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SMART GRID VOLTAGE CONTROL USING AI BASED CONTROLLERS

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Master's Thesis

Supervisor

Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN

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Mustafa Ahmed Mahdi AL-KHAFAJI

Signature

DEDICATION

I dedicate this research work to my supervisor who was for guiding me through the whole research work as well as my family for always assisting me in my difficult time.

PREFACE

First and foremost, I would like to thank my supervisor Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN for guiding and helping me along the way in writing this dissertation. Discussing my progress, problems, and ideas with my supervisor Asst. Prof. Dr. Ayça Kurnaz TÜRKBEN a couple of times every week helped me tremendously in understanding the logic behind the research. It made me better realize the technical need for this research work.

ABSTRACT

SMART GRID VOLTAGE CONTROL USING AI BASED CONTROLLERS

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Electrical micro-grids are, as the name suggests, small electrical networks compared to conventional ones. They encompass the generation, distribution, and consumption of electricity in a small area. These new electrical system structures integrate advanced devices for the production and conversion of electrical energy, and incorporate modern and sophisticated control, automation, and communication strategies In the context of this research, the microgrid utilizes many power-generating sources but lacks a centralized controller or other kind of communication system. A controller is required to regulate the actual power output and reactive power output of several generations simultaneously. Both the actual and reactive power generated by these two diesel generators are under control. Consequently, the resilience of the Microgrid will be enhanced. In the case of a power outage, diesel generators will be utilized to keep the lights on, while alternative energy sources will be used to charge the batteries. Due to the absence of a clear link between the two generators, neural networks are an ideal tool for addressing non-linear problems.

Keywords: ANN, CNN, SG, DEG, MG.

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ABBREVIATIONS

ANN	:	Artificial Neural Network
CNN	:	Convolutional Neural Network
SG	:	Smart Grid
DEG	:	Distributed Energy Generation
MG	:	Micro Grid

1. INTRODUCTION

1.1 BACKGROUND

Electrical micro-grids are, as the name suggests, small electrical networks compared to conventional ones. They encompass the generation, distribution, and consumption of electricity in a small area. These new electrical system structures integrate advanced devices for the production and conversion of electrical energy, and incorporate modern and sophisticated control, automation, and communication strategies. Faced with the rupture of models and procedures of vertical and centralized operation, large-scale generation, transmission over kilometres of line, passive distribution and consumption away from production, students, researchers and professionals in the electrical sector must understand and develop technologies and methods to take advantage of all the benefits of micro-grids.

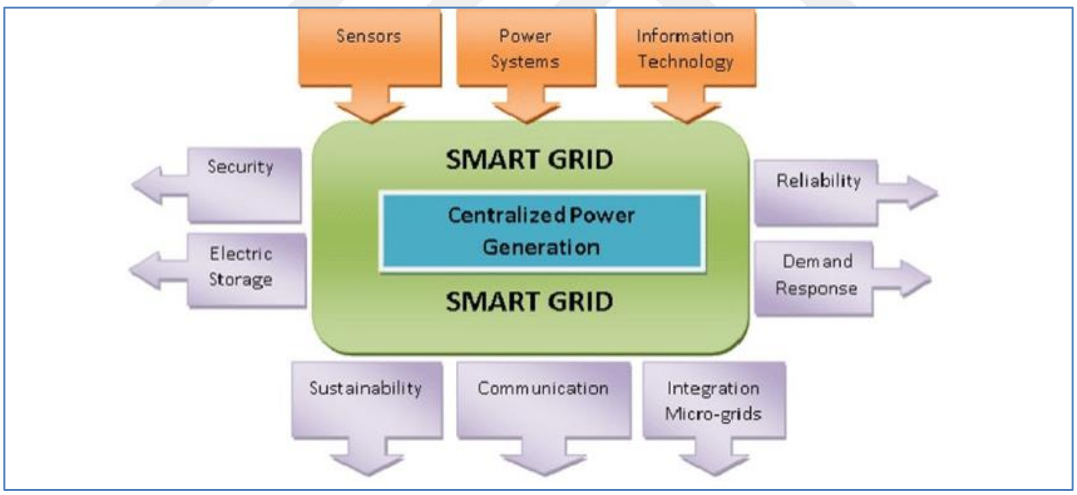

Figure 1.1: Architecture od smart grids.

1.2 PROBLEM STATEMNT

It is projected that the number of microgrids in operation will skyrocket over the course of the next few decades. Voltage is one of the most essential elements to consider when developing power systems. This previous research similarly seeks to prove, although in a different method, that there is no central communication system or controller that connects successive generations.

This thesis also aims to demonstrate the same idea, but using a different technique. In order to manage the microgrid's voltage, neural networks are used. When there is a major change in load demand, there is a chance that the terminals of sensitive loads may experience low or high voltage issues. It may be able to eliminate these disturbances by careful regulation of the actual and reactive powers of diesel generators.

1.3 AIMS AND OBJECTIVES

In the context of this research, the microgrid utilizes many power-generating sources but lacks a centralized controller or other kind of communication system. A controller is required to regulate the actual power output and reactive power output of several generations simultaneously. Both the actual and reactive power generated by these two diesel generators are under control. Consequently, the resilience of the Microgrid will be enhanced. In the case of a power outage, diesel generators will be utilized to keep the lights on, while alternative energy sources will be used to charge the batteries. Due to the absence of a clear link between the two generators, neural networks are an ideal tool for addressing non-linear problems. This makes neural networks an ideal tool for addressing nonlinear problems. The capabilities of various neural networks are correlated with their architecture, dynamics, and training techniques, which are all sorts of neural networks. There are a number of neural network architectures. It outperforms traditional technology in several areas, such as signal filtering, data segmentation, optimization, and scheduling, to mention a few [8].

1.4 CONTRIBUTIONS

In the not-too-distant future, fossil fuel resources will run out, and in order to avert this catastrophe, humanity will need to develop other energy sources. Renewable energy sources are increasing market share as fossil fuels lose ground in the energy industry. In the sphere of electric power production and distribution, the microgrid idea was quickly gaining favor. The most successful technique for ensuring the security of one's energy supply is to depend on a number of smaller generators rather than a single huge generator. When employed in commercial, industrial, and mission-critical contexts, microgrid systems have the ability to be combined with renewable energy sources to suit the needs of a wide variety of users. Microgrids will manage the delivery of power in rural areas to an increasing degree. Self-sufficiency is one of the benefits that microgrids bring. This generator's reliability and stability surpass those of traditional generators. It is far more dependable and stable. In electrical distribution networks, failures and load imbalances cannot be avoided and are unavoidable. A controller is essential to preserve order and consistency. It was determined if load-induced imbalances might be mitigated by adjusting distributed generation systems [5]. When operating in grid-connected mode, controls the voltage of sensitive loads and shows both actual and reactive power flow. The simulation results are used to demonstrate the controller's efficacy in the study. The controller runs at a single frequency, which was beyond the scope of our inquiry.

1.5 THESIS OUTLINE

In the first chapter, the history of microgrids is concisely narrated, starting with primordial electrical systems, going through the precursor technologies and ending with the emergence of its modern conception. Then the research problem and questions are provided in accordance to the scientific contribution of the research.

The second chapter provides a literature review shows the state of the art on the subject. Besides listing the various techniques proposed in the literature, succinct analyses are made, outlining advantages and disadvantages, as well as difficulties and restrictions in this control.

The third chapter deals with the micro-grids connected to the network. In the hierarchical structure, this control forms the tertiary level. An overview of the subject is presented. This is followed by explanations of synchronization techniques and the interconnection key that connects the two systems. Following the first section, the second provides an overview of the research and development of microgrids in recent years, pointing out ongoing projects and confluent areas of study. Microgrids are then defined and the most important concepts involved are considered. Next, the microgrid infrastructure is addressed. That is, its fundamental components, such as distributed generation (DG), power electronics, and energy storage, among others, are outlined. The subsequent topic is the control of microgrids and its different aspects: centralized, distributed, and hierarchical. That said, the possibilities of micro-grid architectures are explored. The insertion of microgrids into the electrical system and its implications are examined in the next three sections, where standards, power quality, and smart grids are discussed in this sequence. Finally, benefits, challenges, and trends of microgrids are discussed.

The fourth chapter deals with AI and smart grids. When connected together, the inverters can be controlled individually and the total power flow between the micro-grid and the grid can be controlled. The system allows continuous, reliable and high-quality operation of the microgrid even under adverse conditions, such as DG losses, load variations, grid faults, etc., causing it to maintain adequate voltage and frequency levels or intentionally switch to islanded mode in case of external problems. Computational simulation results for various operational situations demonstrate the operation of the microgrid control in grid-connected mode.

Finally, a conclusion on the text is given in the fifth chapter in addition, proposals for future work are indicated and commented.

2. LITERATURE REVIEW

2.1 CHAPTER INTRODUCTION

In order to provide a continuous and dependable energy supply in the 21st century, a new power infrastructure known as the Smart Grid (SG), also known as the next generation grid, was constructed to replace the aging power infrastructure. It is believed that when paired with current communication and calculation capabilities, it will increase the reliability and efficiency of energy distribution while simultaneously minimizing its environmental impact. The data produced from the system's architecture, as well as the data derived from its underlying communication network, need the use of a variety of analytical and decision-making techniques. Big data analytics, machine learning (ML), and deep learning (DL) each play a vital part in the process of evaluating and extracting valuable insights from this massive quantity of data. These insights simplify the identification of abnormalities, the detection of fraud, the confirmation of pricing, the discovery of faults, and the monitoring of energy use. As a result, the current iteration of the smart grid is incapable of functioning without continuous and continuous data analysis. In order to provide dependable and efficient energy distribution, the objective of this article is to examine and analyze several architectural components of the smart grid, as well as applications and methodologies based on ML and DL that are applicable to SG. This thesis also examines the limits of prior research as well as the future prospects for ML and DL-based data analytics.

2.2 PREVIOUS WORKS

The article [27] examines renewable energy sources (RES), including solar energy, wind energy, geothermal energy, hydroelectricity, etc. The application of artificial intelligence (AI) in a range of disciplines, such as decision making, control and optimization, and simulations, is a further key factor that may contribute to the enhancement of the efficiency of renewable energy. They concluded that AI-powered solutions have the potential to enhance the functioning of smart grid and microgrids.

The paper [28] provides a quick introduction to load monitoring (LM) method for energy management systems. (EMSs). Nonintrusive LM, on the other hand, refers to single-point sensing and does not need any invasive treatments. In addition, both intrusive and non-invasive LM approaches for the regulation of energy in smart grids are investigated. In addition, this study examines current literature and probable future improvements in LM pertaining to energy management. Their research indicates that future challenges for LM may include precise disaggregation and identification, the use of non-traditional signatures to improve the accuracy of non-intrusive LM, and the integration of smart meters with EMS.

In contrast, Amasyali and colleagues devoted a whole chapter of [29] to data-driven building energy consumption prediction research (BEC). (i.e., data collection, data preparation, training of the model, and testing of the learned model). In addition, they present ML-based algorithms 146 and demonstrate the accuracy of these algorithms in predicting the energy consumption of buildings. In addition, this study reveals the performance evaluation standards employed in previous examinations. Last but not least, the community of researchers working in the topic of data-driven BEC prediction has been supplied with future directions and research needs have been highlighted. There is an additional study of data-driven research approaches at position [30].

In [30], as contrast to [29], data-driven approaches for prediction and BEC categorization are considered. According to the results of their analysis, data-driven techniques may account for a substantial portion of the energy use in buildings. Among them are the power pattern profile, load forecasting and prediction, benchmarking for stock building, and the formulation of recommendations. The final results suggest that academics should investigate the feasibility of energy saving on a smaller scale by considering the needs of individual users.

Voyant et al. presented a full discussion of the ML-based methodologies that may be used to anticipate solar irradiance in a work published in [31]. Before estimating the quantity of energy that solar panels will generate, one must first determine the amount of sun irradiation. This exploration of ML-based prediction models covers a broad variety of issues, including categorization, data preparation, supervised and unsupervised learning, and accuracy assessment. This study also analyzes the degrees of precision attained by a variety of forecasting methods.

[32] Provides a study of the several approaches of smart microgrid energy management, as well as their associated challenges and solutions. The section [32] describes the approaches and strategies that may be used to manage the variable and intermittent behavior of a microgrid. Due to the intermittent nature of microgrid energy production, this is the case. In contrast, the many strategies for developing EMSs, such as classical methods, linear programming, heuristic schemes, and evolutionary methods, are examined in depth. This covers, for example, swarm optimization, fuzzy logic, and neural networks. In addition, a comparative examination of the microgrid's multiple communication methods is offered. This research concludes with 175 possible concerns and present uses of microgrids as its results.

Published in [33] is research on predicting solar and wind energy using DL-based prediction algorithms. [33] Using DL-based algorithms to predict the energy production from 180 renewable energy sources involves a lot of difficulties because to the algorithms' lack of stability and reliability, making it impossible to generalize the findings of such an estimate. When dealing with small datasets, DL-based algorithms perform much worse than other computationally costly prediction approaches, while outperforming these methods when working with large datasets.

According to the authors [35], there are distinct single and hybrid techniques for DL-based forecasting, with the latter producing more accurate results than the former. Wind energy prediction techniques are researched in references [34, 35], whereas solar power prediction methods are researched in reference.

In [35], the authors describe a further use of ANN in the design of WT systems and the discovery of flaws. Fallah and colleagues [36] published a report that analyzes and summarizes the work of scholars who have been developing load forecasting algorithms.

In separate research [37], the forecasting algorithms are classified according to the period of time during which they are employed to anticipate load: short term, very short term, medium term, and long term.

The publication, although it brought to light the name and ideas behind modern microgrids, was sporadic. It was only with the arrival of the 21st century that the projects and publications that would consolidate the path of today's microgrids came into being. In particular, around the year 2000, the *Consortium for Electric Reliability Technology Solutions* (CERTS) microgrids concept and the seminal articles by Lasseter et al. [14], [15] outlined the research on the topic from then on. The proposed microgrid, which already adopted this name, brought together the technological advances discussed here into a single structure. It was a system made for optimal utilization and integration of multiple DG units connected to inverters, operating in parallel, with cogeneration, using modern control methods, similar to those of UPS systems, feeding local loads and being able to operate connected or not to the distribution grid and to the electrical system in general, which, in turn, would see the microgrid as a single entity. The research and development of the microgrids that followed were heavily influenced and based on this project and its ideas.

