulation model, capturing key characteristics of the system and its environment through abstraction. Simulation finds application in diverse fields, enabling product design testing, studying subject behaviour under extreme conditions, employee training, and early demonstrations. The complexity of modelling SG poses challenges, given the multitude of devices and domains involved. Simulations of smart grid aspects often necessitate multiple simulators through co-simulation technologies.

A simulator, be it software or hardware, abstracts certain aspects of a real-life situation to model outcomes under different assumptions without real-world risks. Software simulations can be categorized into two main types: Discrete and Continuous [52], [65]. Discrete simulations model statistical events, such as customers arriving at a bank, using probability distributions to generate events. Continuous simulators model various physical events, including such as electric motor responses, and are employed in early system design stages to optimize controllers and component selection.

Even minor differences in input data can lead to significant discrepancies in output, emphasizing the importance of accurate modelling. In complex system design, models are influenced by the system's surroundings, which encompass elements relevant to experiments and affecting the main system.

3.1.3. LOAD FLOW ANALYSIS

Load-flow analysis, also known as power-flow analysis, is a fundamental and essential study performed in electrical power systems to analyse the steady-state behaviour and

power flow within a network. It involves calculating the voltages, currents, and power flows throughout the system under normal operating conditions [66].

The primary goal of load-flow analysis is to determine the operating point of the power system, which includes voltage magnitudes and phase angles at all nodes, as well as line currents and power flows. This information is crucial for various reasons:

- **Voltage and Current Profile:** Load-flow analysis helps to ensure that voltages at all nodes (buses) within the system remain within acceptable limits. Voltage deviations from nominal values can lead to inefficient operation, equipment damage, and even power outages. By analysing the current flow, the study identifies potential overloads on transmission lines and transformers.
- **Losses Calculation:** Load-flow analysis enables the calculation of active (real) and reactive power losses in the system. These losses result from resistances and inductances in transmission lines and transformers. Minimizing losses is essential for maintaining the efficiency of the power system.
- **Voltage Stability:** The analysis assesses voltage stability, ensuring that the system remains within a stable operating range. Voltage stability is crucial to maintaining proper operation and preventing voltage collapse, which could lead to widespread blackouts.
- **Optimal Power Flow:** Load-flow analysis can be extended to consider optimal power flow, where the objective is to optimize certain parameters (such as generator settings, transformer taps, and reactive power) to minimize losses or operating costs while satisfying operational constraints [67].

The load-flow analysis process involves solving a set of nonlinear algebraic equations that represent the power balance and voltage relationships in the system. The equations are based on Kirchhoff's laws and the characteristics of the system components, such as generators, loads, transformers, and transmission lines. The following are the main steps in performing a load-flow analysis:

- **Node Voltage Initialization:** The analysis begins with the assignment of initial voltage magnitudes and phase angles to all nodes. These initial values are often based on the nominal operating conditions.
- **Power Injections and Flows:** The real and reactive power injections at each bus are calculated based on the specified loads, generators, and shunt devices. The power flow equations relate these injections to the voltage magnitudes and phase angles.
- **Reactive Power Control:** The reactive power outputs of generators and other reactive power sources or devices are adjusted to maintain acceptable voltage levels at different buses.
- **Iterative Solution:** Load-flow analysis involves an iterative process of solving the power flow equations to converge to a solution. In each iteration, the voltage magnitudes and phase angles are updated based on the calculated power injections and flows.
- **Convergence Check:** The iterative process continues until the changes in voltage magnitudes and phase angles between successive iterations are below a predefined tolerance, indicating convergence to a stable solution.

Modern power systems are complex, often involving thousands of buses and interconnected components. Load-flow analysis provides valuable insights into system operation, helps in planning for system expansion, and ensures the secure and efficient operation of the electrical grid. It is an indispensable tool for power system engineers and system operators to maintain reliable and stable electricity supply [68].

3.1.4. SCALE, SYSTEMS AND STATE VARIABLES

The construction of the micro-grid model for this thesis is visually illustrated in Figure 11. As highlighted in Section 3.1.2, the chosen simulation approach employs the phasor solution method operating at a frequency of 50Hz. The micro-grid network design is influenced by H. Mita's Simplified Model of a Small-Scale Micro-Grid [69], and it is composed of two interconnected primary subsystems linked through an intermediary

agent. This intermediary agent, analogous to an 15kV to 230V linear transformer, mirrors the functionality of a standard secondary substation within national grids.

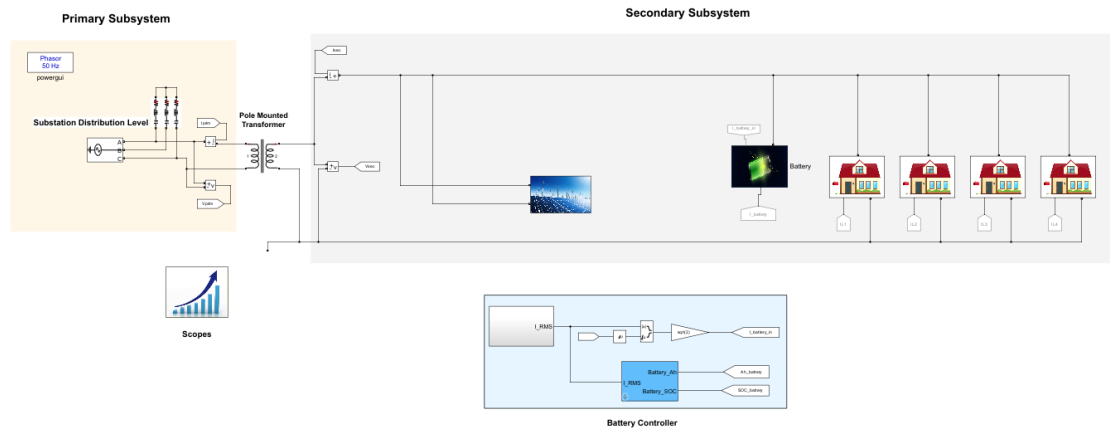


Figure 11: Simulink block diagram of the simulation macro/micro-grid model

Distinctive components of the micro-grid model are characterized by their spatial placements and functionalities:

- Primary Subsystem (Macro-Grid):** In the graphical representation, the primary subsystem is shaded in yellow, often referred to as the macro-grid. This subsystem symbolizes the span of the distribution network from the primary (132kV to 15kV transformer) to the secondary substations (15kV to 230V transformer). Operating at the standard voltage of 15kV, this portion of the model operates with three phases. Notably, two agents are integrated into this subsystem. The first agent models the primary substation, while the second agent embodies the common light industrial loads typically encountered within this tier of the grid. Additional insights into the specific attributes of these agents can be found in Section 3.2.
- Secondary Subsystem (Micro-Grid):** The secondary subsystem, distinguished by a grey background, replicates a localized micro-grid configuration. This subsystem simulates a single-phase circuit operating at a constant voltage of 230V, similar to a smart micro-grid positioned at a secondary substation. Within this subsystem, an assembly of agent types is integrated, each contributing a unique aspect to the micro-grid's behaviour. These agent types encompass Domestic Loads, PV, Windfarms, a Battery and respective controller. It's imperative to clarify that the numerical quantities attributed to agents in Figure 11, such as one battery, one renewable energy subsystem, and four loads, are

arbitrary and do not precisely mirror the actual quantities utilized during simulation activities.

Moreover, alongside these agents, a battery controller is also introduced within the secondary subsystem. Although not classified as a separate agent, this controller is distinguished as an independent entity from the battery. The controller offers an abstract representation that enables continuous modifications for forthcoming projects/simulations. The model encompasses distinct agents and a single object each characterised by a range of attributes:

- **Three-Phase Source:** This agent represents the medium-voltage side (15kV) of a primary substation. Its attributes include the generator type, configuration of internal voltage sources, phase-to-phase voltage, phase angle of the first phase, and a fixed voltage frequency of 50Hz—an ideal model of the real grid [70].
- **Series RLC Loads:** These agents simulate the role of light industrial loads that consume energy from the grid at 15kV voltage. Their attributes encompass load type, nominal voltage, and frequency (50Hz), active power consumption, inductive reactive power, and capacitive reactive power.
- **Linear Transformer:** This agent replicates secondary substations, converting the 15kV input electricity into 230V rated energy. Its attributes include the number of windings, nominal power, and frequency (50Hz), voltage, resistance, and inductance of each winding, as well as overall magnetization resistance and inductance.
- **Loads:** Representing households that consume electrical power from the grid, these agents possess attributes such as load profile based on historical data [71], voltage magnitude (230V), voltage phase, internal resistance, initial current amplitude, phase, and frequency (set at 50Hz). Each Load agent also contains a hierarchical structure of component objects detailed in Section 3.2.
- **Solar Panels:** These agents replicate PV assets, expected to be common Distributed Energy Resources. Their attributes include power generation profiles based on historical data [72], voltage magnitude (230V) and phase, internal

resistance, initial current amplitude, phase, and frequency (50Hz). These agents are composed of multiple components, as elaborated in Section 3.2.

- **Wind turbine:** These agents emulate wind turbine systems, often found as prominent Distributed Energy Resources (DERs). Their characteristics encompass wind power generation profiles influenced by historical meteorological data from a simulink example [73], rotational speed (RPM), torque and pitch angle.
- **Battery:** Representing local energy storage capacity found in households or commercial buildings, this agent's attributes encompass the initial amplitude, phase, and frequency (50Hz) of its Controlled Current Source (CCS).
- **Battery Controller:** This entity complements the battery agent and models its physical characteristics. It also simulates aspects of command software found in controlled energy storage. Attributes of the Battery Controller include storage capacity, charge and discharge current magnitudes and phases, current saturation limits, minimum and maximum capacity thresholds for battery charge and discharge, and initial state of charge.

Within this context, the term "agent" signifies a dynamic entity that interacts within the micro-grid, whereas an "object" pertains to an element with inherent attributes. Noteworthy attributes of these entities encompass voltages, power generations, load profiles, internal resistances, currents, and frequencies, among others.

In the broader architecture of the micro-grid model, depicted in Figure 11, these diverse agents and objects interconnect to simulate real-world interactions and interdependencies. This integrated model stands poised to serve as a versatile platform for evaluating an array of scenarios and operational scenarios, thereby unravelling the characteristic behaviour of the micro-grid under varying conditions.

In Table 2, presented below, provides a concise overview of all entities integrated into the model, accompanied by their associated attributes. It's worth noting that the "categorical" attribute type pertains to arrays of qualitative data, encompassing values drawn from a finite set of distinct nonnumeric data, as outlined by Simulink [74]. It's also

important to mention that all instances of "cell array" types exclusively contain numeric data.