2.3 CHAPTER CONCLUSION

To get an idea of the space that the subject has gained in scientific research, simple searches were made in the databases of the Institute of Electrical and Electronics Engineers (IEEE - *Institute of Electrical and Electronics Engineers*), *IEEE Xplore*®, and *Scopus*®. The term "*microgrid*" was searched for. By early March 2022, about 14,000 publications were found in the former and 14,500 in the latter, in total without exclusions. To show the development of the search, only papers related to the field of electrical engineering, power or energy electrical systems or similar were considered. For this purpose, journals, publications, books and conference proceedings from other disciplines were excluded. Between 2001 and 2010, the numbers are exact. From 2010 on, the number of publications was approximated downwards, because part of them may be files that are not papers, but covers, abstracts, etc., or because they are from other fields of study. The idea here is not to give precise values, but only to illustrate the dimension of the evolution of scientific research on microgrids in recent years.

The topics of interest in research are quite varied by the very characteristics of microgrids. Besides DG, power electronics and energy storage, the topic of control methods for microgrids in islanded and/or grid-connected modes is perhaps one of the most popular. A great deal of effort has been made to solve problems and propose solutions for microgrids that allow parallelism of the converters associated with sources, proper sharing of active and reactive power, power quality enhancement, and connection to the power system [16]. Protection, economic factors, and communication techniques for microgrids are also prominent subjects in scientific papers [17]. As for the techniques applied to microgrids, there is a plethora of them, coming from the most diverse fields. Some examples are multi-agent systems, artificial neural networks, game theory, blockchain, among others.

3. MATERIALS AND METHODS

3.1 HISTORY OF MICROGRIDS

The primordial electrical grids, which emerged as early as the 19th century, can be considered microgrids. They did not have the advanced technologies and techniques of their modern versions, but they fulfilled fundamental characteristics of microgrids. The systems presented in chronological order below were not the only ones existing at the time. However, all were of great importance in the evolution of the electricity sector and correspond to what can be called primitive micro-grids.

The street lighting installations in Paris, France from 1878, found in places such as the *Avenue de l'Opéra*, are quite similar to micro-grids, in the sense that they consisted of multiple generators located close to the loads and installed at the consumption sites themselves. The dynamos, which were attached to the steam engines, were located inside the basements of the respective powered buildings or neighbors and were connected to the lamps by underground cables [1].

The first public supply of electricity is credited to the English cities of Godalming and Chesterfield, with their systems dating from 1881 [2]. In the former, in addition to public lighting, private properties could be supplied by a small hydroelectric plant with alternating current (AC) output (taking advantage of an existing water wheel and later converted to steam power) in their vicinity. In the second, two dynamos were used to supply public electricity.

In 1882, Thomas Edison's Pearl Street electric power station was inaugurated [3]. In the financial center of New York City in the United States, the system was capable of supplying buildings and businesses up to a mile away. Unlike past experiences, Edison developed a complete structure for the generation and distribution of electricity. It was the first known cogeneration plant. What's more, it was probably the first parallel connection of direct-current (DC) generators to supply electricity. By the end of the decade, these systems, which were nothing more than DC microgrids, were spread all over the United States and several other countries.

Also in the same decade, systems emerged that used batteries for electrical power distribution. Installed at distant points from the generators, they were used to transmit electricity at higher DC voltages, reducing losses and allowing power supply at peak hours. In the city of London, in 1888, the measure was adopted in different neighborhoods. A few years earlier, in Colchester, England, a system with two DC generators in parallel and battery packs at six stations fed businesses [1].

In the 1890s, the electricity sector in Berlin, the German capital, was made up of many small generating systems attached to business and industry in a kind of "feeder block. Electricity in Chicago, in the United States, was supplied by about 36 different small companies. London, likewise, had a large number of companies for supplying electricity. Each system was in a district corresponding to an administrative division, and the licensed companies had to build their own generating stations as well as their own distribution network [4].

These examples demonstrate how micro-grids are essentially nothing new in terms of power, length, proximity between generation and load, cogeneration, parallelism of generators, use of batteries, and diversity of electricity suppliers. At the beginning of the 20th century, however, electricity consumption expanded and so did the electrical grid, which became larger and larger in area and size. Because of economies of scale, agglomeration of supply companies, and natural contingencies, high-capacity power plants, far from demand and connected to transformers and kilometer-long transmission lines, became the standard worldwide. The adoption of three-phase AC systems, with standardized voltage and frequency values, allowed interconnections to be made between the two world wars. The electrical grids became colossal systems, occupying entire countries, and causing the primordial micro-grids to disappear. Thus, they would resurface in a modern conception only at the turn of the millennium.

Different factors have led to the return of research and development for small electrical grids. One decisive reason was technological progress on different fronts in the electrical sector. The evolution of semiconductors and power electronics converters definitely played a role. The invention of the transistor by Bardeen, Brattain and

Shockley at Bell Laboratories in 1948 and the commercial thyristor by General Electric Company in 1958 and the development of microelectronics in the 1970s and 1980s are some of the defining moments in this trajectory [5]. The advancement of control, automation and communication methods and computing and information technologies in the last 50 years was another crucial element.

However, the expansion in the use of DG in more recent years was the critical condition for the consolidation of modern microgrids. The history of DG over the years will not be detailed here (it can be seen in [6]), but some events should be highlighted. In the 1960s and 1970s, when the electricity sector was dominated by large thermoelectric, hydroelectric, and nuclear power plants, there was substantive progress in the technologies that originated the recent growth of DG, fuel cells [7] and photovoltaic systems [8]. This was mainly due to the US government's investments in the space race, which sought small-scale sources of electricity. At the time, the first tests were made with these generators for electricity production in homes, businesses, and industries.

The turning point in the adoption of DG was the oil crises of the 1970s [9]. In 1973, the Yom Kippur War broke out, between Arabs from Egypt and Syria against Israel. Western support for Israel caused the Arab members of the Organization of the Petroleum Exporting Countries (OPEC) to impose embargoes and cut oil production. The impact was felt throughout the world with a high increase in the price of the product. Already in 1978 and 1979, the Iranian Revolution, and in 1980 and 1981, the war between Iran and Iraq, led to a reduction in the supply of oil and once again nations around the world felt the consequences of its price increase. Faced with threats to energy security in the following years, several countries changed their energy behaviour. Some demanded higher levels of energy efficiency in various sectors, as is the case of Japan and Sweden, others began to increase the share of electricity production by nuclear power plants (France), hydroelectric plants (Norway) and wind power plants (Denmark) and some more, Brazil in particular, invested heavily in biofuels. The United States, in 1978, enacted the *Public Utility Regulatory Policies Act* (PURPA) [10]. This document was a milestone for DG and also for microgrids, as it promoted, for the first time after the transformations throughout the century in the world electrical system, rules that encouraged and allowed the generation and sale of electricity by independent producers with small sources to utilities through connection to distribution systems. All these events paved the way for the expansion of the use of DG and, in the future, of microgrids. In the 1980s and 1990s, DG and renewable technologies saw massive development and started to be adopted worldwide. Figure 3.1 illustrates the relative evolution of electricity production from 2005 to 2022.

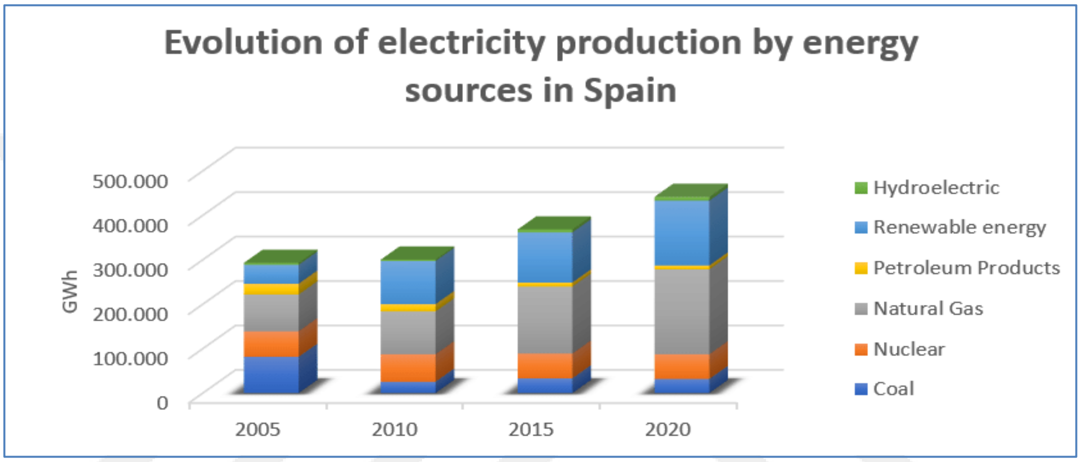

Figure 3.1: Percent electricity production by source, between the years 2005 to 2022.

Another technology that contributed on several fronts to the birth of modern microgrids were *uninterruptible* power supplies (UPS), especially in their distributed forms [12]. The research on the subject and its applications took place mainly in the 1980s and 1990s. Conceptually, UPS systems were the forerunners of microgrids because they were devices that increased reliability by allowing the continuous supply of electricity, working in connection with the grid or separate from it, in case of failure of the grid. In technical terms, microgrids have adopted much of the controls developed for UPS systems, such as their topologies and the methods of inverter parallelism, elements commonly employed with DG sources, and adequate and automatic power sharing. The absence or minimization of communication between inverters is another premise imported by microgrids from UPS systems.

All of this technological progress, together with growing environmental concerns about climate change and pollution, and increasing social demands regarding access to and affordability of electricity, power quality and reliability of electrical systems, made it only a matter of time before modern microgrids appeared. In fact, the term "*microgrid*" and its concept as applied to the power and electricity sectors first appeared, it seems, in a 1986 thesis [13]. The microgrid in this case was a hybrid renewable energy system consisting of a wind turbine, a closed-loop steam turbine (with cogeneration), batteries, and a central controller with control, monitoring and management functions. It was built to supply electricity to AC and DC loads at the INMARSAT remote ground station in Antarctica.

3.2 DEVELOPMENT OF MICRO-GRIDS

Actual research on modern microgrids appears to have begun in the year 2000, with no publications using the concept within power and electricity systems being found until then, with the exception of the 1986 isolated one discussed in the previous section. Despite its topicality, its growth has been rapid and widespread. Project development seems to be following the same trend. With this, this section aims to indicate the direction of micro-grids in relation to the theoretical world of academia and real-world applications, mainly with quantitative and statistical data from the beginning of the 21st century.

The motivations for adopting and building micro-grids are numerous and it is difficult to trace them all, as they can be regional, social, cultural, environmental, economic, and technological advances. The pretexts for remote projects in areas without access to a power grid are more obvious. It is a popular saying that "the electric system is the biggest machine in the world". So one can imagine how extremely expensive it is to build a system as complex as a traditional electrical grid, with its centralized power plants, distribution and transmission lines, transformers, etc., and the long time it takes to do so. Planning and erecting a micro-grid with its small-sized DG technologies is easier, requires little capital and simple transport and installation of the components. In cases where a conventional power grid is already present and operating well, the reasons are less clear. However, the advantages are equally numerous and favour adoption. For [18], there are three categories that stand out most for this situation: energy security, economic benefits, and clean energy integration. In the first, severe weather, cascading failures, and cyber and physical attacks are some of the related motivations, while in the second, savings in infrastructure and fuel costs can be cited, as well as the provision of ancillary services.

Finally, in the third classification, there is a need for greater control over variable and intermittent sources. In addition to these factors, there is a dependency with all the others mentioned above, as is the case in the region. In the United States, for example, reliability and resiliency are more important than in Europe, where environmental concerns, such as climate change, weigh more heavily in the use of microgrids.

Thus, microgrids find applications in different sectors of society. They can be employed for homes, between neighbours in a neighbourhood, in buildings or in horizontal condominiums, as well as in rural communities. Business centres and industries can also take advantage of these technologies. Public buildings, schools, and university campuses are other favourable locations. Places where electricity supply is critical today, such as hospitals, military bases, and *data centres*, are fertile ground for microgrids. In order to address these and other applications, several tests have been done and prototypes built around the world [18]-[20].

In this regard, the number of implemented projects is progressing. According to recent research by Navigant Research [21], by mid-year 2019 there were 4475 projects with installed and planned microgrid power capacities in the world. Of the total 27 GW, the Asia Pacific region stands out with approximately 9.94 GW, followed by North America with about 8.88 GW and the Middle East and Africa with a figure close to 3.63 GW. Percentage-wise, of the regions surveyed, Asia Pacific holds 37%, North America takes 33%, followed by Africa and the Middle East with 14%, Europe with 11%, and Latin America with 5% of the total power capacity in the global market. Navigant Research further divides the projects into the following market segments (with their respective shares in the same period of the first half of 2019 in parentheses): Commercial/Industrial

(36%), Community (4%), Distribution/Concession (8%), Institutional/Campus (6%), Military (5%), Remote (41%), and Direct Current (less than 1%) [22], [23]. It is worth noting that projects are only considered if they have one or more renewable sources and that remote microgrids that are formed only by diesel generators are excluded [18]. In terms of investments [24], it can be seen in Figure 3.2 those revenues have been increasing and significant over time, with a global peak in 2017 of $10.2 billion.

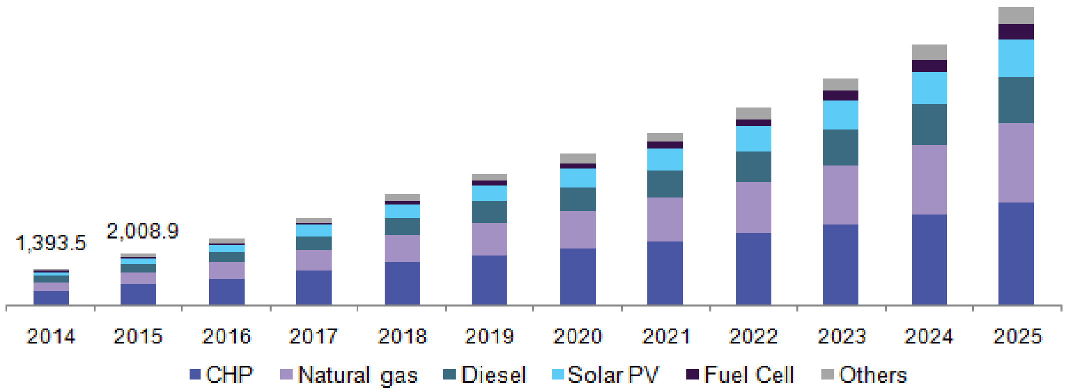

Figure 3.2: Global revenues related to microgrids between 2011 and 2022 (in billion 2018 dollars).

In this section an overview has been given of the development of microgrids in the first two decades of the 21st century. There is a vast effort on the part of researchers to make it feasible to implement them with maximum benefits. Investment in projects is also growing in different sectors of society. However, the question remains to be answered: What exactly are microgrids?

3.3 MICROGRID CONCEPTS

Having explained the origins of microgrids and their recent development, it remains to give them a precise definition. What, in fact, makes a power system a modern microgrid? What properties and concepts determine and relate to microgrids?