Table 2: Simulink model entities and their characterizing attributes

Entity	Attribute Name	Attribute Type	Description
Three-Phase Source	Generator type	Categorical	Generator type of the voltage source
	Configuration	Categorical	Internal connection of 3 internal voltage sources
	Phase-to-phase voltage	Double	Internal phase-to-phase voltage (V_{RMS})
	Phase angle of phase A	Double	Phase angle of voltage generated by phase A($^{\circ}$)
	Frequency	Double	Source frequency (Hz)
Series RLC Load	Load Type	Categorical	Load type selection
	Nominal Voltage	Double	Nominal load voltage (V_{RMS})
	Nominal frequency	Double	Nominal load frequency (Hz)
	Active power	Double	Load active power (W)

	Inductive reactive power	Double	Load inductive reactive power L (V_{ars})
	Capacitive reactive power	Double	load capacitive reactive power C (V_{ars})
Linear Transformer	Pn	Double	Nominal power rating (VA)
	Nominal frequency	Double	Nominal transformer frequency (Hz)
	Two windings	Boolean	Select between 2 or 3 windings transformer
	Winding voltage	Double	winding nominal voltage (V_{RMS}) of each winding
	Winding resistance	Double	winding resistance (Ω)
	Winding inductance	Double	leakage inductance (H)
	Magnetisation resistance	Double	resistance (Ω) simulating the core active loss
	Magnetisation inductance	Double	inductance (H) simulating the core reactive loss

Load	Data specification	Categorical	Method of table and breakpoint specification
	Table data	Cell array	Load profile time output values (s)
	Breakpoints specification	Categorical	breakpoint specification (explicit/even spacing)
	Breakpoints 1	Cell array	Load profile active power output values (W)
	Gain6	Double	Negative inverse of micro-grid voltage (V^{-1})
	Vsec	Double	secondary voltage phase (Im)
	Resistance	Double	Branch resistance (Ω)
	Initial amplitude	Double	CCS initial peak current (A)
	Initial phase	Double	Initial CCS phase ($^{\circ}$)
	Initial frequency	Double	Initial CCS frequency (Hz)

Solar Panel	Data specification	Categorical	Method of table and breakpoint specification
	Table data	Cell array	Load profile time output values (s)
	Breakpoints specification	Categorical	breakpoint specification (explicit/even spacing)
	Breakpoints 1	Cell array	PV profile active power output values (W)
	Gain5	Double	Negative inverse of micro-grid voltage (V^{-1})
	Vsec	Double	Secondary voltage phase (Im)
	Resistance	Double	Branch resistance (Ω)
	Initial amplitude	Double	CCS initial peak current (A)
	Initial phase	Double	Initial CCS phase ($^{\circ}$)
	Initial frequency	Double	Initial CCS frequency (Hz)

Wind turbine	Data specification	Categorical	Method of table and breakpoint specification
	Table data	Cell array	Load profile time output values (s)
	Breakpoints specification	Categorical	breakpoint specification (explicit/even spacing)
	Breakpoints 1	Cell array	PV profile active power output values (W)
	Gain5	Double	Negative inverse of micro-grid voltage (V^{-1})
	Vsec	Double	Secondary voltage phase (Im)
	Resistance	Double	Branch resistance (Ω)
	Initial amplitude	Double	CCS initial peak current (A)
	Initial phase	Double	Initial CCS phase ($^{\circ}$)
	Initial frequency	Double	Initial CCS frequency (Hz)
Battery	Initial amplitude	Double	CCS initial peak current (A)

	Initial phase	Double	Initial CCS phase (°)
	Initial frequency	Double	Initial CCS frequency (Hz)
Battery Controller	Capacity	Double	Battery capacity (Ah)
	Isec	Double	Secondary current (Re & Im)
	Vsec	Double	Secondary voltage (Re & Im)
	Limit output	Boolean	Set current integral output limits (yes/no)
	Upper saturation limit	Double	Maximum value of current integral (A)
	Lower saturation limit	Double	Minimum value of current integral (A)
	Initial condition	Double	Internal initial value of current integral (A)
	Switch1 threshold	Double	Minimum battery SOC to allow discharge (%)
	Switch2 threshold	Double	Maximum battery SOC to allow charge (%)

	Constant1	Double	Initial SOC of battery at simulation start (%)
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3.2. BLOCK AND SUBSYSTEMS

In the preceding Section 3.1.4, a general overview of the micro-grid and its components was presented. To facilitate a more comprehensive understanding of the underlying logic and mathematical models in this thesis, the subsequent chapter explores and details the specific processes of various entities. This exploration begins with an examination of the Simulink blocks employed in the model. The objective is to provide an in-depth analysis of these essential components to elucidate the aspects of micro-grid modelling.

3.2.1. SIMULINK BLOCKS

Three-Phase Source

In the context of this thesis, the modelling approach introduced in Section 3.1.4 involved the utilization of the Three-Phase Source Simulink block to replicate the characteristics of typical primary substations commonly encountered within macro-grid infrastructures. Notably, these real-world substations function as transformers, facilitating the conversion of electricity from a 132kV voltage to a derated 230V value. It is essential to highlight that these transformers exclusively permit the flow of current from the high-voltage side to their lower-voltage windings. Given that this thesis's primary focus lies below the high-voltage network, extending only to the scope of primary substations, a judicious approximation was made to model these substations as ideal voltage sources without impedance.

To achieve a realistic model, meticulous attention was paid to configuring the block parameters, as meticulously detailed in Table 2. These parameters were carefully selected to closely emulate the distinctive attributes of real transformers [75].

The block's electrical output was defined as three sinusoidal voltage and current waveforms, each exhibiting a 120° phase separation and harmoniously operating at the targeted frequency of 50Hz, mirroring the characteristics of common grid [70]. It is important to underscore that the output voltage for each phase adheres to a Root Mean

Square (RMS) value of 15kV, faithfully aligning with the standards established for a typical network. This level of precision in modelling ensures a faithful representation of the electrical dynamics within the micro-grid context.

In the context of electrical engineering, it is elucidated, as per the scholarly reference 'A Dictionary of Physics' (6th ed.) [76], that the Root Mean Square (RMS) value associated with an electric Alternating Current (AC) assumes particular significance. In this context, the RMS value signifies the equivalent magnitude of Direct Current (DC) that would be requisite to yield an identical average power dissipation in a resistive load [76]. This fundamental principle highlights the quantitative relationship between the RMS and peak values of a perfect sinusoidal function, such as the AC voltage or current encountered within the model's domain.

The sinusoidal voltage, in its periodic constancy, is rigorously expressed as $V(t) = V_{peak} \cos(\omega t)$, wherein V_{peak} characterizes the waveform's peak magnitude, and ω denotes its angular frequency [77]. The analytical derivation of the RMS voltage is subsequently facilitated by the following mathematical expression:

$$VRMS = \sqrt{\frac{1}{T} \int_0^T V_{peak}^2 \cos^2(\omega t) dt} \quad (1.1)$$

Where T represents the period of the function, linked to the angular frequency through the equation $\omega = \frac{2\pi}{T}$. Integration of the equation by parts, in accordance with the trigonometric identity $\cos^2(\theta) = \frac{\cos(2\theta)+1}{2}$, culminates in the subsequent form:

$$VRMS = \sqrt{\frac{V_{peak}^2}{2T} \left[\frac{\sin(2\omega t)}{2\omega} + t \right]_0^T} \quad (1.2)$$

Upon further substitution of the integral limits, namely 0 and T , the expression unfolds as follows:

$$VRMS = \sqrt{\frac{V_{peak}^2}{2T} \left[\frac{\sin(2\omega T)}{2\omega} + T \right]} \quad (1.3)$$

Lastly, considering that $\omega T = 2\pi$, the resultant relationship between V_{RMS} and V_{peak} can be expressed as follows:

$$V_{RMS} = \frac{V_{peak}}{\sqrt{2}} \quad (1.4)$$

It is important to highlight that the same equation applies equivalently to the current waveform. Additionally, within the micro-grid model, all voltages and currents measured through the Simulink measurement blocks are presented as peak values [78]. Therefore, Equation (1.4)

has been extensively utilized to convert these values into the standard RMS measurements adopted within the energy industry.

As previously stated, was derived under the assumption that the electricity supplied by the three-phase voltage source adheres to the characteristics of an ideal sinusoidal function. Nonetheless, practical scenarios involve continuous load switching on the grid, resulting in the generation of transient effects. These transients can influence the shapes of voltage and current waveforms circulating throughout the network, subsequently impacting the power consumption and generation of various interconnected components [37]. Nevertheless, as the primary focus of this research does not encompass the grid's stability or associated losses, the approximation utilized to establish Equation (1.4)

remains valid.

Series RLC Load

To replicate certain industrial loads in the micro-grid model, the Simulink Series RLC Load block was employed. Although this industrial power consumption remains ancillary to the core focus of the micro-grid model and exerts minimal impact on downstream electricity flow within the region of interest, Simulink mandates the inclusion of some form of resistance between the three-phase voltage source and the linear transformer.

To foster the development of a more authentic model, three series RLC loads were incorporated, with each one designated to a distinct phase of the primary subsystem (as illustrated in Figure 11). These three loads were chosen to mirror the attributes of constant active and reactive power. Their active power consumption, set at 10kW [79]. In line with

expectations, these blocks were configured to operate at an 1kV RMS voltage and adhere to a nominal frequency of 50Hz. Furthermore, both inductive and capacitive reactive powers were maintained at the default values specified by Simulink, quantified at 100 VAR (volt-ampere reactive) for both parameters. It is important to acknowledge that due to the specialized nature of these variables, historical data is notably scarce or non-existent. Following a swift parametric analysis elucidating their impact on power consumption within the series RLC loads, it became evident that these two parameters wielded negligible influence on power demand. Consequently, Simulink's default values were deemed the most pragmatic choices for utilization.

Linear Transformer

To establish a connection between the primary three-phase circuit and the secondary single-phase subsystem (as illustrated in Figure 11), the utilization of a Simulink linear transformer block was instrumental. This block effectively emulates a secondary substation similar to those prevalent in the grid infrastructure. In alignment with the operational principles of an actual pole-mounted transformer, this block permits bidirectional current flow [80]. It facilitates the transfer of electricity from the 15kV primary side to the 230V secondary side, and vice versa.

The transformer's nominal power rating was designated at 25kVA, a choice made to modestly surpass the maximum attainable product of secondary current and voltage when the system operates without battery intervention. As stipulated by MathWorks, this parameter exhibits negligible influence on the transformer model under the default SI Units parameter setting [80]. Nonetheless, within the context of a real world grid, transformers are designed to closely align their nominal power rating with the product of maximum secondary current and voltage, considering both current operational conditions and future connectivity predictions.

In the simulation model, the transformer configuration comprised three windings, with two secondary winding output ports conventionally grounded in accordance with industry standards. The primary winding was defined with an RMS nominal voltage of 15kV. Simultaneously, the secondary winding was assigned an RMS voltage of 230V.

Furthermore, it is imperative to note that this thesis, not oriented towards grid loss analysis, implemented an idealized transformer model. This idealization was executed by

configuring the winding resistances and inductances for all three windings as 0, while the magnetization resistance and inductance were set to infinity as per MathWorks' guidelines [80]. This idealized modelling approach yielded the desired outcome of substantially reducing the simulation processing time.

Cables

In constructing this micro-grid model, the electrical interconnections among various blocks and agents were conceptually represented as ideal. This simplification aligns with the thesis's scope, which does not delve into an examination of electrical losses within the grid.

Within the context of the real-world grid, cable losses assume a non-negligible role. These losses, account for a substantial portion of the total energy dissipation, ranging from 4.2% to 9.1% [81] of the annually generated energy within the entire network. A notable attribute of these losses is their proportionality to the square of the electric current traversing the cables [82].

3.2.2. SUBSYSTEMS

To comprehensively depict the distinct secondary grid agents (illustrated by the grey background in Figure 11) and the battery controller, the creation of those subsystems for each entity was imperative. This chapter expounds upon the intricacies of these subsystems.

Domestic Loads

To replicate the behaviour of domestic loads commonly found in households, a structured equivalent circuit was meticulously crafted, as depicted in Figure 12. This circuit, intricately connected to the wider micro-grid via connectors 1 and 2, adheres to the fundamental principles of Norton's theorem [83]. In essence, Norton's theorem, the converse of Thevenin's theorem, postulates that any linear electrical system solely comprising voltage sources, current sources, and resistances can be substituted at its terminals by an equivalent current source in parallel with an equivalent resistance. This equivalence becomes particularly evident when the system's terminals are short-circuited, leading to the concept of an equivalent current and resistance at these terminals [83].

Leveraging the power of Norton's theorem, the micro-grid simulation model adopts a Simulink Controlled Current Source block [84], configured with an AC source type. This block is ingeniously placed in parallel with a resistance element. To establish the model's fidelity, the initial amplitude and phase angle of this Controlled Current Source were rigorously set to 0, with a defined operating frequency of 50Hz. Furthermore, the parallel resistance element was meticulously calibrated to 106Ω , a value carefully chosen as the threshold beyond which any further increase in resistance insignificantly affects the current traversing the equivalent circuit.