First of all, a micro-grid is an electrical grid, but relatively smaller. As such, it must necessarily incorporate in its structure: generation, distribution and consumption of electricity. It is, therefore, an agglomeration of loads and sources of electrical energy locally linked together [14], [19], [25] [28]. From this conception, it can be said that a microgrid must have some essential characteristics. Electricity production must naturally be done by smaller generators than large centralized power plants, i.e., by low- and medium-power DG technologies. Indeed, as seen, one of the explanations for the emergence of modern microgrids was precisely the integration of DG. For similar reasons, the length of distribution lines and the distance between generation and consumption must be small. While the traditional power grid extends continuously, undergoing expansions from time to time to reach more and more loads, microgrids have limited areas and the number of consumers is limited in their occupied region. Not only that, microgrids must be provided with clearly defined electrical boundaries [29].

Despite the spatial constraints of microgrids, they are even more diverse than traditional electrical grids, having arbitrary configurations [30]. As long as it is far from having the large dimensions of conventional electrical systems, a microgrid can have a high range of sizes. Likewise, it is difficult to score maximum and minimum power levels for them. As for the architecture, topology, and equipment layout, microgrid designers can develop their proposals taking into account conditions as varied as local geographical, physical, social, political, legislative, economic, cultural, and environmental. When it comes to the technology employed, the types and the quantity of sources, there are no reservations. So, at least in the case of these properties, as Oscar Wilde wrote, "to define is to limit". It is extremely difficult to delineate them precisely in order to elaborate the concept of a micro-grid. Since diversity of area, capacity, architecture, and technologies is a great benefit of microgrids, they may not be specified in their general definition.

One thing must be clear, however. An electrical system consisting exclusively of a single source of electricity with no access to the grid, commonly called an isolated system, cannot be considered a microgrid, because it does not have a structure similar to electrical grids with distribution from multiple generators providing electricity to multiple consumers. Moreover, in most cases it does not adopt the techniques used in modern micro-grids and differs from micro-grids in that it is sometimes not a fixed and permanent system.

Therefore, only electrical systems that have more than one DG unit can be considered microgrids. This is a highly relevant characteristic. Since almost all DG sources are accompanied by power electronics, parallelism of static converters, power sharing, and setting voltages and frequencies locally are important in the concept of microgrids [16].

When a microgrid is not associated with some pre-existing electrical grid, it can be called an isolated or remote microgrid. If, for whatever reason, it is erected within an electrical system, it must have the fundamental property of operating in two modes: isolated and grid-connected. A system is considered isolated when it produces internally voltage and frequency references by its own controls, dispensing with those generated externally. In grid-connected (or parallel to it) mode, the opposite occurs and the system works following external references, usually coming from a main power grid [31]. This is one of the major differences of microgrids compared to traditional DG use. Standards [32], [33], for operational and safety reasons, prevent DG from operating in islanded mode, which leads to the employment of so-called anti-aliasing techniques and the disconnection of the grid and the complete shutdown of DG. In micro-grids, on the other hand, islanding is intentional and the possibility of exercising it is a must. A remote microgrid, obviously, is permanently in islanded mode. For the power grid, the microgrid is seen as a single locally controllable entity.

The elements discussed so far are basic to the concept of microgrids. There are, however, other properties that are not necessary, but which, if followed, improve the operation of microgrids.

One is that they must be reliable and flexible. For this, islanding must occur whenever necessary, and loads must be powered most of the time. Their components, in turn, should preferably have two attributes. The first is called "*Peer-to-peer"*, which indicates that there are no critical elements for the operation of the micro-grid, all having the same importance, and that the lack of any of them does not affect its overall operation. The second is "*plug-and-play"*, which is related to the possibility of connecting the generation at any point of the system and at any time, without modifying the controls and general protections of the micro-grid [34].

Another interesting condition for microgrids is that they should be intelligent [35][37]. Such a particularity brings together different factors. It indicates that the microgrid aggregates innovative technologies. It also points out that it works with modern control methods and even artificial intelligence, being able to quickly detect situations for islanding, make smooth transfers between modes, synchronize with the grid, improve power quality indices, provide ancillary services, optimize processes, have active participations in electricity markets, and reduce pollution. All done, primarily, in an automated way.

As far as the purely electrical characteristics are concerned, microgrids are varied. They can be single-phase or three-phase. If they can be connected to a main electrical grid, this can be of low or medium voltage [19]. They can also be DC, AC or have parts of both, in which case they are called hybrids [37].

In the installations of a microgrid it is possible that it is designed to feed not only electrical loads, but also thermal loads, with cogeneration techniques (CHP - *Combined Heat and Power*) [34]. Due to the reduced distance between production and consumption, the waste heat from certain DG units can be reused, either to increase the efficiency of the system itself, or to be used in other equipment and processes in the micro-grid environment.

In short, a microgrid is a unique (mandatorily encompassing production, transmission, and consumption of electricity) and locally controlled small electrical grid that can work in islanded and connected modes to the main grid (if it exists together). It must consist of multiple small or medium-sized DG units operating in parallel to supply power to loads over distribution lines in limited physical areas with clear electrical boundaries. There are no exact restrictions on size, location, architecture, technologies employed, or electrical characteristics, and there is a high diversity of possible microgrid configurations that depend on elements as diverse as site geography, social and political decisions, economic factors, etc. It can include cogeneration in its structure. Finally, it is desirable that microgrids are fully controllable, reliable, flexible, and intelligent.

3.4 MICRO-GRID COMPONENTS

Microgrids are fundamentally composed of power production units connected to converters and loads, but they can have elements that make operation enhanced. Among these are energy storage, cogeneration, and protection. This section addresses each of these components, dealing with their competencies and relevance in the operation of microgrids.

3.4.1 Distributed Generation and Micro-Grids

Electricity generation in a microgrid is realized almost exclusively by DG and the development of the two systems is strictly related. For some authors, a DG source is defined as the electricity production technology connected directly to the distribution network or on the consumer's metering side [38]. DG can still be considered as the sources of powers less than 10 MW [39]. a distinction is made between distributed microgeneration and distributed mini-generation. The former is formed by electricity generation units (renewable and qualified cogeneration) with a capacity of less than 75 kW connected to distribution, while the latter is summarized to powers of 75 kW up to 3 MW for hydro sources and up to 5 MW for qualified cogeneration and remaining renewable sources [40], [41]. The definition employed in the present work considers that a DG source is any electric power generation apparatus that can be easily installed in a wide range of geographical and physical locations, no matter where it is connected, whether in transmission, distribution or consumption itself, and of the size, being distributed throughout the power grid or even isolated [6].

Regardless of the definition taken, small and medium power DG clearly qualifies as the main production device for micro-grids. With recent advances, the list of DG devices is vast. Some sources and technologies that serve for microgrids can be pointed out [42], [43]. Photovoltaic systems, which directly transform sunlight into electricity, and wind turbines, which produce electricity from wind forces, are two renewable sources of DG for microgrids. Fuel cells, which convert chemical energy into electricity continuously with low greenhouse gas emissions and high efficiency, are applicable. The transformation of river water movement into electricity by small hydroelectric plants is another case in point. Finally, bioenergy and small thermal generators associated with reciprocating machines, gas or combustion turbines and microturbines are examples for use in microgrids.

In addition to the production of active power, DG can bring several benefits to any electrical system in which it is interconnected and, consequently, to micro-grids. Among the various potential benefits of DG can be cited are improved power quality, voltage regulation, reduced losses in distribution lines, grid support, expansion and avoided costs of the overall power system, and reduced power flow in transmission leading to lower chances of instability [44], [45]. However, such additional positive results will only be realized if the integration of DG is done properly.

This is because in circumstances where DG is installed only for energy production without developing its full potential, it can lead to new problems. DG can worsen voltage regulation and increase losses, raise the levels of *flicker*, harmonic distortion and voltage variations, modify the short-circuit level and interfere with protection devices causing them to act erroneously [46], [47]. In the face of the potential benefits presented, some of the difficulties seem even paradoxical and conflicting. This fact further elucidates the importance of a correct integration of DG. Thus, the microgrid has emerged as an innovative solution for integrating DG that allows maximizing its benefits and minimizing its negative impacts, besides granting it new positive capabilities.

3.4.2 Power Electronics

Power electronics converters, which bring together electronics, power, and control for efficient conversion of electrical energy, play a major role in modern microgrids.

Without them, the operation and control of micro-grids would be impractical, because they perform indispensable functions.

Most DG technologies interface with some kind of static converter [48], [49]. Its primary assignment is to match the output of the DG to the system where it will be connected. Generally, there is incompatibility of voltage and frequency levels, waveforms and current between the output of the DG technology and the loads. For the correct supply of electricity, converters act on the voltage, current, and power of the sources to deliver it in the proper form. In the case of the electrical grid, standards determine the operating conditions in AC voltage sine waves with limits on amplitude and frequency. With this flexibility coming from the converters, a wide range of possibilities opens up for designing micro-grids that are suitable for the special needs of each consumer, with voltage and frequency values and AC or DC conditions no longer being so rigid.

Some examples illustrate these facts. Photovoltaic systems produce DC power and it can be advantageous or even mandatory to use them with a DC-DC converter and/or an inverter [50]. The former allows controlling the voltage as desired and maximizing power production with maximum *power* point tracking (MPPT) methods [51], while the latter allows integration to AC systems and microgrids and synchronization. Similar procedures and equipment are applicable to fuel cells [52]. More advanced wind turbines, on the other hand, may have one or more converters in their composition, which increase speed control, provide mastery over reactive supply, and smooth starts [53]. Even small hydroelectric plants employ power electronics, as they are more susceptible to sudden variations in water velocity than traditional large hydroelectric plants and need greater control over output [54]. The use of rectifiers and inverters with microturbines is mainly related to maintaining the output frequency, since the production takes place at speeds of 50,000 RPM up to 120,000 RPM [55].

It is clear how significant the adoption of the converters is. The potential benefits of DG, of paramount importance for the operation of micro-grids, can be easily realized with power electronics. Indeed, some of the advantages of converters for DG and for microgrids in general can be listed, such as improved power quality with reactive support and harmonic control, improved protection coordination, interoperability between different DG sources, and use of static switches for interconnection and fast transfer between microgrid and grid [56].

Particularly in modern microgrids, control is done entirely based on power electronics. Their operation is based on inverter parallelism and load sharing [57]. The synchronization and connection of the microgrid to the main electrical grid is also performed by inverters.

3.4.3 Energy Storage and Micro-Grids

Often, the production and consumption of electricity do not occur simultaneously and at the same level. However, electricity is a physical entity that must be used immediately after it is produced and cannot be directly stored. Energy storage serves, then, to store the generated electricity in another form of energy, postponing its use. For this, there are many options available on the market. Some of these are batteries, supercapacitors, *flywheels,* compressed air storage, and pumped or reversible hydroelectric power plants [58]. The technical advantages of using energy storage are also quite numerous. Its technologies can provide voltage and frequency support to the microgrid, serve as a *spinning reserve*, compensate for load imbalance, improve power quality, and participate in *fault ride-through* [59]. All of these improve the performance of microgrids, but there are features that are even more interesting.

In islanded microgrids, especially those that are remote and composed of variable and intermittent DG sources such as solar PV and wind, energy storage is a substantial player in the operation. In this situation, it will increase the reliability of the microgrid [20]. It will, on the one hand, assist in the continuity of the energy balance when production and consumption are not in balance and, on the other hand, it can maintain the supply of sensitive loads for a certain time when fuel runs out or climate changes stop generation.

Some control methods work correctly and are stable only if the source on which they are applied is dispatchable. That is, the availability of electrical power must be continuous and practically constant. With adequate energy storage, this can be done at least in a time interval sufficient for normal operation.

3.4.4 Cogeneration

Cogeneration (CG), in particular small-scale, micro-cogeneration, which recovers heat exhausted by certain DG sources, such as small thermal generators, bioenergy and fuel cells, can be an additional item of a microgrid to increase its efficiency and improve the conditions of its members by also providing heat sources [34].

For DG technologies that start to integrate cogeneration, thermal efficiency can jump from about 40% to approximately 70% and even 90%, this being the maximum case for large installations. Cogeneration is a consequence of electricity generation and should always be related to it with regard to the amount of heat produced. There is, however, a close correlation between electricity and heat consumption, as occurs in industries and countries with cold climates in winter. There is also a strong dependence of cogeneration on heat demand. In industries, for example, the demand for heat can be constant, but in residential environments it will depend on climatic conditions, location and the time of day and year [43]. In the design of the micro-grid with cogeneration, one should therefore pay attention to the variations in production and consumption of electricity and the thermal needs.

One factor worth noting here is the optimal placement in microgrids for cogeneration. The distribution of heat is more complex and can have higher losses than that of electricity. For this reason, in certain microgrid projects, the proximity between DG units with cogeneration and the heat consumption hotspots should be prioritized over the distribution of power to electrical loads.

3.4.5 Loads and Micro-Grids

The micro-grids should feed any type of loads in islanded or grid-connected modes, seeking to maintain satisfactory levels of power quality, reliability and stability. The loads can be passive, such as units or sets of fixed or variable resistive, inductive and capacitive loads, motors and nonlinear electronic devices.

As in any electrical system, generation and load must be in balance at the same time. In view of this and within the new possibilities of microgrids, the loads can be classified by priority of work in sensitive and non-sensitive with different control plans [28]. Those in the first category are generally those whose operation is critical and must be continuously supplied with electricity, such as hospital appliances, public and emergency lighting, among others, while those in the second category can be those whose disconnection does not affect too much the members of the microgrid. This division, however, is not strict. This is due to the more versatile dynamics of the microgrid. Classes can be segregated by project or through contracts. Thus, *load shedding* or load *curtailment* can be allowed, with complete or reduced supply of non-sensitive loads. Micro-grids should precede sensitive loads.

These situations are more relevant when the micro-grid is in islanded mode to conserve its energy balance and stability. The production can be insufficient in certain cases or the control over loads can be done for economic and environmental reasons, reducing costs, fuel use, pollution, and greenhouse gas emissions. When the microgrid is connected to the electrical grid, the lack of power from the DG sources installed there can be supplied by it, and no load needs to be harmed.

In this sense, microgrid loads can also be supported with Demand *Side Management* (DSM) techniques [17]. DSM methods allow loads to be controlled in real time, locally or remotely, reducing consumption and increasing efficiency, or economic incentives to be provided via fluctuating energy prices in order to modify consumption patterns. In any case, the application of

DSM can be accompanied by different approaches that can help its effects, such as encouraging the use of appliances with higher efficiency, changes in user habits, energy education, operation with *smart* meters, and direct control of device charging

3.4.6 Protection of Micro-Grids

Protection systems for microgrids differ substantially from those normally used in traditional electrical networks. As the possibilities for microgrid designs are numerous, so are their specificities [60]. The number and type of DG units and loads, in addition to their arrangements, are quite varied and, by themselves, would already be a problem in the choice and acquisition of protection for the microgrid. However, the major difficulties arise from the operation, control, and dynamics of microgrids.

The first point of divergence between conventional and microgrid protection is in the presence of bidirectional power flows arising from the use of DG sources and their production changes over time with load changes and by the very variable and intermittent nature of some of them. Such effects did not previously exist in the power system and thus their protection devices were designed for unidirectional flows and radial configurations. Therefore, applying them to microgrids could cause hindrances such as spurious separations of the microgrid with the grid, leading to unintentional islanding, false opening of switches of the internal elements of the microgrid, and protection coordination problems [61].

The second difference in the protection of the micro-grid lies in the fact that it can have two modes of operation, the isolated and the grid-connected, with transition between them, which inevitably transforms the working conditions of the protection devices. In the first case, in addition to the voltage and frequency levels that may be outside the acceptable levels set by the norms of the distribution systems, requiring different ranges of operation of the protection devices, the shortcircuit level is much lower than what is commonly found in the conventional electrical grid and can be expected in grid-connected mode. Added to this is the limitation in the fault current capability of the converters that are present in the vast majority of DG units for micro-grids. Not being designed to provide high short-circuit currents, they may produce them only on the order of 1.5 times their rated currents [62]. Overcurrent relays and fuses will not be able to act and be sensitized quickly enough to provide the necessary protection. Therefore, new protection methods must be adopted in order to circumvent the dynamics in the magnitude of the fault currents.

Another protection requirement for the microgrid is the inclusion of protection devices at strategic points, such as at the connection between the microgrid and the grid itself, at each of the DG sources and at certain loads with respect to priority levels. In this way, internal faults can be isolated and loads can be contingent to continue the operation of the micro-grid with minimal losses. It will be able to safely make transitions between operating modes, avoiding faults or disturbances in the grid, safeguarding the grid from disturbances and making resynchronization and reconnection in a timely manner [60]. For these reasons, the protection logic should be part of the control strategies of the microgrid itself.

In view of all these difficulties, several new protection schemes are proposed especially for microgrids [63]. Among the possibilities, such as centralized, variable-based, distance, multi-agent and current limiting protections, the adaptive method should be highlighted. Because of the microgrid's own dynamics of constant changes over time and its changing modes of operation, the response of the protection must change and work well for each situation. Adaptive protection meets these requirements, despite the higher implementation cost.

Equally interesting for protecting the microgrid, and even indispensable for some techniques, is the use of communication between the devices. By doing this, the system can act slightly for each event. Nevertheless, whether for this or another function, the exchange of information, which may be paramount to the operation of a given microgrid, may suffer threats from cyber-attacks, thus giving rise to other types of protection problems that must be carefully analyzed [61].

3.5 MICROGRID CONTROLS

Despite raising the benefits for society and the environment, the reduction of electrical grids into microgrids makes the electrical system more complex. In a small space it is necessary to manage power distribution between DG units and connect them in parallel, switch smoothly between islanded and grid-connected modes, exchange information, make the system more efficient, do the proper protection, charge and discharge energy storage at the right times, maintain the balance between production and consumption, minimize environmental impacts, enable economic transactions between users and the electricity market, etc. As if the long list of tasks to be accomplished inside a micro-grid were not enough, all the processes must be automated, flexible, secure, and reliable. In the absence of operators and specialists to constantly monitor and supervise these various movements in each of the micro-grids, the vast majority of procedures are carried out with artificial intelligence by microprocessors, computers, and digital systems. For all these reasons, control is the essence of the modern microgrid.

Over the years numerous control techniques have been developed, but they can be basically classified into centralized and distributed (or decentralized) [30]. In the fully centralized control, the microgrid has a central controller that exchanges data via communication with each unit, whether of DG, energy storage or load, makes calculations and decides how each one will work. The central controller can be a separate device or be associated with some component of the microgrid. In fully distributed controls, the components of the micro-grid rely only on local measurements and controls, and in some cases may even work without any communication. The limits between the classifications are not rigid and there may be controls that are in between the two, taking advantage more or less of the attributes of each, which will depend only on gradation and even interpretation. In other words, in some micro-grids that are strongly controlled by a central controller, local measurements and calculations can be interesting. The same is true on the other side, where a central controller and communication can be added, but are not indispensable in the operation. Figure 3.4 illustrates the two types of microgrid control. In general, the control variables in microgrids are voltage, frequency, active and reactive power for the AC case, and voltage and current or output power for the DC case.

Some examples perhaps shed more light on the two categories of control. In [64] a microgrid central control system is presented that governs all the actions of the DG units and the loads to define how the internal power flow will be and with an external grid, optimizing and maximizing production with participation in the energy market through mathematical formulations computed by it. Another example is given in [25]. In it, a central controller installed in a substation issues set points with control and generation profiles for the components of the microgrid. Furthermore, a master-slave system is applied, such that one or more master converter units provide the voltage references for the others under its command. A very popular fully distributed control model is the *droop* control method [57]. In an islanded AC microgrid, each inverter unit is responsible for local voltage and current measurements. From these data, the active and reactive powers they are producing are calculated. These values are employed in *droop* equations, which relate active power to frequency and reactive power to voltage, and are used to define the voltage waveform generated by the respective converter. This is how the proper sharing of power and parallelism of the inverters is achieved, without any communication between the units and with any central manager.

This last control will be discussed in more detail in the following chapters.

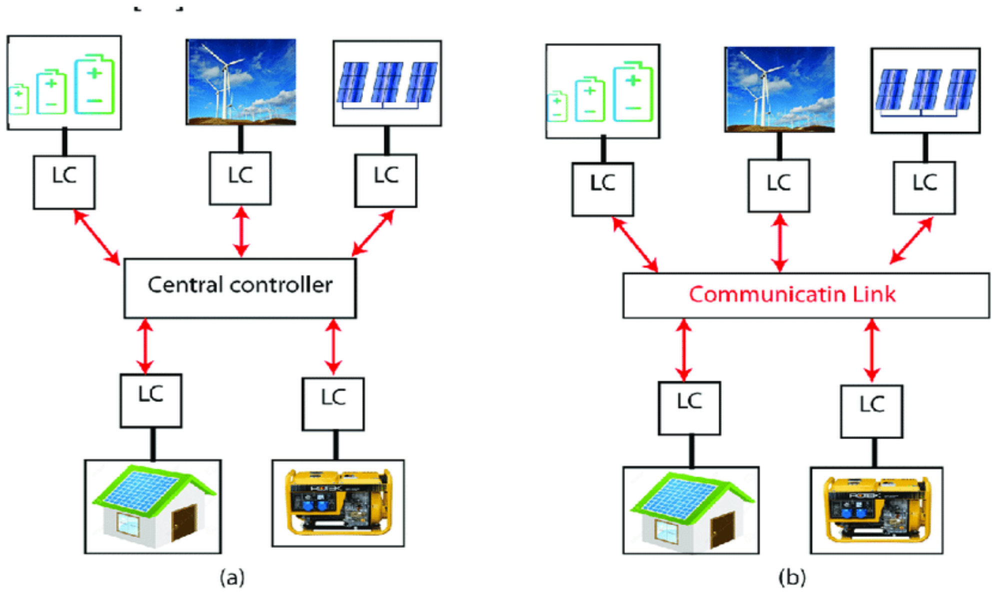

Figure 3.3: Control strategies for microgrids: (a) fully centralized; (b) fully distributed.

To overcome the difficulties and limitations inherent in the operation of AC and DC microgrids, hierarchical control has been proposed [26]. In this approach, the control of the microgrid is divided into overlapping levels. The zero level comprises the internal current and voltage control loops of the converters. It is an inherent part of the converters and is therefore sometimes not considered within the hierarchical perspective. The primary control determines the fundamental control of the microgrid in islanded mode, the internal power sharing and the parallelism of the converters, and the *droop* control method is often used. The secondary control operates in restoring the voltage and frequency parameters (the latter only in the AC case), correcting their deviations from the primary control to nominal values. Finally, the tertiary control works on the synchronization and connection of the micro-grid with the utility's electrical grid and/or with other micro-grids, besides controlling the power flow between them. It also incorporates ancillary services, power quality, economic, and environmental aspects.

The control functions of the converters in an AC microgrid, in turn, can be separated into three: grid-forming, grid-feeding, and grid-supporting [27, 28]. Converters of the first type (Figure 3.5 (a)) are tasked with setting the voltage amplitude and frequency of the microgrid. They are usually connected to dispatchable DG sources (fuel cells, small hydro, microturbines, etc.) and it is thanks to them that islanded mode operation can be performed. They operate as an ideal voltage source. In the second function (Figure 3.5 (b)), the converters use voltage and frequency references from the grid-forming units to export power to the microgrid. They are commonly established with renewable DG technologies, such as photovoltaics and wind turbines, given variable and intermittent operation and control via MPPT systems. They can be represented as ideal current sources. Converters with the last of the functions (Figure 3.5 (c)) have their outputs controlled to keep the voltage magnitude and frequency in the microgrid close to nominal values by making their settings. They are symbolized as voltage or current sources.

For energy storage used in microgrids, the controls are also more sophisticated than those traditionally used. These devices, like DG, need to do power sharing without damage to the microgrids and their components. Additionally, however, their specific characteristics of bidirectional flow, load state, direct work with variable and intermittent renewable sources, and possible risks require special controls that coordinate and maintain the balance in the energy balance automatically and efficiently, minimally affecting their lifetime. To this end, [65] points out three control strategies for energy storage applied to microgrids: decentralized, centralized, and distributed multi-agent. In the first, each unit works from its locally collected information without any communication with the others. The modified *droop* control method to handle load state is one possibility. Unlike its application in DG, it does not prove as effective here because of the difficulties of accessing certain data from these devices. In centralized control, a central controller, by acquiring load state and available power estimates from the energy storage units, determines the optimal dispatch and receipt of energy from each one. This strategy can suffer from monitoring, communication, and data processing problems, especially if the microgrid has several small energy storage units. The third and final control method makes the devices autonomous agents that take advantage of local measurements and communication only between neighbors to achieve overall goals. It performs well, is robust and flexible, making it a strong trend for use in microgrids for energy storage.

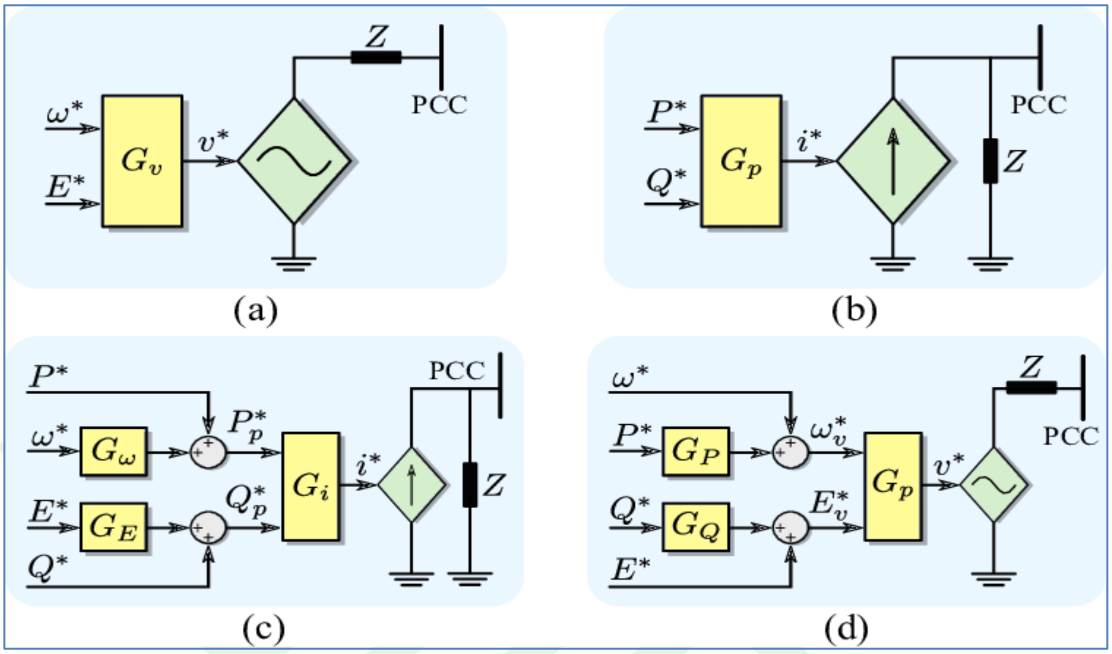

Figure 3.4: Control functions of converters in AC micro-grids: (a) gridforming; (b) grid-feeding; (c) grid-supporting; (d) grid connected.

Since a microgrid encompasses not only power sharing, its improved operation depends on supervision and management. The control system must deal with very broad issues, such as power quality, ancillary services, energy markets, process optimization, and environmental considerations. Supervisory controllers and energy management systems are thus important tools that should be added to any microgrid. These controls should be multi-objective, interdisciplinary, and intelligent [66]. In terms of structure, they can be centralized or distributed, and a trade-off between reliability, flexibility, costs, security and efficiency, determination of their advantages and disadvantages, and the anticipated situation of the microgrid underpins the appropriate choice of methods. Moreover, different time scales and uncertainties are some of the points to be addressed in these controls. Therefore, techniques as varied as genetic algorithms, linear and non-linear programming for optimization, rule-based systems, *machine learning*, and multi-agent systems have been applied to circumvent the problems of supervision and energy management in microgrids.

In the not so distant future, when the number of micro-grids is high and they work together in their neighborhoods, control will be needed for the operation of multiple micro-grids connected together. Clearly the complexity will be increased further. Designing controls for micro-grids that coordinate internal operation with transfers and energy markets with other micro-grids while maintaining stability, optimization and reliability is an undertaking that needs further study and research. The present work does not cover such a control.

The control for connecting a micro-grid to the electrical grid is another topic that requires special attention. For the two systems to operate together, they must necessarily be synchronized in amplitude, phase, and frequency. The DG units of the microgrid will have their controls conditioned by the grid and will obey the limits of its standards. Only then should the interconnection switch be closed. When they are working in parallel, power flow and other functionalities, from those of power quality to economic and environmental ones, should be established between the microgrid and the grid. The problems and their solutions on this subject are discussed and analyzed in detail in the third chapter.

The central focus of this work is the control of microgrids and their components in their two modes of operation. Therefore, the controls for the isolated mode, mainly the primary one, and those for synchronization and connection of the micro-grid with a conventional electrical grid will be studied in more detail in the following chapters.