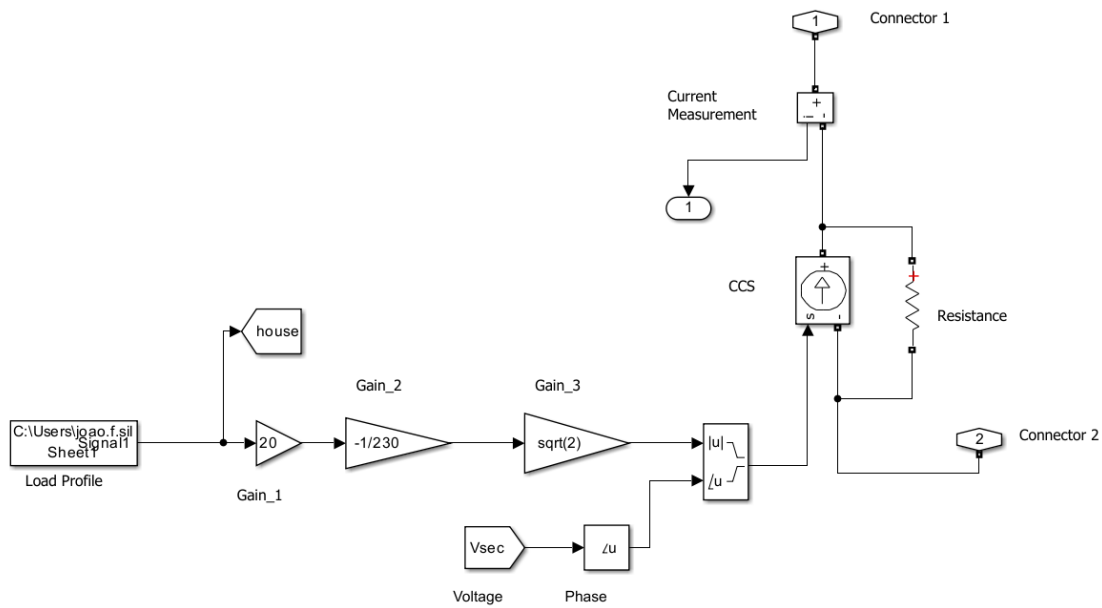


Figure 12: Simulink block diagram of the domestic load subsystem

The first block directly imports data from an XLS file containing load profiles of specific typical household loads. The significance of this change is underscored by the adaptation of Gain 1, which is set to 20. This adjustment effectively simulates the load profiles of 20 homes, each characterized by the same type of load profile. With this approach redundancy is reduced since it's not necessary to have 20 subsystems of homes.

The Simulink Controlled Current Source (CCS) block necessitates a current phasor input signal (complex number) at its "s" port, as illustrated in Figure 12. To achieve this, a transformation process was initiated to convert power data from the load profile into an RMS current value, as previously detailed in Section 3.1.2.

Within the realm of AC circuits, instantaneous power (denoted as "p") emerges as the product of instantaneous voltage ("v") and instantaneous current ("i") [135]. In this context, assuming sinusoidal waveforms for both voltage and current at the same frequency, "v" can be expressed as:

$$v(t) = V_{peak} \sin(\omega t + \theta_v) \quad (2.1)$$

Here, V_{peak} signifies the maximum voltage waveform value in volts (V), ω denotes angular frequency in radians per second (rad.s^{-1}), and θ_v represents the initial phase-shift in radians. A corresponding expression for i emerges as:

$$i(t) = I_{peak} \sin(\omega t + \theta_i) \quad (2.2)$$

Here, I_{peak} denotes the maximum current waveform value in amperes (A), ω remains the angular frequency in rad.s^{-1} , and θ_i designates the initial phase-shift in radians. The multiplication of Equations 4.5 and 4.6 yields the following expression for instantaneous power:

$$p = V_{peak} I_{peak} [\sin(\omega t + \theta_v) \sin(\omega t + \theta_i)] \quad (3.1)$$

Employing the product-to-sum trigonometric identity [85], specifically:

$$\sin A \sin B = \frac{1}{2} [\cos(A - B) - \cos(A + B)] \quad (3.2)$$

While considering the phase difference between the voltage and current waveforms as $\theta = \theta_v - \theta_i$, Equation (3.1)

transforms into:

$$p = \frac{V_{peak} I_{peak}}{2} [\cos \theta - \cos(2\omega t + \theta)] \quad (3.3)$$

Furthermore, in line with Equation (1.4)

which relates peak values to RMS values, with a factor of $\sqrt{2}$, the expression becomes:

$$p = V_{RMS}I_{RMS} \cos \theta - V_{RMS}I_{RMS} \cos(2\omega t + \theta) \quad (3.4)$$

This equation elucidates that p comprises two terms: a constant and a time-varying sinusoid. Since the micro-grid employs the phasor solution mode, which focuses solely on the mean power value over time, the instantaneous power of the sinusoid simplifies to:

$$p = V_{RMS}I_{RMS} \cos \theta \quad (3.5)$$

Moreover, within the secondary subsystem of the simulation model, there is only a single-phase present, implying no phase difference between voltage and current waveforms. Consequently, $\theta = 0$, and power is succinctly expressed as:

$$p = V_{RMS}I_{RMS} \quad (3.6)$$

To implement this transformation, the power from the load profile was divided by the secondary circuit voltage of 230V (referred to as "Gain 2" in Figure 12). Notably, "Gain 1" is negative to account for the fact that the power from the load profile corresponds to consumption rather than generation. After this conversion into an RMS current value, further transformation into a current phasor ensued. This was achieved by multiplying the RMS value by a factor of $\sqrt{2}$ ("Gain 3" in Figure 12), thereby yielding the current's peak value, as derived in Equation (1.4)

. Finally, the peak current value underwent a transformation into a complex phasor using a magnitude-angle to complex signal block [86]. The magnitude input corresponded to the peak current value, while the phase was derived from the micro-grid voltage measurement (V_{sec} in Figure 12), ensuring in-phase alignment of current and voltage. Subsequently, the current phasor output was supplied to the CCS, generating the desired single-phase AC current.

Solar Panel

The replication of the Solar Panels in this model involved the utilization of an equivalent circuit analogous to that employed for domestic loads, which is visually represented in

Figure 13. This approach facilitated the integration of solar panel characteristics into the micro-grid simulation.

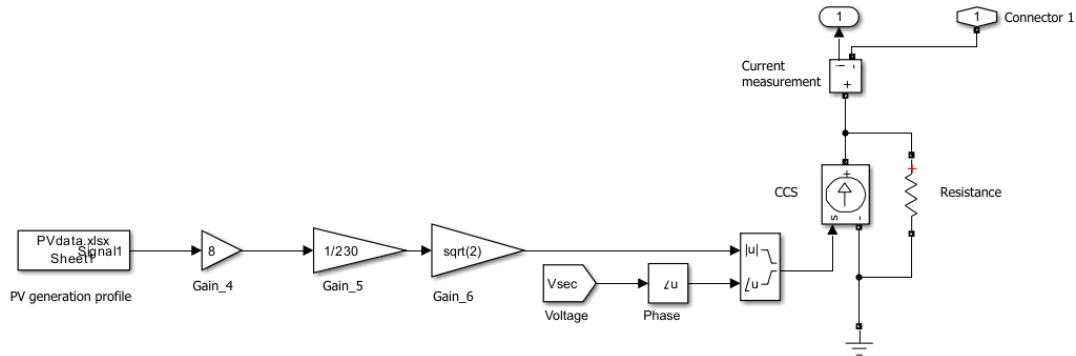


Figure 13: Simulink block diagram of the solar panel subsystem.

The PV power generation data is from the National Renewable Energy Laboratory (NREL) from 11th of August of 2006 in Florida [72]. This divergence in data source allows the model to account for the unique characteristics of solar power generation. An extrapolation in data from 58MW panel to a 5kW panel was made. The model considers 8 panels of 5kW thus the Gain 4 is 8.

The gain applied to convert the power data into a current value. Specifically, Gain 5 in Figure 13 assigns a positive value, gain 6 converts the current value into RMS current. This adjustment is essential to reflect the nature of power generation by solar panels, which contributes energy to the micro-grid.

Lastly, the model portrays a generator scenario, where power flows unidirectionally from the solar panels to the micro-grid. This contrasts with the bidirectional operation of loads. Consequently, the Controlled Current Source (CCS) in this subsystem is grounded, distinguishing it from the parallel configuration utilized for other micro-grid agents. This configuration aligns with the physical attributes of solar panels functioning as generators in real-world scenarios.

Wind turbine

Incorporating wind turbines into the micro-grid simulation requires the creation of a dedicated subsystem within Simulink to capture the unique characteristics of wind energy

conversion. This subsystem plays a pivotal role in modelling the behaviour of wind turbines and their interaction with the micro-grid.

The replication of the Solar Panels in this model involved the utilization of an equivalent circuit analogous to that employed for solar panels, has presented in Figure 14.

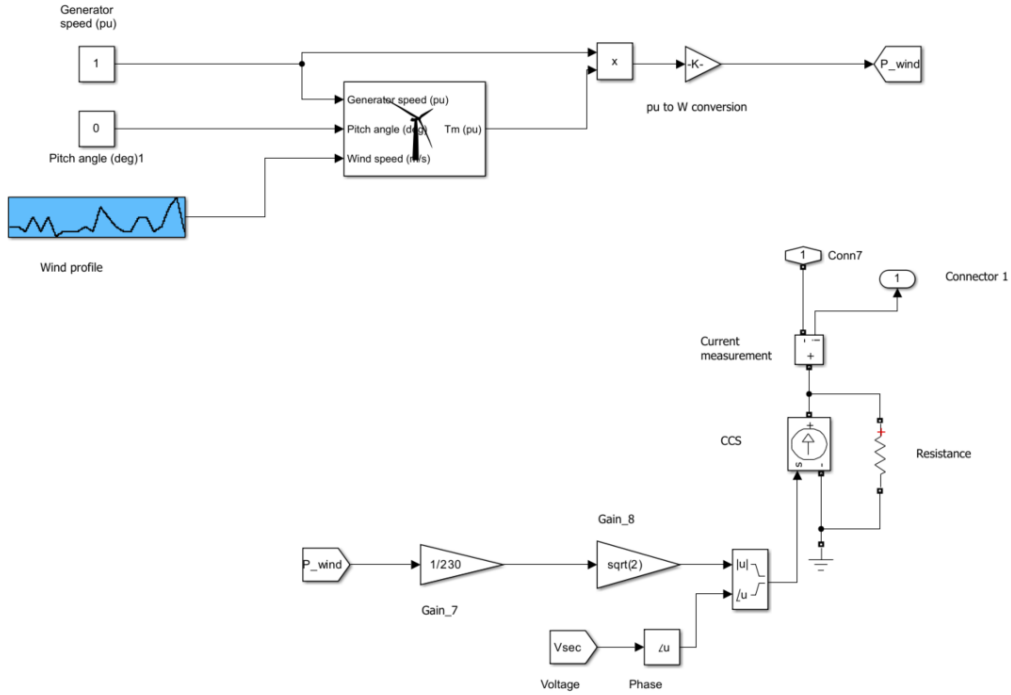


Figure 14: Simulink block diagram of the wind turbine subsystem

The wind speed data is from MATLAB 24-hour simulation of a V2G system [87]. This wind turbine has a 15kW generator with a power factor of 0.9. Pitch angle and generator speed was considered static since most wind turbines have controllers to maintain generator speed fixed allowing to increase the overall efficiency.

Power (P), torque (T) and angular velocity (ω) are correlated by the following formula [88]:

$$P = T * \omega \quad (4.1)$$

The product block is calculating the product between ω and T, both in pu resulting in P in pu. The following block “pu to W conversion” converts pu to W multiplying it with the nominal power.