3.6 MICROGRID ARCHITECTURES

In view of all that has been said so far, a brief discussion can elucidate the innovative characteristics of microgrid architectures. Traditional electrical systems are extremely rigid in terms of structure. They are formed, always in this vertical order, by generation, transmission, distribution and consumption of electricity. The production of electricity is invariably a plant of enormous proportions and capacity, working far from the large load centers for which they are built. Until recently, there were only three options for this: thermal power plants powered by coal, oil or natural gas, hydroelectric power plants, and nuclear power plants. All of them consist of large rotating electrical machines. The sheer size, construction time, capital required, and negative environmental impacts, such as air pollution and deforestation, made generation unchangeable and incapable of rapid adaptation. The transmission and distribution systems, mediated by transformers, have also kept their components and designs practically intact. The former, with its kilometer-long cables and support towers, operates at high voltages connecting generation to the distribution system which, in turn, is passive and serves only to complete the electricity supply process. All this is subordinated to the three-phase AC sine wave system.

Microgrids, on the other hand, go through a completely opposite path. In fact, one of the great advantages of microgrids is their diversity in design and construction. To begin with, there are many choices of DG sources and energy storage devices. As seen, the former can run on sunlight, wind, water forces, hydrogen, and biomass. With different sizes of DG units, varying power values can be established. Moreover, most are modular and allow for multiple source arrangements. The latter are mostly batteries that exist in different technologies and sizes and can be connected in series and parallel to obtain multiple energy storage possibilities. Clearly, new opportunities for generation are opened up by micro-grids.

The recurrent use of power electronics as the interface of DG and energy storage is another item that expands the plurality of microgrids, especially with regard to electrical specifications. It is by static converters that one can connect DG technologies with completely different behaviors and make a uniform and reliable operation. It is also with them that micro-grids of heterogeneous electrical nature are created. As already commented, microgrids can be AC, DC, or hybrid, single phase or three-phase, and have different voltage and frequency levels, both between and within them. By determining the boundaries well, power electronics makes the different electrical characteristics of the components compatible and offers different working conditions.

Consequently, microgrids also allow for different sizes, structures, and topologies. Microgrids can range in size from one block to a neighborhood. Obviously, they will not be large enough to characterize an entire city and lose their essence of being a relatively small electrical system, but it is difficult to say what areas they can occupy and what power ranges they can cover. The infrastructure of the micro-grid is equally diverse, as it depends on the chosen installation site, which is, in turn, very large. The network can be aerial or underground. As for the arrangements of microgrids, they can be radial or meshed [67]. A radial microgrid (Figure 3.6 (a)) is one in which all feeders are connected to each other through a single busbar or node. A meshed microgrid (Figure 3.6 (b)), on the other hand, is one in which feeders are connected by more than one bus. According to [36], the vast majority of research on microgrids has focused on the radial configuration. Such a choice is understandable. Due to the inherent complexity of micro-grids, power flow studies, protection schemes and distributed controls in meshed structures are more arduous to implement and involve more laborious mathematical development. Add to this the fact that radial systems are the most common in distribution and rural installations.

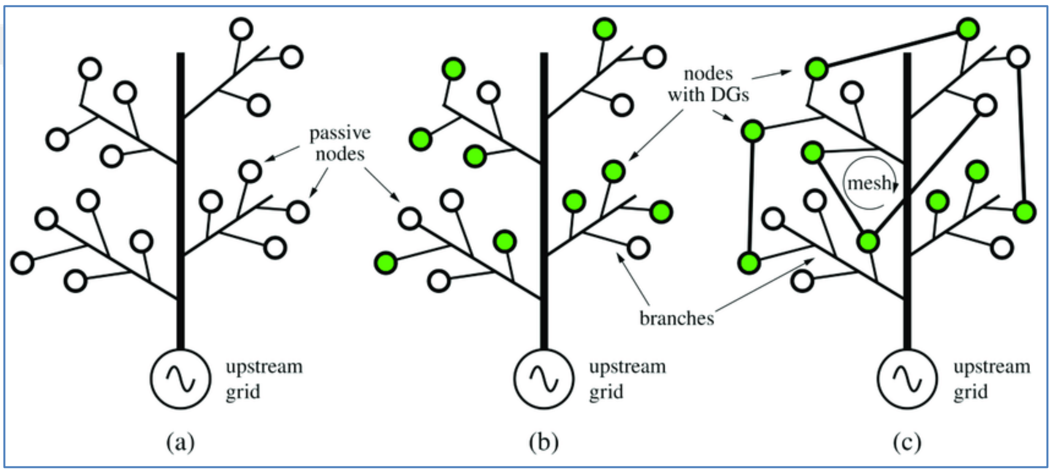

Figure 3.5: Examples of microgrid structures: (a) radial; (b) meshed; (c) tree.

Still in dissonance with traditional electrical grids, micro-grids have temporary changes in their architecture more frequently. It should be remembered, primarily, the possibility of working in two modes: islanded and grid-connected. On the generation and energy storage side, changes occur by reforming the system, expanding it, or just to improve the operation of the microgrid in real time. Since the devices are mostly modular, small, and *plug-and-play*, it is easier and simpler to restructure a microgrid than a conventional power grid. Something similar can be concluded for the load side, where modern load *shedding* and DSM techniques are adopted, which constantly modify the organization of the microgrid.

The consequences of all this diversity is an extremely versatile micro-grid architecture. Electricity systems will not just be designed by governments and large corporations from the top down. Instead, it is possible for local groups to have greater power and participation over these choices. With micro-grids, users will have generation and distribution for their loads according to their needs, wishes and geographical, economic, cultural, social and environmental conditions. In urban centers, there may be micro-grids consisting of microturbines and photovoltaic systems connected to underground grids shared by neighbors in a neighborhood. In natural extremes, such as deserts and forests, microgrids could be built taking advantage of available resources, such as sunlight, but also advanced fuel cell and battery technologies. In rural communities where rivers and biomass are accessible, highly sustainable micro-grids can be built. Islands, remote places, regions where electricity has never been accessible, etc. There are no physical barriers for those favored by micro-grids. They can be designed for schools, condominiums, industries, *shopping centers,* residential buildings, sports centers, and more. If the noises of spinning machines bother the participants of a micro-grid, other DG units can be selected. If the used DG is found to pollute, it can be replaced. If economic resources are not sufficient initially, in the future the microgrid can be expanded with the addition of DG or energy storage.

Despite the benefit of the diversity of microgrid architectures, it does cause some difficulties. In this direction, perhaps one of the biggest is with regard to the development and enforcement of appropriate standards. The conventional electrical system, by proving to be quite inflexible over time, has allowed for the easy creation of devices and guidelines that regulate operation while maintaining high levels of power quality, reliability, and safety for its consumers. With plurality at the core of micro-grids, the regulatory impasse is covered. In the next section this issue is addressed.

3.7 MICROGRID STANDARDS

Because modern microgrids are a relatively new technology and because of the abundance of architectural options available, there remain many obstacles to consolidating rules to support and enable their operation. In addition, many micro-grids will have to work under special conditions different from those of the traditional electrical system. Nevertheless, it is essential that regulations are created and put into practice. Without them, it can become dangerous for people, animals, nature and electrical appliances to use micro-grids if they are implemented improperly.

Regardless of the microgrid, there are minimum technical requirements that are universal. The first and unconditional is safety. Protection devices must be sensitized and acted upon quickly. It is important to take special care with the generation that is now closest to the consumers. Overcurrents and overvoltages need to be avoided for extended periods and may only occur transiently. If the controls fail, operational alternatives have to come into play to ensure the continued operation of the micro-grid, or its complete shutdown if necessary. Also in this sense, synchronization, connection and disconnection between a microgrid and an external power grid or between microgrids will only be done smoothly, without affecting either system severely. In islanded operation, minimum and maximum voltage, frequency, and power levels should be recommended so that the equipment of the members of a microgrid is not damaged. Maintaining high reliability is another point to consider. It is also essential to draw up limits for pollution and other negative effects on the environment, animals, and humans that are on the perimeters of a microgrid. Apart from this, micro-grids will be subject to the requirements of government legislation in their different spheres.

For these reasons, there are as yet few standards, regulations, guidelines, and laws in force that deal exclusively with microgrids and their particularities. They are either too recent to talk in detail about their effects, or they are still in the process of being debated and have not yet come into effect. In this thesis, only the main protocols and technical standards known are cited for broad information and understanding of the subject, but none of them are discussed in much detail.

As can be seen, among the few publications, most serve as a basis for conducting design, planning, controls, and operation specifications for microgrids, rather than for imposing strict principles. This is clearly a consequence of the difficulties already listed with the adoption of micro-grids. There are also, due to similar situations, doubts about the role of microgrids, their operation and controls over their own power quality and that of the electric systems they are interconnected to, and the provision of ancillary services.

3.8 POWER QUALITY OF MICRO-GRIDS

Power quality refers to the working characteristics of any given electrical system. It can be understood as the combination of voltage and current qualities. The first is related to the effects of the supply voltage on the loads, while the second deals with the implications of the load currents on the rest of the system where they are connected. In both cases, the interest lies in the search for the correction of anomalies of what is defined as ideal for the electrical system in question [74]. Thus, the studies and efforts made in the area of power quality are to solve its problems, which consist of deviations in voltage, current (in magnitude and waveform) and frequency that adversely affect electrical equipment. Its main phenomena involved are transients, harmonic distortions, short and long duration voltage variations (sags, swells and interruptions) and frequency variations, unbalances and fluctuations [75]. Sometimes, power quality is also divided into product and service qualities. In the latter, the concern is over the quantity, frequency and time interval of interruptions, i.e. reliability. All other disturbances are the responsibility of the former. The microgrids, with their operational peculiarities, bring new challenges in the field of power quality, especially when it comes to the uniqueness of the two modes of operation, islanded and grid connected. It is necessary to understand not only the internal power quality of a microgrid, but also the impact, either positive or negative, that it has on the power quality of other electric systems and microgrids when interconnected to them.

In grid-connected mode, the power quality procedures are similar to what is routinely done with DG and other devices connected to the conventional electrical system. The components of the micro-grid and the grid as a whole must meet the conditions and limits imposed by utilities, regulators, and operators through the standards of each region. Some examples can be given. The micro-grid is connected to the distribution system, it should follow what is indicated in the

This is not to say that micro-grids connected to the grid cannot work in special regimes. As long as they do not impair the normal operation of the system to which they are connected, it will be extremely beneficial to take advantage of their controls and functions to improve the overall operation beyond the exchange of active power. One way to do this is through the provision of ancillary services by the microgrids [62]. In addition to active power, the microgrid can inject and support reactive power into the grid in a controlled manner. This is a great advantage, as it allows the local distribution voltage to be regulated within its thresholds smoothly and quickly, which can improve the power supply for consumers, reduce losses, postpone investments such as capacitor bank installation, and maximize the useful electricity generation capacity of utility plants. Microgrids can serve in the availability of power reserves to maintain the energy balance when any contingencies occur. They can also assist in load following, partial and full *black-start*, and grid stability. To expand participation in ancillary services by micro-grids, economic incentives need to be created in the form of markets for selling and buying ancillary services instead of paying or offering credits exclusively for active power. Contracts can be designated between owners of micro-grids and distribution networks for this purpose and control can be done automatically depending on the conditions of the power system or via commands by external operators.

The biggest difficulty of micro-grids with respect to power quality and reliability is in the operation in islanded mode. There are two reasons. The first is that for this mode there are no standards for precise and clear regulation with performance indicators. The second, which adds to the first, is in the enormous plurality of microgrid architectures, as previously discussed. Due to the atypical conditions and their particularities, it will be complicated to draw up guidelines that encompass all micro-grids. However, some points should be considered universally. Because they work in special situations that are different from those of the conventional electricity system, the performance indicators cannot be as rigid as before. If the limits are too strict, it may be that certain controls or operation maneuvers are not available in the microgrid. One of them is the already mentioned *droop* control method. Its working principle is precisely in the purposeful deviations of voltage amplitude and frequency in the permanent regime, when there is no secondary control, and transients, in any case, so that proper sharing of power and parallelism of converters can be done. The more frequent load rejections and contingencies also change the scenario in terms of power quality. Therefore, for these and other procedures, it is advantageous to extend the limits for microgrids [78]. Making the system economical is another aspect to be raised in the definition of the indicators. It should be pointed out that the internal load variations of the microgrid will be more abrupt in relation to the total power, which can lead to greater oscillations in voltage and frequency, and that the short-circuit levels are small. The very possibility of islanded operation brings greater reliability. However, for users of the microgrid, internal reliability and quality of service indices and respective penalties can be developed for the islanded mode depending on applications and supply priorities [7].

Thus, the power quality performance indicators of a microgrid may be based on conventional standards and should embrace them in the connected mode, but should meet the specifics of each one in the islanded mode. The limits will depend on the loads installed in the micro-grids, but it is essential that, as in any other power grid, failures occur minimally and the safety of equipment, people and animals, the stability of the system, and the balance between generation and consumption are maintained.

3.9 SMART GRIDS AND MICROGRIDS

*Smart gr*ids are the new model for the electricity system. They are its transformation, incorporating a wealth of innovative communication, control, information and digitalization technologies, in addition to the advanced devices and methods of the electricity industry. Not only that. Smart power grids tend to be structures that carry decentralized intelligence with the ability for their components to solve problems locally, automatically, and in a coordinated way with information exchange between them. Because they correct errors and operate with little supervision, they can be considered "self-regulating" and "self-regenerating" systems made up of "*plug-and-play"* elements that work by constantly updating operational parameters and requirements [80]. Smart electricity grids must be able, through bidirectional flows of electricity and data, to monitor the entire operation by continuously analyzing generators and loads, and to "enable near-instantaneous balancing between supply and demand at the device level" [8].

For all that has been discussed in this chapter and now presented, it is clear the close relationship between *smart microgrids* and smart electricity grids. Much of what lies at the core of the latter is found in the concepts, components, controls, and architectures of the former. Smart grids are not another electricity system, built from scratch, but rather an evolution of the existing one. The first transformations in this sense will certainly be in distribution, where failures are most frequently found. Therefore, with the development of technology and its expansion, smart electricity grids will tend to be the integration of various smart micro-grids, which will be connected by communication channels and with power flows between them [82]. One way to accomplish this is by the hierarchical perspective. It can be employed in clusters of multiple smart micro-grids with the appropriate change in scale of the hierarchy, i.e. with the tertiary of the micro-grids working as a primary control of the cluster and so on [26].

Equally important to note is that the electrical power distribution network was designed as a passive system and should, with the integration of micro-grids and their elements, become an active system [83]. In other words, the distribution was built to initially only receive externally produced electricity. If costs are to be reduced and overall performance improved, the "*fit-and-forget*" methodology should be dropped. Along these lines, more might have to be invested in connecting the new devices than in the traditional network, because without the proper conditions, they can worsen performance on a large scale. All the controls and functions of microgrids should be leveraged, making use of active management of the grid with power quality improvement and participation in ancillary services, in order to maximize work, improve overall operation, reduce dependence on large conventional sources that are highly polluting and environmentally degrading, and minimize costs. Table 3.1 shows typical structures of traditional and smart electricity grids.

Table 3.1: Difference between conventional and smart grids.

Conventional grid	Smart grid
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

3.10 MICRO-GRID BENEFITS, CHALLENGES AND TRENDS

This chapter provides an overview of microgrids. The various topics that underlie microgrids have been covered. History indicates a return to the use of smaller grids close to electricity users and this is mainly due to technical advances in recent years, but also to social, economic, and environmental issues. Since the beginning of the third millennium, with the expansion and widespread adoption of DG, strong progress in research and development of microgrids has begun that looks very promising and continues to grow.

A definition of microgrids has been suggested from a critical analysis of the concepts surrounding them. Some properties are imperative, while others are malleable by the very multiplicity of microgrids. The basic components of micro-grids were explored in detail, with emphasis on their functions. Even equipment commonly used in traditional electrical grids must be adapted for proper operation of microgrids. The different controls were discussed. Each one has advantages and disadvantages, but there are situations where it is essential to have a centralized control and others where reliability is very low if you don't adopt the distributed one. The hierarchical perspective was suggested and seems to have great acceptance in academic and scientific circles.

The innumerable architectures of microgrids was also a topic of discussion. The plurality of constructions is one of the greatest benefits of microgrids, since it allows more people access to electricity in a sustainable and economical way. Because of the variety, it is still a difficult task to determine universal rules for microgrids. The standards that already exist or are in the process of being developed seek to provide guidance for projects and controls that can bring security, regardless of the choices for micro-grids. Understanding power quality in micro-grids is another complex issue. In the grid-connected mode, there are not many bottlenecks, and they should follow what the norms of the grids they are connected to indicate. They can be assisted with contracted ancillary services. In the isolated mode, there are no regulations, but for various considerations and circumstances unique to micro-grids, when they arise they will invariably be less strict than conventional ones. Finally, it can be said that the future of the electric system will be intelligent and that its evolution will irrevocably go through the union of multiple micro-grids.

In the following chapters the controls in islanded and grid-connected operation modes, respectively, for AC microgrids will be studied in detail. The main methods used will be reviewed and discussed, and results will be presented.

4. PROPOSED METHODOLOGY

Microgrids are self-sufficient power distribution systems. In order to be self-sufficient, the system needs an intelligent controller to determine where the power should come from. In this paper, a microgrid controller implementation will be explored using a genetic algorithm. There will be two types of survival methods and two types of reproduction methods that will be analyzed and compared to see what solution combination of methods can give the best results. The reproduction methods that will be used are mutation and crossover. The survival methods that will be utilized are elitism and random selection.

Microgrid control is complex. Create a model of an islanded microgrid and an optimizing controller for the power generation in the system using a genetic algorithm. The model will be tested by simulating the control of this microgrid model over a 24 hour period of time.

Islanded Microgrid Model and Design Specifications:

i. Power generation at 1 hour increments.

ii. The generation behavior for the next hour based on the previous hour's load data.

iii. The generation update behavior is the control of power generation contributions from each of the four sources in the microgrid.

iv. The determination of the new generation distribution across the sources is determined using your genetic algorithm.

v. Excess power generation is allowed.

vi. Power deficit is not allowed.

vii. Assume snow is not a factor in load differences.

viii. The user must be able to select the method of offspring generation and selection for the genetic algorithm that is used for the controller.

ix. Assume that economic and environmental outcomes are equally significant in the generation decision (one is not more important than the other).

Mandated Microgrid Specifications:

i. 1 load - Design a time series for this behavior.

ii. Power usage for the load must be between 15 and 100 W at all times.

iii. The first hour as the initial load demand, thus controlling 22 following hours of power generation.

x. The first hour of load in the 24 hours is used as an initial evaluation.

xi. The last load cannot be used since there is nothing to control after, so it should not be calculated.

xii. During the first hour assume that the exact load is generated.

xiii. 4 sources.

a. Source 1: Capable of generating 20 W. For each W produced, it costs.

i. 0.02$ and produces 0.01 tons of emissions.

b. Source 2: Capable of generating 120 W. For each W produced, it costs.

i. 0.2$ and produces 0.05 tons of emissions.

c. Source 3: Capable of generating 15 W. For each W produced, it costs 0.01$ and produces 0.02 tons of emissions.

d. Source 4: Capable of generating 50 W. For each W produced, it costs.

i. 0.02$ and produces 0.04 tons of emissions.

ii. User determination of survival approach.

iii. User determination of reproduction approach.

iv. Mandated Generator Control Outputs for Implementation:

v. The implementation will only produce the following outputs:

a. Plot of load vs power generated

b. Plot of economic factor

c. Plot of environmental factor

d. Plot of run time for each hour

e. Total excess power generated during the 23 hours

f. Total cost over the 23 hours

g. Total emissions produced over the 23 hours

4.1 MICROGRID DESIGN

i. Microgrid Block Diagram

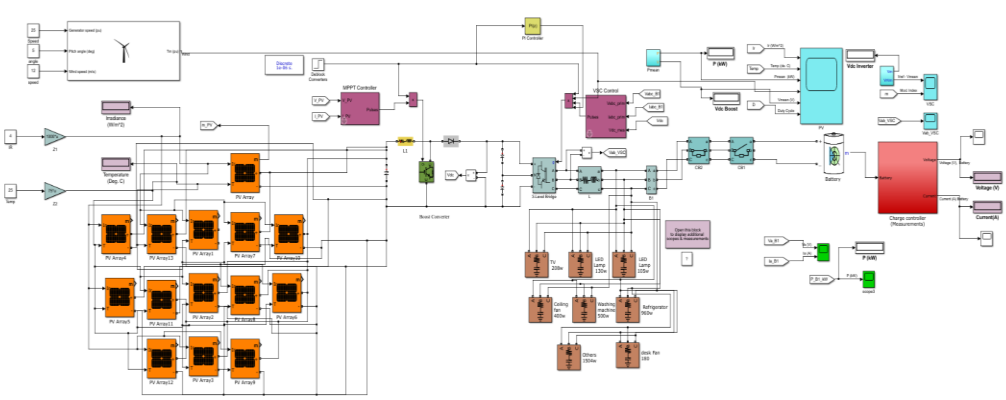

Figure 4.1: Proposed system design.

ii. Load Time Series

This time series was designed by deciding with the idea that the power is being sent to a residential area. The usage would be low in the middle of the night and high when residents are home from work. It would gradually increase/decrease throughout the other parts of the day. The assumption is that a week days are being explored.

To find the values, a range was given for each hour throughout the day. A value for each hour within these ranges is randomly selected. A set number of days can be produced. In order to smooth out the curve an additional parameter was utilized to combine a set of days into a group and take the mean. The purpose of this is to smooth out the curve into something that would look more realistic.

iii. Source Chromosome Format The chromosome format for each source is [cost, emission].

iv. The defined boundaries are:

a. $15W \leq power \leq 100W$

b. $\$.15 \leq cost \leq \$6.55$

c. $15tons \leq emission \leq 3.75tons$

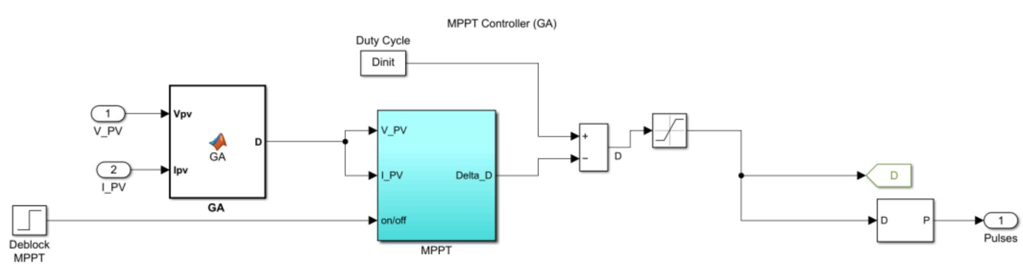

Figure 4.2: GA processing in MPPT controller.

vi. Fitness Optimization

Economic optimization means that lower cost is better. If the requirements can be met with lower cost this would be a beneficial economic adjustment.

Economic boundary for fitness function are [0, 1], 0 being the best.

Environmental optimization would imply that less emissions produced would be better for the environment.

Environmental boundary for fitness function are [0, 1], 0 being the best.

The equation used to find the fitness of these optimizations is:

$$W * \frac{cost - min}{max - min}$$

Another optimization that is required is the amount of power is delivered. If there is not enough power being delivered then outages will occur.

Figure 4.3: GA algorithm inputs in MATLAB.

v. Defined Constants

The population size that will be used is 100 chromosomes with a mutation rate of .1. The stopping condition for the fitness function is .08. The cross over point that will be used is 2.

4.1.1 Load Time Series

Here is a rough idea of what the load time series will look like. It is subject to change.

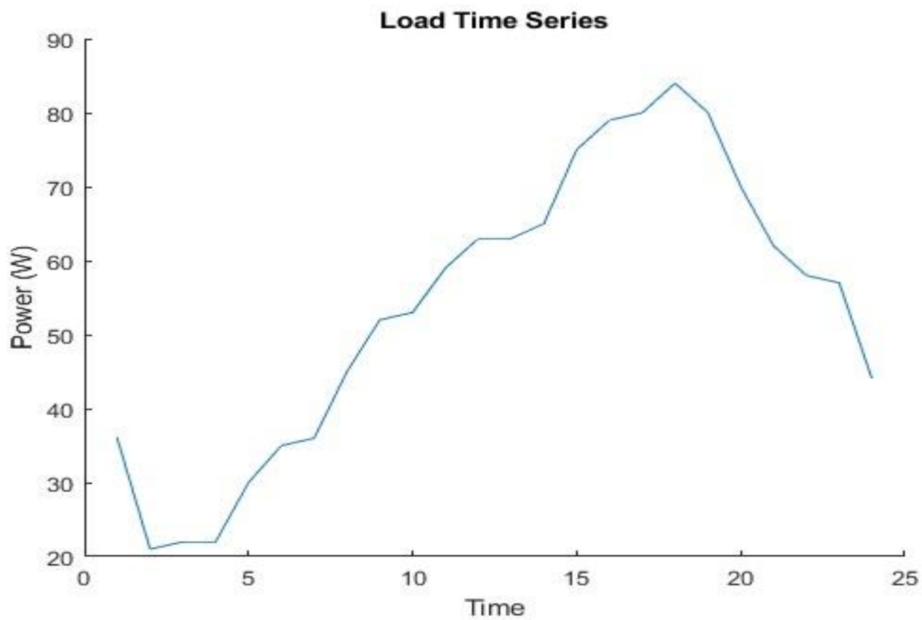

Figure 4.4: Load time series.

4.1.2 Load Time Series Generation

This time series was designed by deciding with the idea that the power is being sent to a residential area. The usage would be low in the middle of the night and high when residents are home from work. It would gradually increase/decrease throughout the other parts of the day. The assumption is that a week days are being explored.

To find the values, a range was given for each hour throughout the day. A value for each hour within these ranges is randomly selected. A set number of days can be produced. In order to smooth out the curve an additional parameter was utilized to combine a set of days into a group and take the mean. The purpose of this is to smooth out the curve into something that would look more realistic.

4.1.3 Gene Boundaries

Each gene has a power boundary corresponding to its potential source output. The source cannot output more than its limit.

i. Source 1: [0, 20]

ii. Source 2: [0, 120]

iii. Source 3: [0, 15]

iv. Source 4: [0, 50]

4.1.4 Economic Optimization

Economic optimization means that lower cost is better. If the requirements can be met with lower cost this would be a beneficial economic adjustment. Economic boundary for fitness function:

i. $\$.15 \leq cost \leq \$6.55$

This range was chosen because the minimum is the least possible cost based on the power constraints and the max is the best possible cost plus a little extra due to the difficulty of finding the ”best” solution in a GA.

The economic fitness is ideally on a scale of 0 to 1, 0 being the most fit, but there will be some cases early on that goes off scale.

$$W * \frac{cost - min}{max - min}$$

4.1.5 Environmental Optimization

Environmental optimization would imply that less emissions produced would be better for the environment.

Environmental boundary for fitness function:

i. $15 tons \leq emission \leq 3.75 tons$

Again, the lower bound is the least possible emission and the upper bound is the best plus a little extra.

The environmental fitness is ideally on a scale of 0 to 1, 0 being the most fit, but there will be some cases early on that goes off scale. After the emissions for the chromosome was calculated equation that was used to determine the fitness is:

$$W * \frac{emssion - min}{max - min}$$

$$15 \leq \sum_{i=1}^{n} P_i \leq 100$$

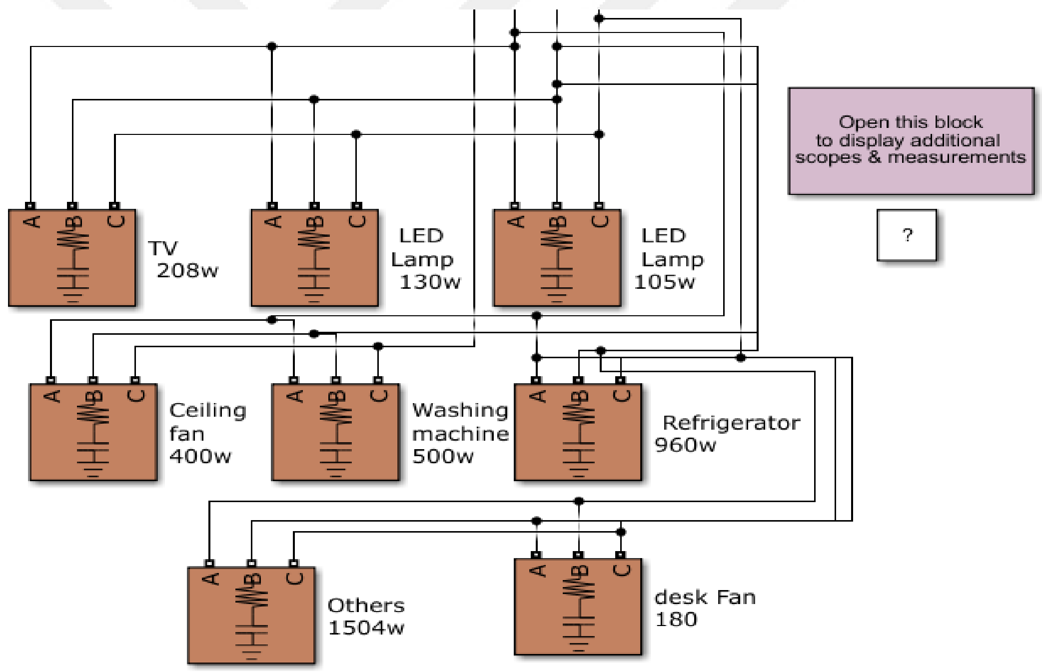

Figure 4.5: Loads accumulation in the proposed scenario.