Similar to the method used for solar panels, Gain 7 and 8 convert power into current and then RMS current respectively. The CCS uses the same model to obtain the current generation as explained in **Solar Panel**

Battery and Battery Controller

The battery subsystem, denoted by the green block within the secondary system in Figure 11, has been meticulously constructed using an equivalent circuit grounded in Norton's theorem [83].

Much like the load and PV models, the alternating current (AC) type Controlled Current Source (CCS) was initialized with zero amplitude and phase, and it operates at a frequency of 50Hz. An accompanying resistance, with a value of 106Ω , was included in parallel with the CCS and ground is in series as shown in Figure 15. This configuration closely mimics real-world battery characteristics and ensures accurate modelling.

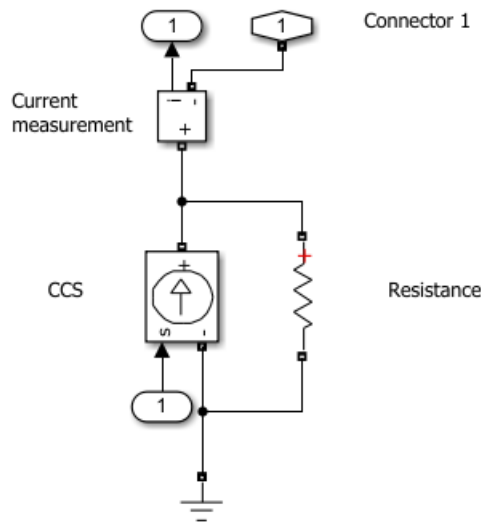


Figure 15: Simulink block diagram of the battery subsystem

The input current phasor provided to the CCS was determined based on the output from the comprehensive battery controller showcased in Figure 16, specifically the variable labelled "I battery in tag." Achieving this required an intermediate step involving the conversion of peak voltage and current values within the secondary system into an active power value, as presented in. To perform this conversion, the Simulink Active & Reactive Power block [89] was employed.

Subsequently, this active power value underwent another transformation, converting it into an RMS current value using the methodology established earlier, drawing upon Equation (3. 6). It's crucial to note that the model allows for the dynamic control of both maximum and minimum RMS current values, thus emulating the battery's capability to manage charge and discharge currents effectively.

To govern the State of Charge (SOC) interval within which the battery can function, the model incorporates a set of switches illustrated in Figure 18. These switches are instrumental in regulating the battery's operating range, further enhancing the realism of the simulation. The instantaneous SOC of the battery is determined from the RMS current value using a Simulink integrator block [90], as depicted in Figure 17. This integrator block calculates the integral of the input signal, providing an essential parameter for monitoring and controlling the battery's state during micro-grid operation.

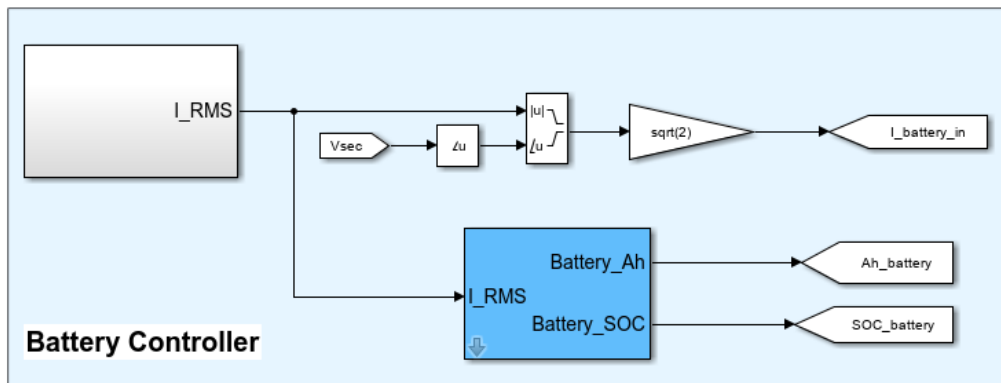


Figure 16: Battery controller subsystem

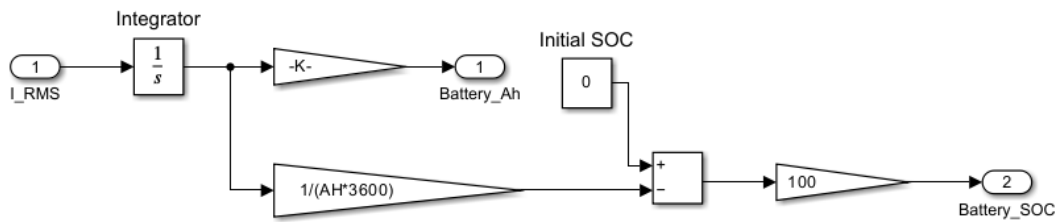


Figure 17: Capacity and battery controller subsystem

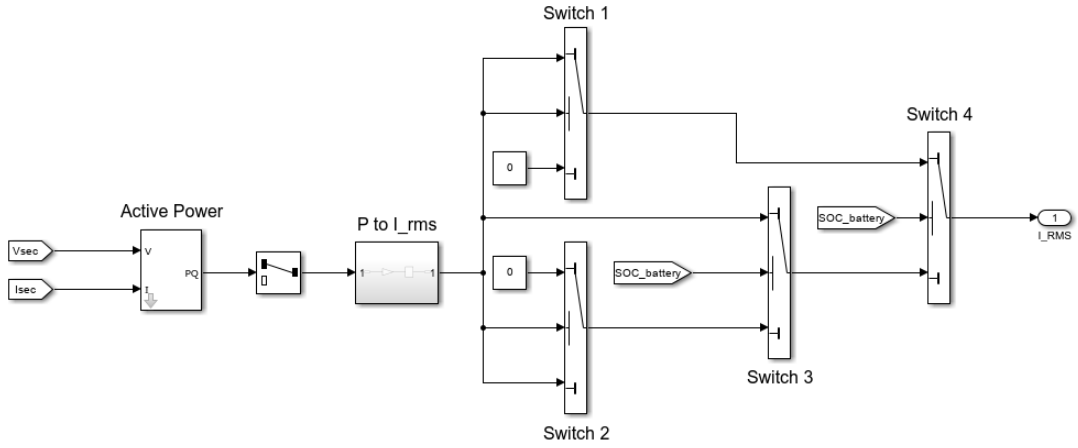


Figure 18: Charge and discharge current battery controller subsystem

The State of Charge (SOC) of a battery can be mathematically expressed in relation to the current, denoted as 'i', flowing through it and its total capacity, represented by 'Q,' as shown in equation [91]:

$$SOC = 100(\alpha - \frac{1}{Q} \int_0^t i(t) dt) \quad (5.1)$$

Here, α corresponds to the initial SOC of the battery, which falls within the range of 0 to 1. In the simulation model, the value of ' α ' was modulated, allowing for a dynamic representation of the battery's initial state of charge. This adjustment was facilitated using a Simulink constant block, labelled as 'Initial SOC' in Figure 17.

It's essential to highlight, the integral term in Equation (5.1) encapsulates the concept of instantaneous battery capacity, and this value is made available as an output labelled 'Battery Ah' in Figure 17.

The instantaneous SOC value obtained through this equation plays a pivotal role in the battery control loop. Specifically, it is employed to dynamically update the thresholds of switches 3 and 4 in Figure 18. This updating mechanism ensures that the battery operates effectively within the predefined SOC range, contributing to the overall stability and performance of the micro-grid.

It's noteworthy that prior to being inputted into the Controlled Current Source (CCS) of the battery subsystem, the instantaneous RMS current value, identified as 'I RMS tag' in

Figure 18, underwent a conversion process to become a current phasor, as depicted in Figure 16. This transformation is a crucial step in generating the desired single-phase AC current and maintaining the integrity of the battery's electrical interactions within the micro-grid.

4. RESULTS AND DISCUSSION

As outlined in chapter 1 and substantiated by an extensive literature review in Chapter 2, the primary motivation behind this project was the simulation of a smart grid. Accordingly, the model developed, as elaborated in chapter 3.1, possesses a high degree of flexibility and scalability. Despite designating agents as "Solar Panels" or "domestic loads" and assigning specific generation and load profiles derived from NREL [72] and the UK Household Electricity Survey [92] respectively, it remains entirely feasible to model other types of generation (e.g. hydro power, thermal power units) and loads (e.g. commercial loads) and also other types of load/generation profiles. The fundamental parameters to adapt in this scenario are the input power supply and demand profiles, which undergo conversion into RMS current phasors, as explained in Section 3.2.2. This adaptability extends to the battery agent, which, with further and more specific parameterization, can solve problems like PV ramps, low inertia that are common in small grids.

In accordance with the discussion in Section 3, the main challenges in implementing smart micro-grids predominantly revolve around energy storage capabilities. While various studies have attempted to model battery characteristics, especially their aging and

temperature dependency, e.g., Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment by Bolun Xu et al [14], there are limited work that explore the impact of battery characteristics within a SG environment (below the 11kV to 230V transformers, as depicted in Figure 11). Thus, this work contributes with insights regarding the non-linearity of batteries in SG.

To quantify this storage impact, a range of parameters in the battery and controller models underwent alteration during simulations. The primary metric for quantifying the battery's role in the smart grid was the daily energy consumption drawn from the distribution network (above the secondary substation). This metric was computed by measuring the instantaneous current (Isec tag in Figure 11) and instantaneous voltage (Vsec tag in Figure 11) at the low voltage side of the linear transformer using Simulink measurement blocks [78]. These peak value measurements, resulting in a power "load" profile. This profile was subsequently integrated utilizing the trapezoidal rule embedded in the trapz MATLAB function [93], yielding a single value representing the daily energy consumption of the micro-grid for each 24-hour simulation.

This energy consumption metric was chosen because it accurately quantifies the amount of power drawn from the distribution grid above the secondary substation. This level is critical as it incurs the most significant energy losses and associated costs, as previously explained in Chapter 3.22. Moreover, this metric aligns with the two network cost charging methods proposed by Piclo [94] in their whitepaper (Locational DUoS Methods 1 and 2). It isolates the electricity drawn from the distribution grid without offsetting excess supply generated by the PVs during the day when supply exceeds both load consumption and battery capacity. Thus, it effectively measures the energy consumed by the micro-grid during periods of insufficient local power generation, addressing the challenge raised by Piclo regarding the measurement of locally matched supply and demand [95].

To examine the impact of battery characteristics on the micro-grid, a parametric study was conducted. Four key independent parameters were tested:

- Battery total capacity measured in Ah.
- Maximum charging current allowable into the battery measured in A.
- Maximum discharging current allowable out of the battery in A.

Table 3: Parameters' values for the parametric study of four different scenarios.

Test parameters	Capacity (Ah)	Initial SOC (%)	Peak SOC (%)	Maximum charging current (A)	Maximum discharging current (A)
1 st scenario	400	0	92.47	80	-80
2 nd scenario	400	0	93.5	85	-85
3 rd scenario	400	0	94.91	100	-100
4 th scenario	450	0	84.37	100	-100

This parametric study paves the way for a more comprehensive understanding of the dynamic interplay between battery characteristics and smart micro-grid performance, shedding light on critical factors impacting micro-grid stability and efficiency.

In the initial scenario, the State of Charge (SOC) approaches 92.47%. In the first cursor, Figure 19 the power generated by renewable sources is greater than the load power thus secondary power is 0W (it reaches 0W when renewable power equals load power) and the battery starts to charge (SOC increases). After the second cursor Figure 19 renewables power is greater than both battery power and load power, the difference is fed back into the transmission grid, hence a positive power secondary.

After the 6000s of simulation secondary power a noteworthy shift occurs. At this point, the power in the secondary turns negative despite SOC being over 80% this is due to the fact the renewables power and the discharging power aren't enough to surpasses load power.