4.2 GENETIC ALGORITHM

i. Algorithm Flow

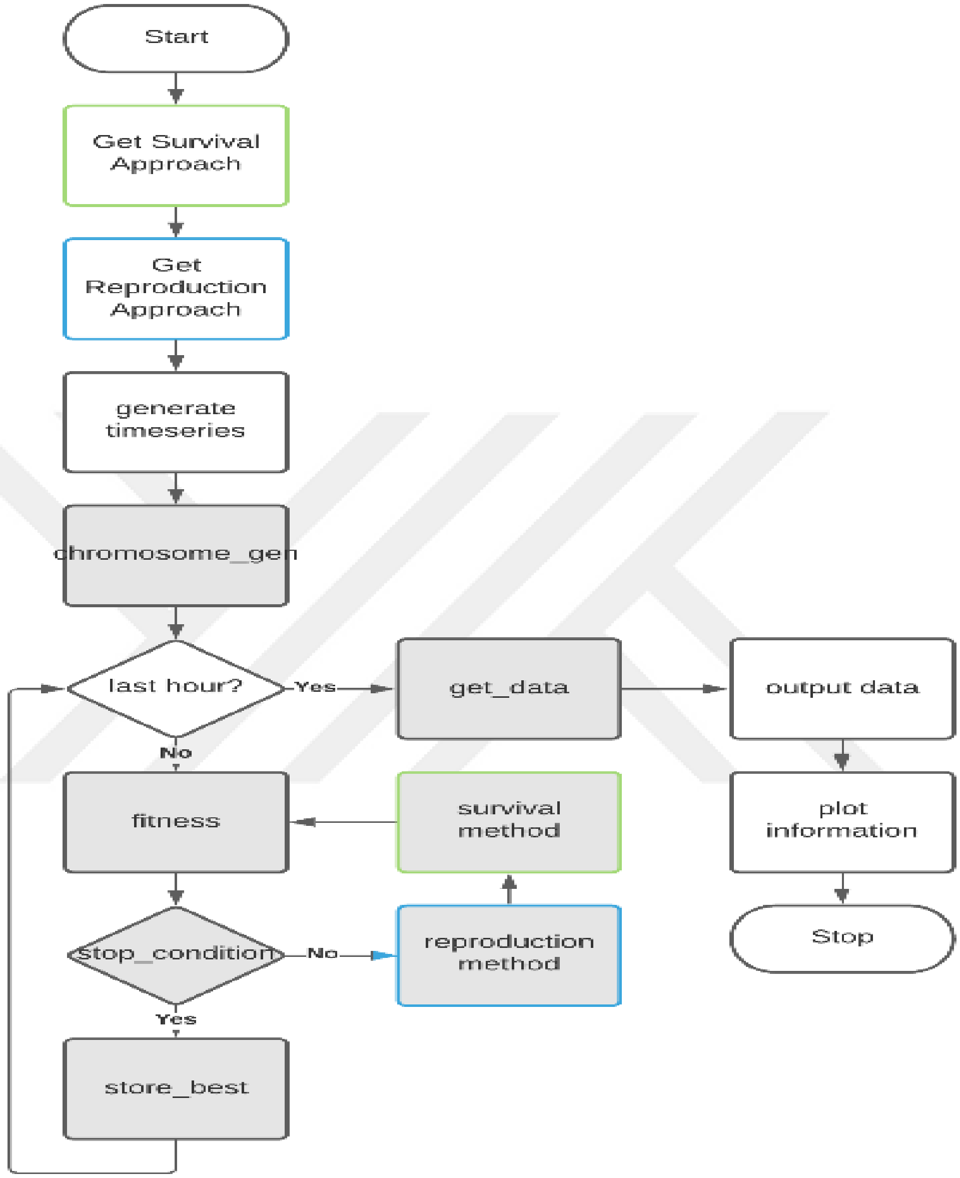

Figure 4.6: Algorithm workflow chart.

ii. Reproduction Methods

a. Mutation: For mutation to occur, first random chromosomes in the population are selected to be mutated. If the produced chromosome is feasible it is added into the population. The genes that are selected are chosen at random.

b. Crossover: In crossover, two parents are randomly selected to be used to reproduce. Two children are produced corresponding to the crossover point. The crossover point is the point at which the parent chromosomes are split and which genes the children inherit.

iii. Survival Methods

a. Elitism: Elitism reduces the population to the correct population size by killing off less ideal chromosomes. This is done by looking at the fitness of each function at removing the chromosomes with the worst fitness.

b. Random Selection: Random selection reduces the population by randomly selecting chromosomes to kill off. This is done by creating a random permutation of indices to determine which chromosomes should be remove.

4.3 EVALUATION CRITERIA

i. Excess Power

It can be seen that the random mutations causes an increased amount of excess power that is produced due to its random nature. Random selection also hinders the excess power even further when combined with random mutation. When mutation is paired with elitism, the results are slightly more efficient. When crossover is combined with random selection, the results are similar to mutation due to its lack of diversity. When crossover is combined with elitism, the best result are made due to only reproducing with the most elite chromosome for each generation.

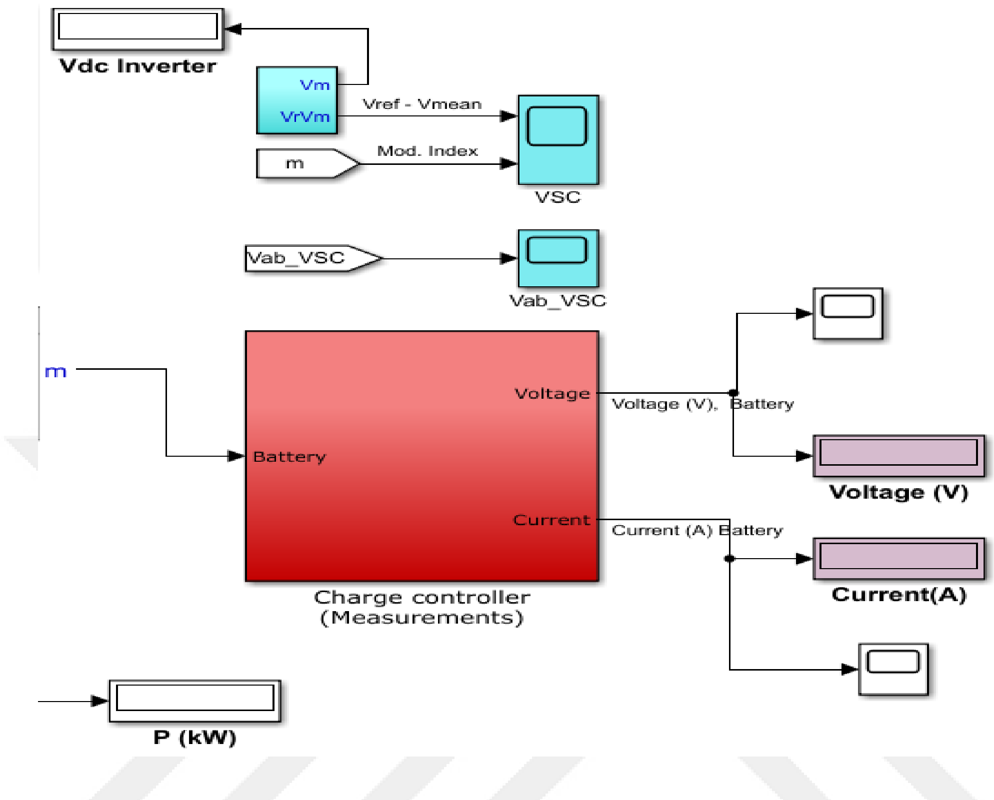

Figure 4.7: Smart metering structure in MATLAB.

ii. Cost

The cost for each method is quite similar and behaves as you might expect. The cost throughout the day typically follows the trend of the power output. The typical range for cost is $\$50 \leq cost \leq \$65$

iii. Environmental Impact

The emissions also follows a similar trend to the power across all methods. Interestingly, the curve is typically a little wider than that of the power curve. Perhaps this is due to the defined weights. The range for emissions is typically $40 \leq emissions \leq 48$ tons.

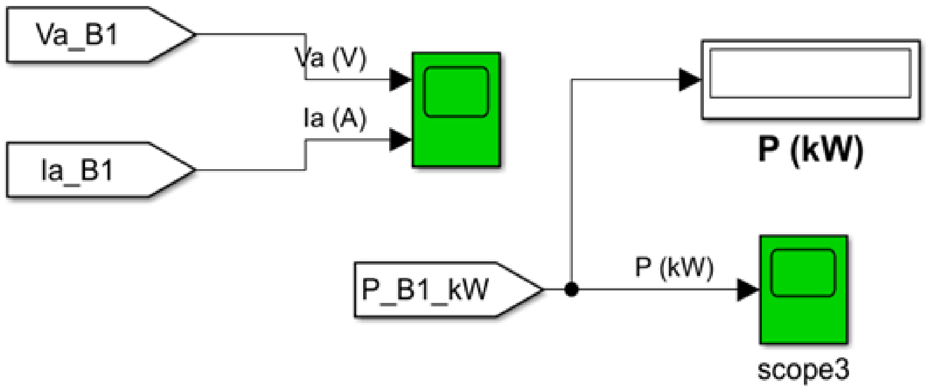

Figure 4.8: VSC scopes in MATLAB.

iv. Calculation Time

The time it took to generate across all methods was quite predictable. The main driving factor that hindered the calculation time was the survival method. Random selection typically took longer than that of elitism. Interestingly, the difference between mutation and crossover time was not that different as long as the crossover set received a good starting point. There are some cases where crossover is unsolvable due to lack of diversity.

5. RESULTS OF THE SIMULATION

5.1 MUTATION & RANDOM SELECTION

5.1.1 Excess Power

Excess power produced: 130W

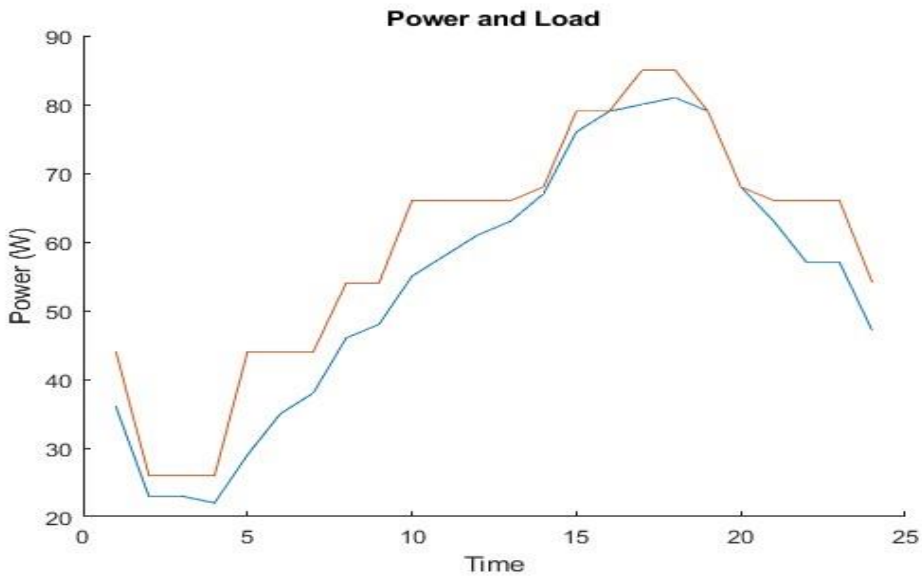

Figure 5.1: Excess power produced.

5.1.2 Cost

Total cost for the day: $54.37.

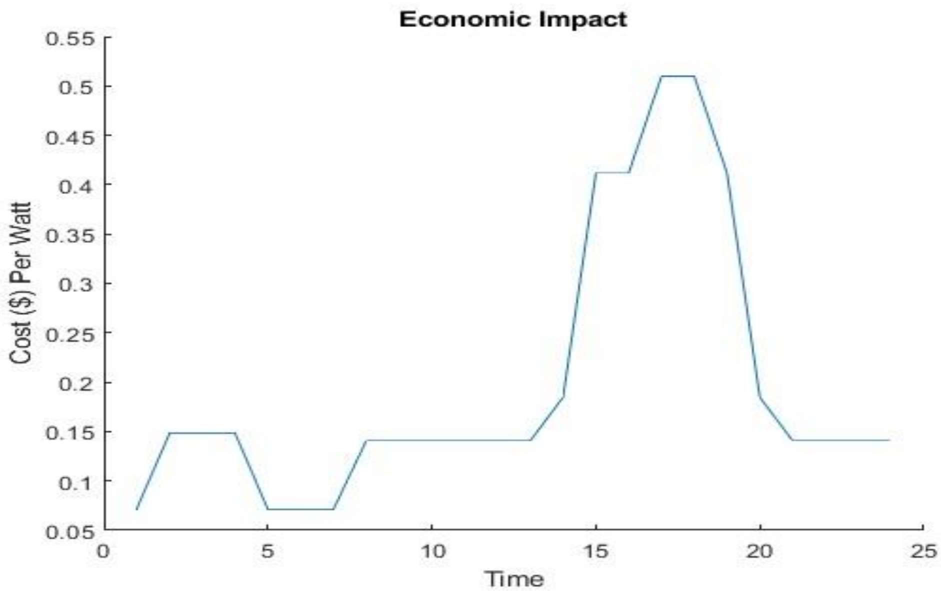

Figure 5.2: Total cost for the day.

5.1.3 Environmental Impact

Total emission for the day: 45.17 tons

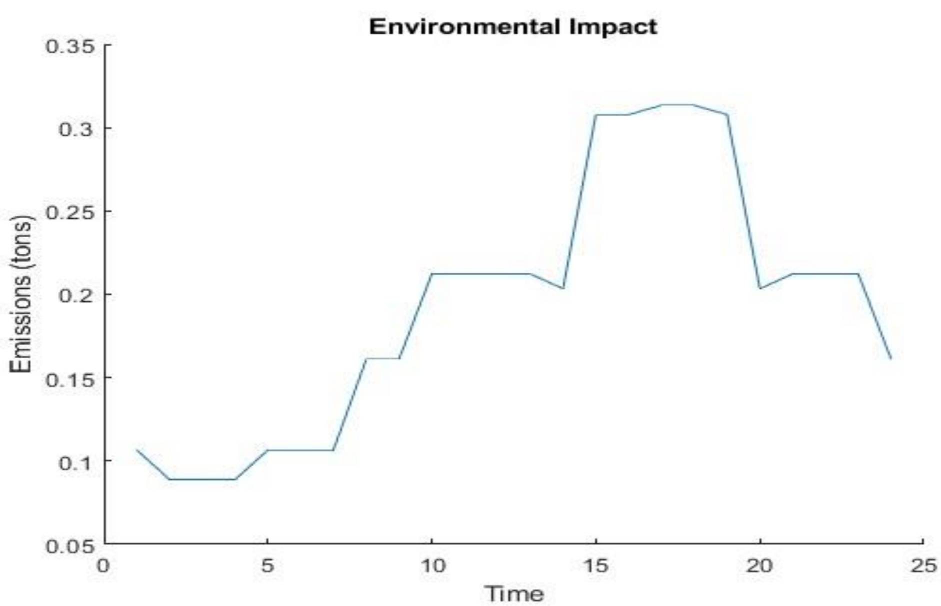

Figure 5.3: Total emission for the day.