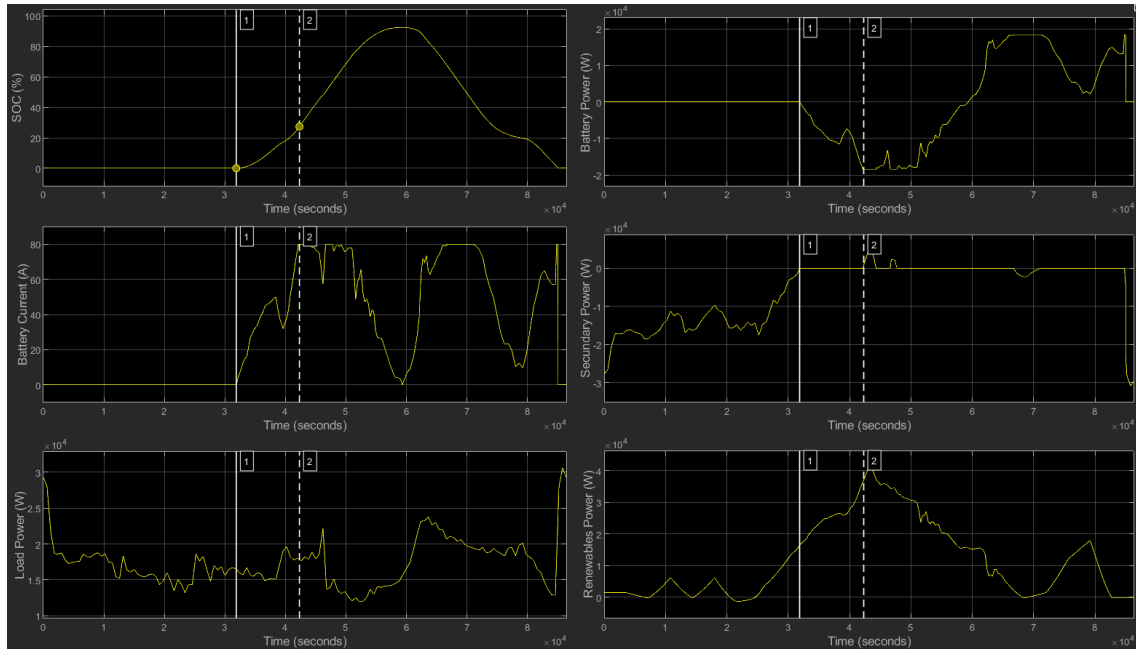


Figure 19: 1st Scenario overview

With this scenario it can be concluded that the charging and discharging power of the battery are bottlenecking the system.

In the 2nd scenario, the battery continues to bottleneck the system although the power shifts have lower amplitude as shown in Figure 20. The SOC has increased when compared to the 1st scenario from 92.47% to 93.5% which proves charging power wasn't enough during peak production periods.

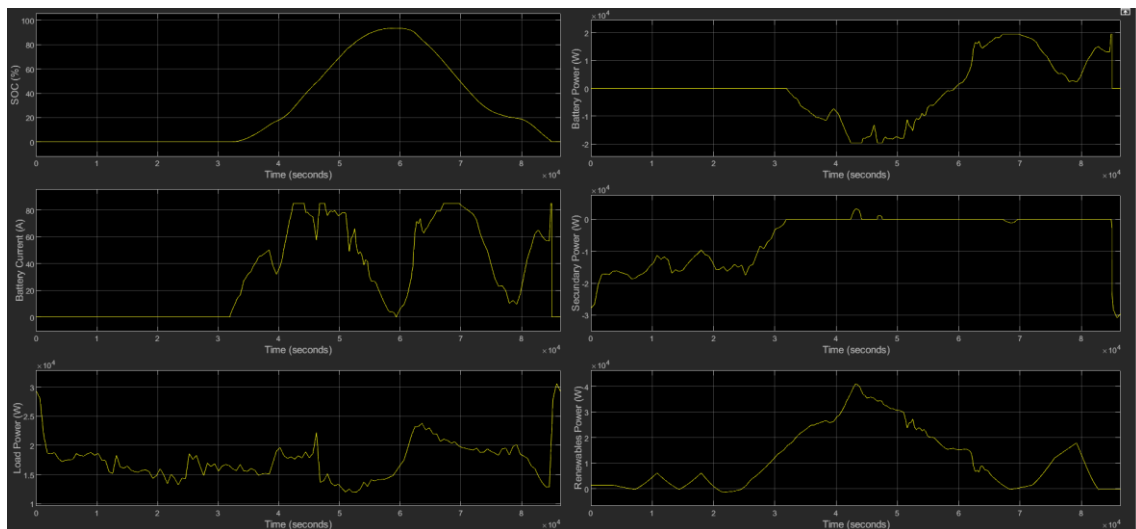


Figure 20: 2nd Scenario overview

In the 3rd scenario, the micro-grid optimally harnesses renewable energy. Any surplus electricity generated by renewable sources, beyond what the load requires, is efficiently utilized to charge the battery as show in Figure 21. Consequently, the battery can discharge its stored energy to meet all the load demands until its capacity is entirely depleted. As anticipated, the State of Charge (SOC) reaches 94.91%, an increase when compared to previous scenarios. In the previous scenarios, a portion of the energy from renewable sources was being injected into the transmission grid whereas in the 3rd scenario all the energy from renewable sources is absorbed by load and or battery as shown in Figure 21.

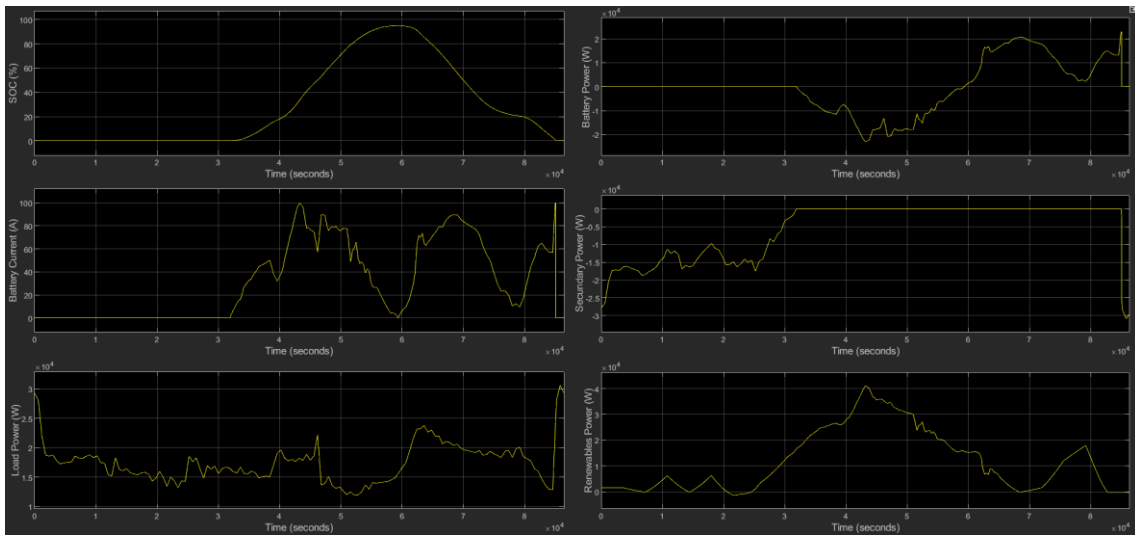


Figure 21: 3rd Scenario overview

Given that the State of Charge (SOC) in the third scenario is approaching its maximum capacity, it becomes evident that increasing the battery capacity to 450Ah is a logical procedure for future grid expansion. This augmentation in battery capacity enhances the grid's adaptability, allowing it to better accommodate additional renewable energy sources and fully capitalize on their potential. This adjustment provides the micro-grid with increased resilience and the capability to store surplus renewable energy, further improving its overall efficiency and sustainability. Since all the energy produced by renewable energy was being absorbed by the load and or battery in the previous scenarios the only difference from the 4th scenario is the SOC level since battery has higher capacity as shown in Figure 22.

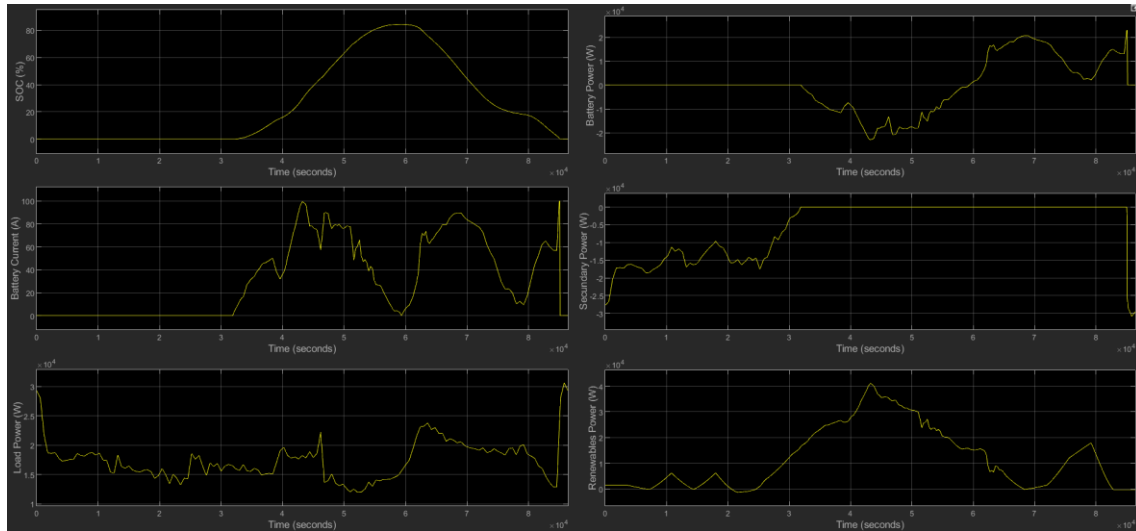


Figure 22: 4th Scenario overview

After the parameters of the battery are defined an analysis of the whole grid is done Figure 23.

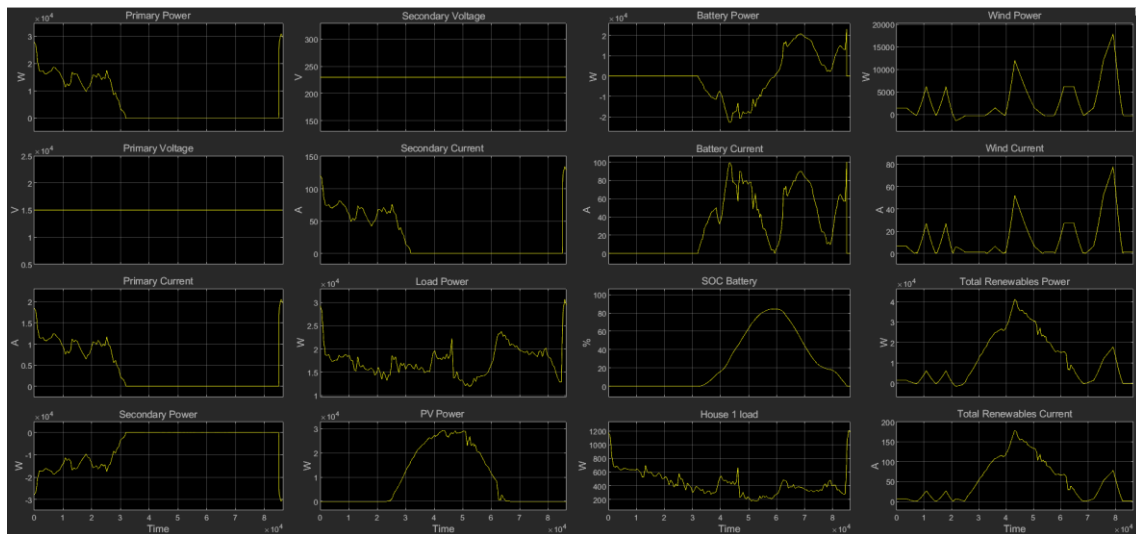


Figure 23: Grid overview

Renewable energy has a huge impact in the total production of electricity. The battery enhances the amount of renewables total installed power since due to the intermittent characteristics of renewable energy it wouldn't be able to have not only that much amount of total installed power but also it wouldn't be able to fulfil the load needs for most of the time (as it is the case with the battery).

Renewable energy plays a crucial role in the overall electricity production system. The intermittent nature of renewable sources has significant challenges that are addressed with

the battery. Without batteries, it would be impractical not only to have this total installed renewable power capacity but also to consistently meet the energy demands of consumers. Batteries, by efficiently storing excess renewable energy, address these issues by ensuring a stable power supply even when renewable sources are not actively generating electricity. Since the battery was oversized, it is also possible to increase the total installed power of renewable energies (reducing even more the dependency in traditional power sources) and or increase the amount of loads.

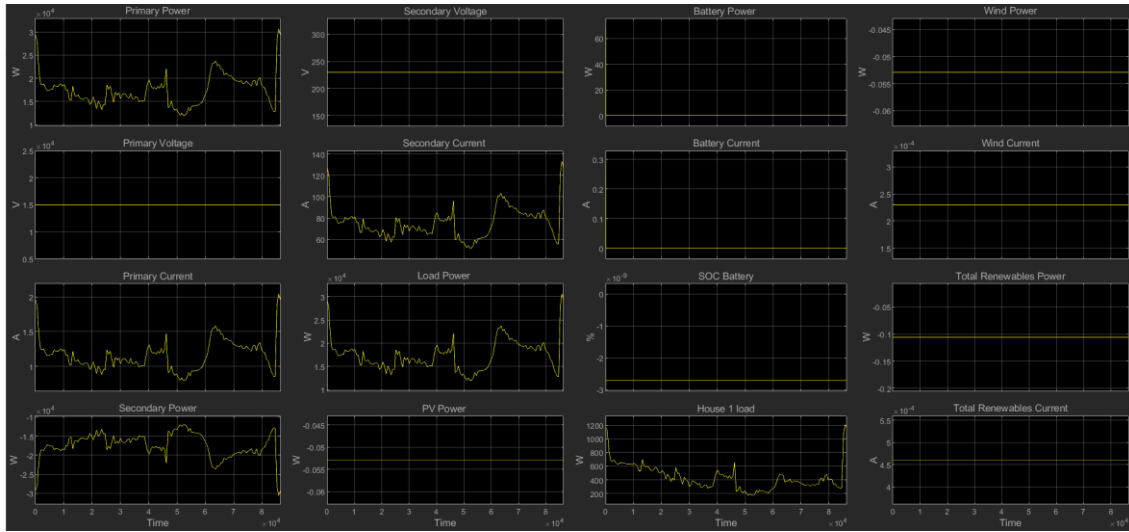


Figure 24: Grid overview without renewable energy

To understand even further the impacts of renewable energy in the grid an in-depth analysis of each technology is done.

Wind power presents a more adaptable solution when contrasted with solar photovoltaics (PV) due to its higher frequency, as wind tends to be more consistently available than sunlight.

In the timeframe indicated by cursors 1 and 2 in Figure 25, there is a noticeable negative power output. This phenomenon is attributed to the power characteristics of the wind turbine.

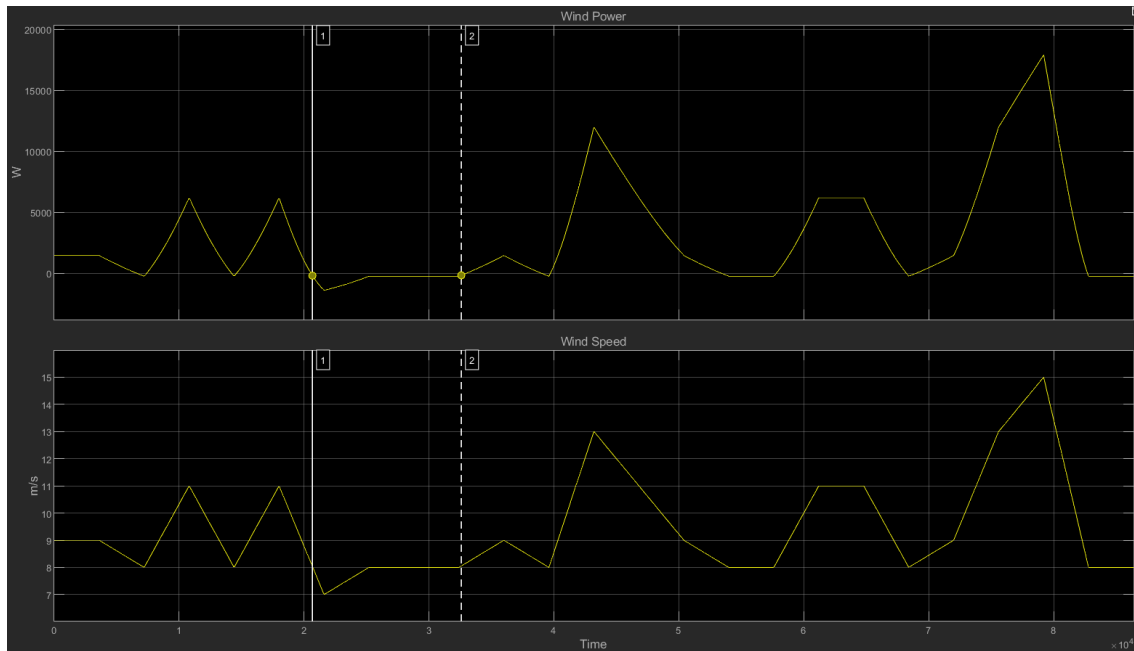


Figure 25: Wind power and wind velocity

Figure 26 further illuminates this behaviour by demonstrating that when the wind speed reaches 8 meters per second (m/s), the wind turbine's power output turns negative.

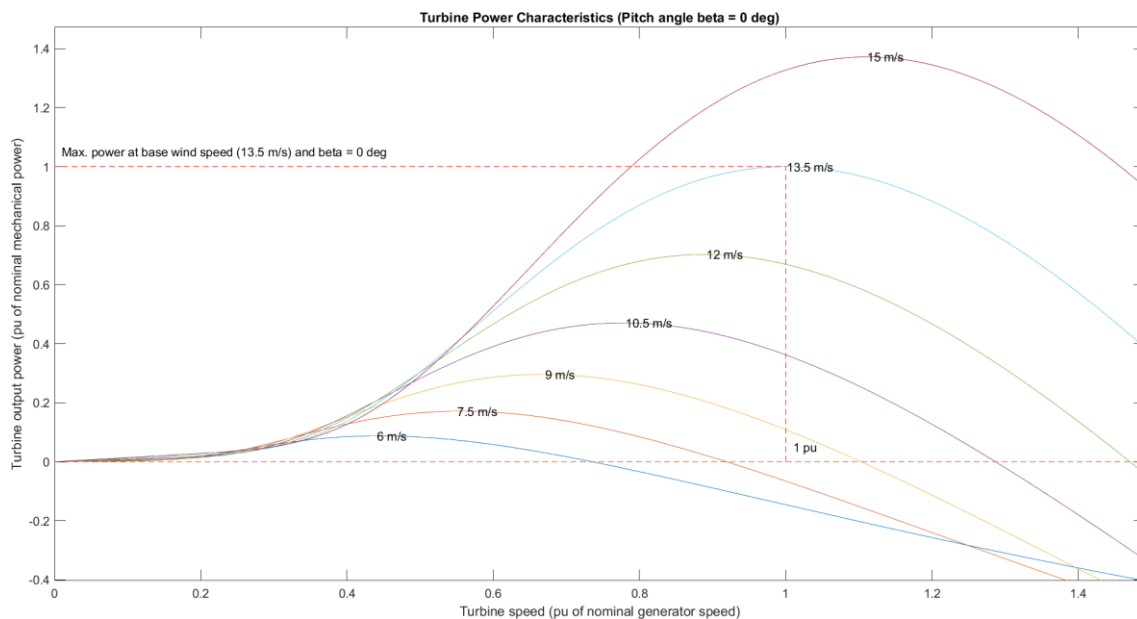


Figure 26: Wind turbine power characteristics

This is a simple wind turbine model without cut-in windspeed systems. In a real-world scenario this wind turbine would have those systems configured to around 8m/s avoiding negative output power. In windspeeds lower than 8m/s wind doesn't provide enough force to overcome inertia of the turbine and the blades. In cases like this the power output is 0

or even negative if there's some energy required to keep the turbine's system working (standby power).

5. CONCLUSION

This thesis has delved into SG technology and highlights its importance potential and its implications in the electrical grid. Through analysis and simulation, several insights and findings were made, which contribute for a deeper understanding of smart grids' role in the constant increasing and evolving energy sector.

The research focused on the electrification, decentralization, and digitalization. These three pillars of a sustainable electrical grid have evolved to allow crucial advancements in SG.

Crucially, this work identified significant challenges standing in the way of broader smart grid adoption, namely metering data protection and a notable knowledge gap concerning energy storage within smart micro-grid environments. In response, a robust, flexible, and scalable smart micro-grid model was designed and implemented. This model's application uncovered insights into the non-linear behaviour of batteries integrated into smart micro-grids. Notably, the model showcased its potential to capture the intricacies of smart grids but still requires further refinement and parameterization for practical business value.

One of the main characteristics of SG is Distributed Power Generation. This type of power generation empowers energy consumers to become producers, blurring the traditional lines between utilities and end-users. With the use of renewable sources like solar panels and wind turbines, consumers can generate their electricity, sell excess power back to the grid, if those consumers are aggregated, they can even provide ancillary services enhancing the reliability of the grid and reducing traditional power generation units like

thermal units that emit greenhouse gases. This characteristic not only gives more freedom to the consumers but also contributes to a more sustainable and resilient energy ecosystem.

Inherent to the smart grid concept is Energy Storage (ES), a type of technology that addresses the intermittent nature of renewable energy sources. Despite recent efforts and economic incentives into ES research and development, these types of technologies (eg: BESS, HESS, UC etc.) still need a lot of development. Longevity, costs of production and maintenance are the main problems that ES faces. Projects like the i-STENTORE (a project funded by EU) aim to solve these problems, the existence of projects like this shows the government's commitment to solve this problem since ES is crucial in SG reducing the impact of renewables intermittency and increasing grid robustness allowing the reduction of thermal dispatch groups. The ES development is the reason why today's grids aren't fully SG and continue to have a lot in common with the traditional grid.

Two-Way Communication, a feature of smart grids that facilitates bi-directional information exchange between utilities and consumers. This digital dialog empowers consumers with real-time data on their energy usage, enabling informed decisions to optimize consumption. Simultaneously, utilities can remotely monitor the grid's stability, detect issues promptly, and even remotely control devices, ensuring grid safety. The devices that this feature needs aren't expensive (especially if the costs are weighted with the increase in efficiency in the grid it allows) the main problem with this feature is the store, management and handling of the data but recent approaches with multi-temporal optimization algorithm handles these problems.

Digital Control in SG enables sophisticated monitoring and management of the entire energy grid. With advanced sensors, automation, and control systems, smart grids can quickly respond to supply and demand, frequency and voltage fluctuations preventing outages and optimizing energy flow. This digital feature provides a self-healing capability in the grids, where the system can automatically reroute power and isolate faults, minimizing downtime and enhancing reliability.

Islanding and Adaptive operation are indispensable attributes of smart grids. In the event of a broader grid failure or natural disaster, smart grids can autonomously create microgrids, ensuring continued power supply to critical facilities. This adaptability is

crucial in enhancing resilience, minimizes disruption during adverse conditions and increases overall safety. This SG feature could be helpful in recent events such as the Hawaii fires.

In summary, SG allows a more proactive approach, where predictive analytics and machine learning anticipate issues before they occur. This foresight allows utilities to address potential problems in advance, reducing downtime and enhancing overall grid efficiency.

During the thesis, a parametric study on battery characteristics highlighted the impact in SG and specially the impact in smart micro-grid. The thesis studies the battery non-linearity and its effects in the grid efficiency, presenting opportunities for optimization. The micro-grid power consumption metric emerged as an ideal tool for implementing Piclo's Locational DUoS methods, addressing the challenge of measuring locally matched supply and demand accurately.

In order to these initiatives to become widely used in real-world applications more efforts from the governments (in both research and regulation fields), utilities (digitalization and updates in obsolete equipment) and consumers (proactivity in becoming producers and having digital meters in their infrastructure). In conclusion, this thesis emphasizes the role of smart grids in shaping the future of energy distribution and consumption, offering a pathway towards sustainability, efficiency, and reliability in the ever-evolving electricity sector.

REFERENCES

- [1] A. Bari, J. Jiang, W. Saad, and A. Jaekel, ‘Challenges in the smart grid applications: An overview’, *Int J Distrib Sens Netw*, vol. 2014, 2014, doi: 10.1155/2014/974682.
- [2] O. Ceaki, G. Seritan, R. Vatu, and M. Mancasi, ‘Analysis of power quality improvement in smart grids’, *2017 10th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2017*, pp. 797–801, Apr. 2017, doi: 10.1109/ATEE.2017.7905104.
- [3] N. Phuangpornpitak and S. Tia, ‘Opportunities and Challenges of Integrating Renewable Energy in Smart Grid System’, *Energy Procedia*, vol. 34, pp. 282–290, Jan. 2013, doi: 10.1016/J.EGYPRO.2013.06.756.
- [4] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, ‘The future renewable electric energy delivery and management (FREEDM) system: The energy internet’, *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133–148, Jan. 2011, doi: 10.1109/JPROC.2010.2081330.
- [5] A. Alsalemi, A. Amira, H. Malekmohamadi, and K. Diao, ‘Lightweight Gramian Angular Field classification for edge internet of energy applications’, *Cluster Comput*, 2022, doi: 10.1007/S10586-022-03704-1.
- [6] O. Majeed Butt, M. Zulqarnain, and T. Majeed Butt, ‘Recent advancement in smart grid technology: Future prospects in the electrical power network’, *Ain Shams Engineering Journal*, vol. 12, no. 1, pp. 687–695, Mar. 2021, doi: 10.1016/J.ASEJ.2020.05.004.
- [7] X. Fang, S. Misra, G. Xue, and D. Yang, ‘Smart grid - The new and improved power grid: A survey’, *IEEE Communications Surveys and Tutorials*, vol. 14, no. 4, pp. 944–980, 2012, doi: 10.1109/SURV.2011.101911.00087.

- [8] S. Singh, D. Shukla, and S. P. Singh, 'Peak demand reduction in distribution network with smart grid-enabled CVR', *IEEE PES Innovative Smart Grid Technologies Conference Europe*, pp. 735–740, Dec. 2016, doi: 10.1109/ISGT-ASIA.2016.7796476.
- [9] S. Tang, Q. Huang, X. Y. Li, and D. Wu, 'Smoothing the energy consumption: Peak demand reduction in smart grid', *Proceedings - IEEE INFOCOM*, pp. 1133–1141, 2013, doi: 10.1109/INFCOM.2013.6566904.
- [10] R. Bayindir, I. Colak, G. Fulli, and K. Demirtas, 'Smart grid technologies and applications', *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 499–516, Dec. 2016, doi: 10.1016/J.RSER.2016.08.002.
- [11] '(PDF) A Discussion Paper on Designing Ambient Assisted Living Systems'. Accessed: Jan. 25, 2023. [Online]. Available: https://www.researchgate.net/publication/269673546_A_Discussion_Paper_on_Designing_Ambient_Assisted_Living_Systems
- [12] M. L. Tuballa and M. L. Abundo, 'A review of the development of Smart Grid technologies', *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 710–725, Jun. 2016, doi: 10.1016/J.RSER.2016.01.011.
- [13] Kwang-Cheng Chen, Ping-Cheng Yeh, Hung-Yun Hsieh, and Shi-Chung Chang, 'Communication infrastructure of smart grid', in *2010 4th International Symposium on Communications, Control and Signal Processing (ISCCSP)*, IEEE, Mar. 2010, pp. 1–5. doi: 10.1109/ISCCSP.2010.5463330.
- [14] 'Implementation of demand response in different control strategies of smart grids | IEEE Conference Publication | IEEE Xplore'. Accessed: Jan. 26, 2023. [Online]. Available: <https://ieeexplore.ieee.org/document/6243525>
- [15] K. Moslehi and R. Kumar, 'A Reliability Perspective of the Smart Grid', *IEEE Trans Smart Grid*, vol. 1, no. 1, pp. 57–64, Jun. 2010, doi: 10.1109/TSG.2010.2046346.

- [16] ‘Key Smart Grid Applications - KIPDF.COM’. Accessed: Jan. 25, 2023. [Online]. Available: https://kipdf.com/key-smart-grid-applications_5afea24c8ead0e506f8b4602.html
- [17] José Pedro Sucena Paiva, *REDES DE ENERGIA ELÉCTRICA. UMA ANÁLISE SISTÊMICA*, 4th ed. Coleção Ensino da Ciência e da Tecnologia, 2015.
- [18] ‘Electricity Transmission, Distribution and Storage Systems - Google Livros’. Accessed: Jan. 25, 2023. [Online]. Available: https://books.google.pt/books?hl=pt-PT&lr=&id=KmVEAgAAQBAJ&oi=fnd&pg=PP1&dq=production+transmission+and+distribution&ots=ftMMhpAfeW&sig=EkAXmi4xX19kOi9NH0DA7CyWKIQ&redir_esc=y#v=onepage&q=production%20transmission%20and%20distribution&f=false
- [19] X. Fang, D. Yang, and G. Xue, ‘Wireless Communications and Networking Technologies for Smart Grid: Paradigms and Challenges’, Dec. 2011.
- [20] ‘An Example of the Traditional Power Grid | Download Scientific Diagram’. Accessed: Jan. 11, 2023. [Online]. Available: https://www.researchgate.net/figure/An-Example-of-the-Traditional-Power-Grid_fig2_51969667
- [21] B. Goia, T. Cioara, and I. Anghel, ‘Virtual Power Plant Optimization in Smart Grids: A Narrative Review’, *Future Internet*, vol. 14, no. 5, p. 128, Apr. 2022, doi: 10.3390/fi14050128.
- [22] A. G. Olabi and M. A. Abdelkareem, ‘Renewable energy and climate change’, *Renewable and Sustainable Energy Reviews*, vol. 158, p. 112111, Apr. 2022, doi: 10.1016/J.RSER.2022.112111.
- [23] C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, ‘Distributed Generation and Renewable Energy Integration into the Grid: Prerequisites, Push Factors, Practical Options, Issues and Merits’, *Energies 2021, Vol. 14, Page 5375*, vol. 14, no. 17, p. 5375, Aug. 2021, doi: 10.3390/EN14175375.

- [24] S. Lukovic, I. Kaitovic, M. Mura, and U. Bondi, 'Virtual Power Plant As a Bridge between Distributed Energy Resources and Smart Grid', in *2010 43rd Hawaii International Conference on System Sciences*, IEEE, 2010, pp. 1–8. doi: 10.1109/HICSS.2010.437.
- [25] M. Musio and A. Damiano, 'Analysis of Vehicle to Grid and energy storage integration in a virtual power plant', *IECON Proceedings (Industrial Electronics Conference)*, pp. 3094–3100, Feb. 2014, doi: 10.1109/IECON.2014.7048952.
- [26] I. Cherukhin, S. P. Gao, and Y. Guo, 'Fully Flexible Polymer-Based Microwave Devices: Materials, Fabrication Technique, and Application to Transmission Lines', *IEEE Trans Antennas Propag*, vol. 69, no. 12, pp. 8763–8777, Dec. 2021, doi: 10.1109/TAP.2021.3083855.
- [27] Q. Ou, Y. Zhen, X. Li, Y. Zhang, and L. Zeng, 'Application of Internet of Things in Smart Grid Power Transmission', in *2012 Third FTRA International Conference on Mobile, Ubiquitous, and Intelligent Computing*, IEEE, Jun. 2012, pp. 96–100. doi: 10.1109/MUSIC.2012.24.
- [28] F. Li *et al.*, 'Smart transmission grid: Vision and framework', *IEEE Trans Smart Grid*, vol. 1, no. 2, pp. 168–177, 2010, doi: 10.1109/TSG.2010.2053726.
- [29] H. Zeynal, M. Eidiani, and D. Yazdanpanah, 'Intelligent Substation Automation Systems for robust operation of smart grids', *2014 IEEE Innovative Smart Grid Technologies - Asia, ISGT ASIA 2014*, pp. 786–790, 2014, doi: 10.1109/ISGT-ASIA.2014.6873893.
- [30] D. Seo, H. Lee, and A. Perrig, 'Secure and efficient capability-based power management in the smart grid', *Proceedings - 9th IEEE International Symposium on Parallel and Distributed Processing with Applications Workshops, ISPAW 2011 - ICASE 2011, SGH 2011, GSDP 2011*, pp. 119–126, 2011, doi: 10.1109/ISPAW.2011.36.

- [31] E. Kabalci and Y. Kabalci, 'Power line communication technologies in smart grids', *From Smart Grid to Internet of Energy*, pp. 119–171, 2019, doi: 10.1016/B978-0-12-819710-3.00004-1.
- [32] L. Lampe and L. T. Berger, 'Power line communications', *Academic Press Library in Mobile and Wireless Communications: Transmission Techniques for Digital Communications*, pp. 621–659, Jul. 2016, doi: 10.1016/B978-0-12-398281-0.00016-8.
- [33] H. T. Mouftah and M. Erol-Kantarci, 'Smart grid communications: Opportunities and challenges', *Handbook of Green Information and Communication Systems*, pp. 631–663, 2013, doi: 10.1016/B978-0-12-415844-3.00025-5.
- [34] 'All-digital power packet dispatching system for effective power management | TLO-KYOTO Co., Ltd.' Accessed: Jan. 25, 2023. [Online]. Available: <https://www.tlo-kyoto.co.jp/english/patent/post-389.html>
- [35] L. Fusheng, L. Ruisheng, and Z. Fengquan, 'Communication of the microgrid', *Microgrid Technology and Engineering Application*, pp. 115–124, 2016, doi: 10.1016/B978-0-12-803598-6.00007-3.
- [36] L. Mariam, M. Basu, and M. F. Conlon, 'Microgrid: Architecture, policy and future trends', *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 477–489, Oct. 2016, doi: 10.1016/J.RSER.2016.06.037.
- [37] N. Phuangpornpitak and S. Tia, 'Opportunities and Challenges of Integrating Renewable Energy in Smart Grid System', *Energy Procedia*, vol. 34, pp. 282–290, Jan. 2013, doi: 10.1016/J.EGYPRO.2013.06.756.
- [38] B. P. Roberts and C. Sandberg, 'The role of energy storage in development of smart grids', *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1139–1144, 2011, doi: 10.1109/JPROC.2011.2116752.
- [39] E. Ancillotti, R. Bruno, and M. Conti, 'The role of communication systems in smart grids: Architectures, technical solutions and research challenges',

- Comput Commun*, vol. 36, no. 17–18, pp. 1665–1697, Nov. 2013, doi: 10.1016/J.COMCOM.2013.09.004.
- [40] M. G. Rosenfield, ‘The smart grid and key research technical challenges’, *Digest of Technical Papers - Symposium on VLSI Technology*, pp. 3–8, 2010, doi: 10.1109/VLSIT.2010.5556140.
- [41] B. P. Bhattarai *et al.*, ‘Big data analytics in smart grids: state-of-the-art, challenges, opportunities, and future directions’, *IET Smart Grid*, vol. 2, no. 2, pp. 141–154, Jun. 2019, doi: 10.1049/IET-STG.2018.0261.
- [42] J. Rodríguez-Molina, M. Martínez-Núñez, J. F. Martínez, and W. Pérez-Aguilar, ‘Business Models in the Smart Grid: Challenges, Opportunities and Proposals for Prosumer Profitability’, *Energies 2014, Vol. 7, Pages 6142-6171*, vol. 7, no. 9, pp. 6142–6171, Sep. 2014, doi: 10.3390/EN7096142.
- [43] N. K. Medora, ‘Electric and Plug-in Hybrid Electric Vehicles and Smart Grids’, *The Power Grid: Smart, Secure, Green and Reliable*, pp. 197–231, Jan. 2017, doi: 10.1016/B978-0-12-805321-8.00007-0.
- [44] P. M. Connor, P. E. Baker, D. Xenias, N. Balta-Ozkan, C. J. Axon, and L. Cipcigan, ‘Policy and regulation for smart grids in the United Kingdom’, *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 269–286, Dec. 2014, doi: 10.1016/J.RSER.2014.07.065.
- [45] L. MEEUS, M. SAGUAN, J.-M. GLACHANT, and R. BELMANS, “‘Smart Regulation for Smart Grids’”, 2010, Accessed: Jan. 26, 2023. [Online]. Available: <https://cadmus.eui.eu/handle/1814/14043>
- [46] ‘AnyLogic: Simulation Modeling Software Tools & Solutions for Business’. Accessed: Sep. 26, 2023. [Online]. Available: <https://www.anylogic.com/>
- [47] ‘mosaik — A flexible Smart Grid co-simulation framework’. Accessed: Sep. 26, 2023. [Online]. Available: <https://mosaik.offis.de/>

- [48] C. N. and G. Madey, 'Tools of the Trade: A Survey of Various Agent Based Modeling Platforms', Mar. 2009.
- [49] 'ePubs'. Accessed: Sep. 26, 2023. [Online]. Available: <https://epubs.stfc.ac.uk/work/50398>
- [50] M. Pipattanasomporn, H. Feroze, and S. Rahman, 'Multi-agent systems in a distributed smart grid: Design and implementation', *2009 IEEE/PES Power Systems Conference and Exposition, PSCE 2009*, 2009, doi: 10.1109/PSCE.2009.4840087.
- [51] 'Simulink - Simulation and Model-Based Design - MATLAB'. Accessed: Sep. 26, 2023. [Online]. Available: <https://uk.mathworks.com/products/simulink.html>
- [52] 'Simulink Documentation'. Accessed: Sep. 26, 2023. [Online]. Available: <https://www.mathworks.com/help/simulink/>
- [53] U. A. Khan, J. K. Seong, S. H. Lee, S. H. Lim, and B. W. Lee, 'Feasibility analysis of the positioning of superconducting fault current limiters for the smart grid application using Simulink and SimPowerSystem', *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3 PART 2, pp. 2165–2169, Jun. 2011, doi: 10.1109/TASC.2010.2089591.
- [54] P. Kulshrestha, L. Wang, M. Y. Chow, and S. Lukic, 'Intelligent energy management system simulator for PHEVs at municipal parking deck in a smart grid environment', *2009 IEEE Power and Energy Society General Meeting, PES '09*, 2009, doi: 10.1109/PES.2009.5275688.
- [55] A. Bergmann, 'Benefits and Drawbacks of Model-based Design', *KMUTNB International Journal of Applied Science and Technology*, vol. 7, no. 3, pp. 15–19, Sep. 2014, doi: 10.14416/J.IJAST.2014.04.004.
- [56] 'Simscape Electrical - MATLAB'. Accessed: Sep. 26, 2023. [Online]. Available: <https://www.mathworks.com/products/simscape-electrical.html>

- [57] R. Marah and A. El Hibaoui, 'Algorithms for Smart Grid management', *Sustain Cities Soc*, vol. 38, pp. 627–635, Apr. 2018, doi: 10.1016/J.SCS.2018.01.041.
- [58] S. Mallapuram, P. Moulema, and W. Yu, 'A smart grid simulation testbed using Matlab/Simulink', *Cyber Sensing 2014*, vol. 9097, p. 909705, Jun. 2014, doi: 10.1117/12.2050392.
- [59] 'Environment block for Simscape Electrical Specialized Power Systems models - Simulink'. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/powergui.html>
- [60] 'Simscape Electrical Block Libraries - MATLAB & Simulink'. Accessed: Sep. 28, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/ug/simscape-electrical-block-libraries.html>
- [61] 'Introducing the Phasor Simulation Method - MATLAB & Simulink'. Accessed: Sep. 28, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ug/introducing-the-phasor-simulation-method.html>
- [62] K. Mets, J. A. Ojea, and C. Develder, 'Combining power and communication network simulation for cost-effective smart grid analysis', *IEEE Communications Surveys and Tutorials*, vol. 16, no. 3, pp. 1771–1796, 2014, doi: 10.1109/SURV.2014.021414.00116.
- [63] J. Soares, F. Lezama, T. Pinto, and H. Morais, 'Complex optimization and simulation in power systems', *Complexity*, vol. 2018, 2018, doi: 10.1155/2018/6562876.
- [64] G. Andersson, 'Modelling and Analysis of Electric Power Systems Power Flow Analysis Fault Analysis Power Systems Dynamics and Stability', 2008.
- [65] 'Use Discrete and Continuous Time - MATLAB & Simulink'. Accessed: Sep. 29, 2023. [Online]. Available:

<https://www.mathworks.com/help/ecoder/ug/using-discrete-and-continuous-time.html>

- [66] ‘Perform a Load-Flow Analysis Using Simscape Electrical - MATLAB & Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/ug/perform-a-load-flow-analysis-using-simscape-electrical.html>
- [67] R. Anand and V. Balaji, ‘Power flow analysis of simulink IEEE 57 bus test system model using PSAT’, *Indian J Sci Technol*, vol. 8, no. 23, 2015, doi: 10.17485/ijst/2015/v8i23/79266.
- [68] ‘Load Flow Analysis Model in MATLAB SIMULINK - File Exchange - MATLAB Central’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/matlabcentral/fileexchange/93800-load-flow-analysis-model-in-matlab-simulink>
- [69] ‘Simplified Model of a Small Scale Micro-Grid - MATLAB & Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/ug/simplified-model-of-a-small-scale-micro-grid.html>
- [70] ‘National Electricity Transmission System Security and Quality of Supply Standard’.
- [71] T. Lineham, ‘R66141 Final Report Issue 4 Household Electricity Survey A study of domestic electrical product usage REPORT Client’.
- [72] ‘Solar Power Data for Integration Studies | Grid Modernization | NREL’. Accessed: Sep. 27, 2023. [Online]. Available: <https://www.nrel.gov/grid/solar-power-data.html>
- [73] ‘24-hour Simulation of a Vehicle-to-Grid (V2G) System - MATLAB & Simulink’. Accessed: Sep. 30, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/ug/24-hour-simulation-of-a-vehicle-to-grid-v2g-system.html>

- [74] ‘Categorical Arrays - MATLAB & Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/matlab/categorical-arrays.html>
- [75] ‘Implement three-phase source with internal R-L impedance - Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/threephasesource.html>
- [76] ‘A Dictionary of Physics’, *A Dictionary of Physics*, Sep. 2015, doi: 10.1093/ACREF/9780198714743.001.0001.
- [77] ‘RMS Voltage of a Sinusoidal AC Waveform’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.electronics-tutorials.ws/accircuits/rms-voltage.html>
- [78] ‘Measure current in circuit - Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/currentmeasurement.html>
- [79] P. A. Verwiebe, S. Seim, S. Burges, L. Schulz, and J. Müller-Kirchenbauer, ‘Modeling Energy Demand—A Systematic Literature Review’, *Energies* 2021, Vol. 14, Page 7859, vol. 14, no. 23, p. 7859, Nov. 2021, doi: 10.3390/EN14237859.
- [80] ‘Implement two- or three-winding linear transformer - Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/lineartransformer.html>
- [81] G. Strbac *et al.*, ‘Innovation Funding Incentive (IFI) Management of electricity distribution network losses Imperial College’, 2014.
- [82] ‘Voltage drop calculator (DC & AC)’. Accessed: Sep. 29, 2023. [Online]. Available: <https://photovoltaic-software.com/solar-tools/voltage-drop-calculator-dc-ac>

- [83] 'Fundamentals of Electrical Engineering, Part 1 - Google Books'. Accessed: Sep. 29, 2023. [Online]. Available: https://www.google.pt/books/edition/Fundamentals_of_Electrical_Engineering_P/fwmzDgAAQBAJ?hl=en&gbpv=1&dq=fundamental+principles+of+Norton%27s+theorem&pg=PA56&printsec=frontcover
- [84] 'Implement controlled current source - Simulink'. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/controlledcurrentsource.html>
- [85] 'Power in AC Circuits and Reactive Power'. Accessed: Sep. 30, 2023. [Online]. Available: <https://www.electronics-tutorials.ws/ac/ac-circuits/power-in-ac-circuits.html>
- [86] 'Convert magnitude and/or a phase angle signal to complex signal - Simulink'. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/simulink/slref/magnitudeangletocomplex.html>
- [87] '24-hour Simulation of a Vehicle-to-Grid (V2G) System - MATLAB & Simulink'. Accessed: Sep. 27, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/ug/24-hour-simulation-of-a-vehicle-to-grid-v2g-system.html>
- [88] *Physics for Scientists and Engineers - Raymond A. Serway, John W. Jewett - Google Books*. Accessed: Sep. 27, 2023. [Online]. Available: [https://books.google.pt/books?hl=en&lr=&id=4g9EDwAAQBAJ&oi=fnd&pg=PP1&dq=Serway,+R.+A.,+%26+Jewett,+J.+W.,+\(2016\).+Physics+for+Scientists+and+Engineers+with+Modern+Physics.+Cengage+Learning.&ots=cQVe3eqYEF&sig=_hWnykYbZ0LWJD2XNkiWmGB5oNs&redir_esc=y#v=onepage&q&f=false](https://books.google.pt/books?hl=en&lr=&id=4g9EDwAAQBAJ&oi=fnd&pg=PP1&dq=Serway,+R.+A.,+%26+Jewett,+J.+W.,+(2016).+Physics+for+Scientists+and+Engineers+with+Modern+Physics.+Cengage+Learning.&ots=cQVe3eqYEF&sig=_hWnykYbZ0LWJD2XNkiWmGB5oNs&redir_esc=y#v=onepage&q&f=false)
- [89] 'Measure active and reactive powers of voltage-current pair - Simulink'. Accessed: Sep. 29, 2023. [Online]. Available:

<https://www.mathworks.com/help/sps/powersys/ref/activeractivepower.html>

- [90] ‘Integrate signal - Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/simulink/slref/integrator.html>
- [91] ‘Generic battery model - Simulink’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/sps/powersys/ref/battery.html>
- [92] J. Che, F. Wang, C. Song, R. Wang, and Y. Li, ‘Modeling of energy carrier in solar-driven calcium-looping for thermochemical energy storage: Heat-mass transfer, chemical reaction and stress response’, *Chemical Engineering Journal*, vol. 463, p. 142435, May 2023, doi: 10.1016/j.cej.2023.142435.
- [93] ‘Trapezoidal numerical integration - MATLAB trapz’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.mathworks.com/help/matlab/ref/trapz.html>
- [94] ‘Publications’. Accessed: Sep. 29, 2023. [Online]. Available: <https://www.piclo.energy/publications>
- [95] ‘Local Grid Charging Exploring the incentivisation of local energy’.