5.1.4 Calculation Time

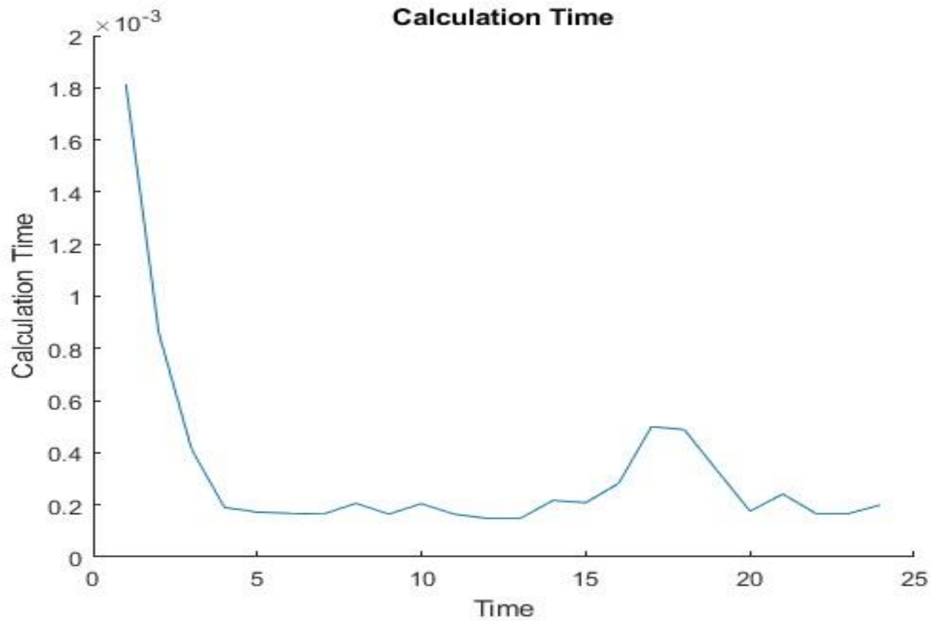

Figure 5.4: Time series prediction.

5.2 MUTATION AND ELITISM

5.2.1 Excess Power

Excess power produced: 100W.

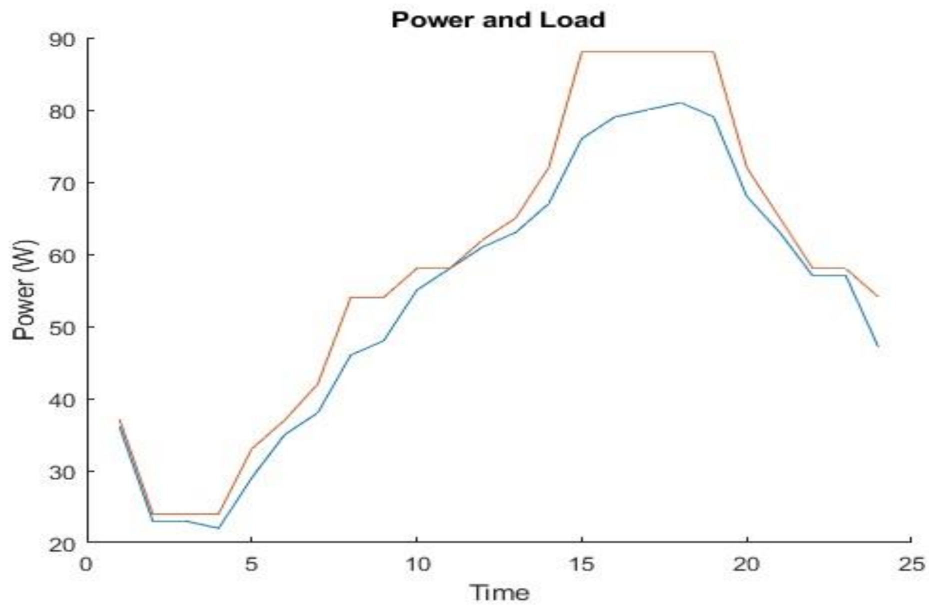

Figure 5.5: Excess power produced after mutations.

5.2.2 Cost

Total cost for the day: $60.33.

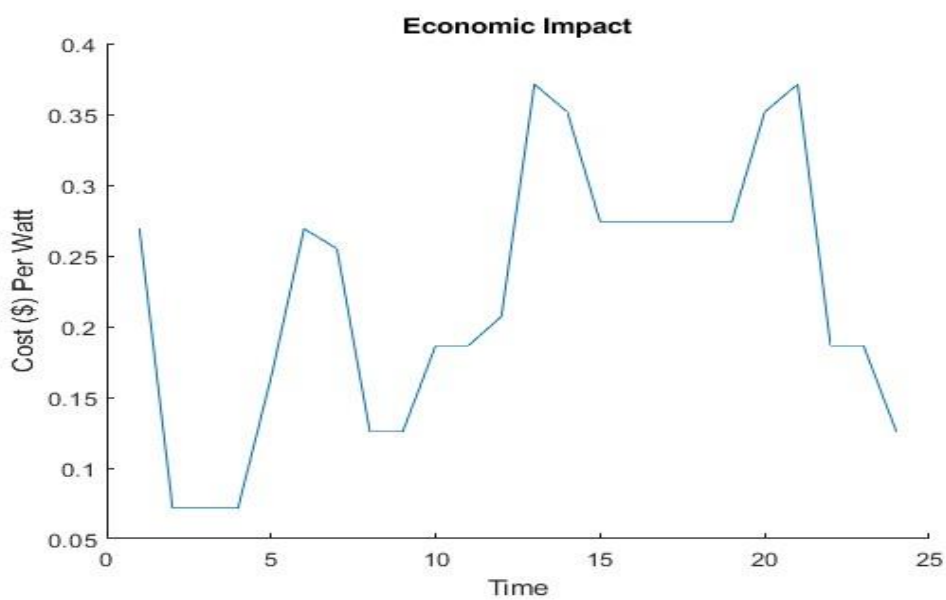

Figure 5.6: Total cost for the day after mutations.

5.2.3 Emissions

Total emission for the day: 45.05 tons.

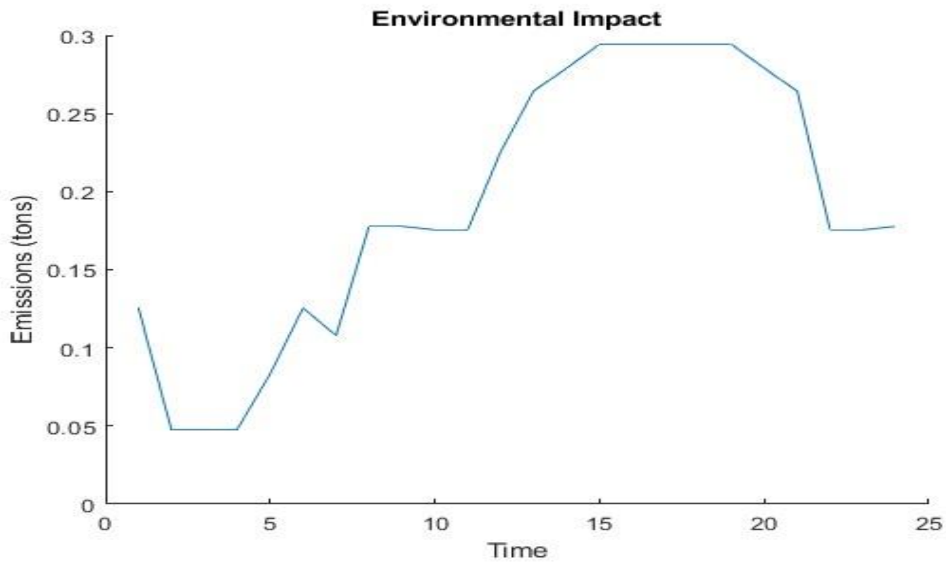

Figure 5.7: Total emission for the day after mutations.

5.2.4 Calculation Time

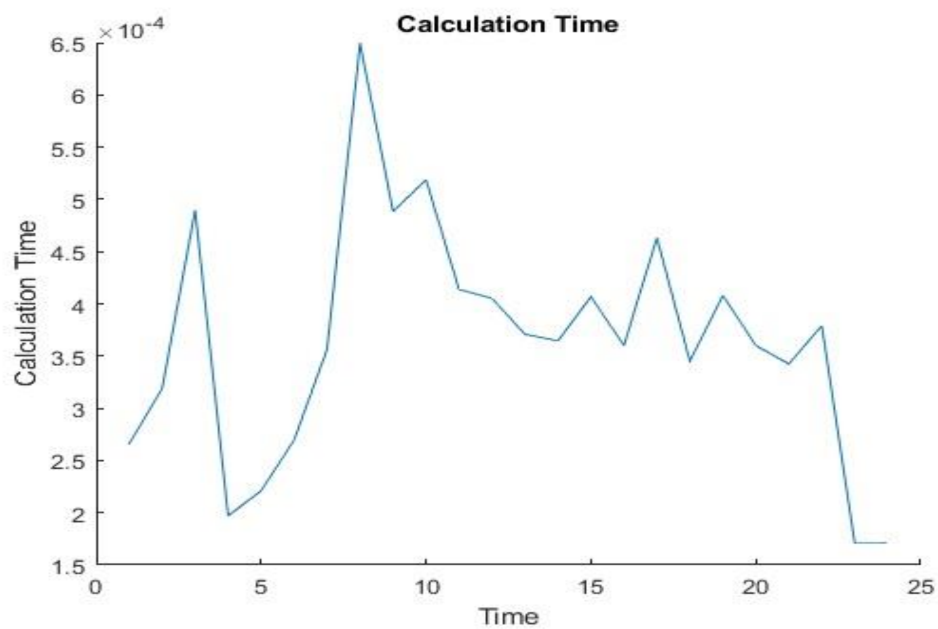

Figure 5.8: Time series prediction after mutations.

5.3 CROSSOVER AND RANDOM SELECTION

5.3.1 Excess Power

Excess power produced: 119W.

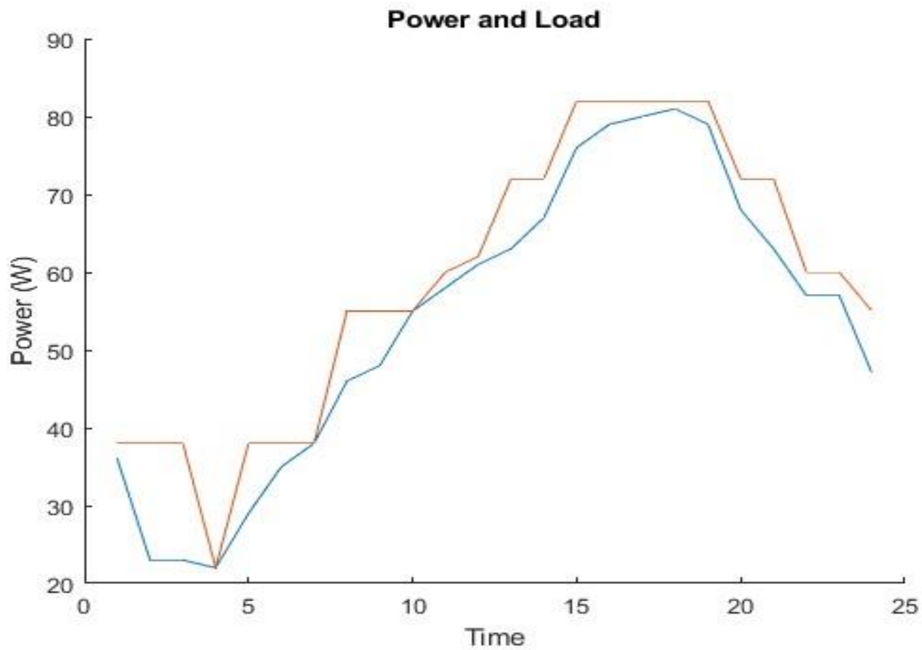

Figure 5.9: Excess power produced after crossover.

5.3.2 Cost

Total cost for the day: $52.48.

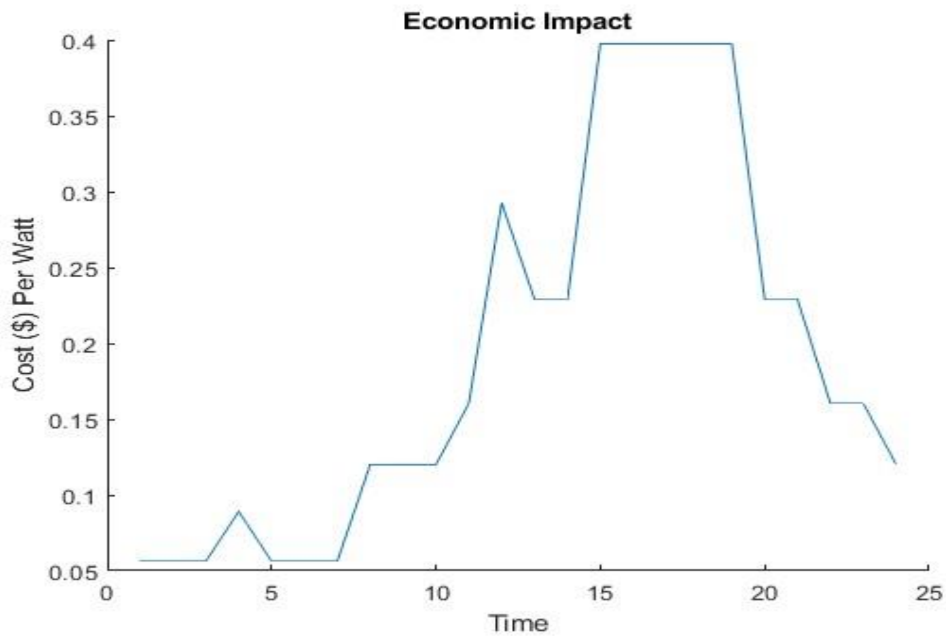

Figure 5.10: Cost calculations after crossover.

5.3.3 Emissions

Total emission for the day: 44.78 tons.

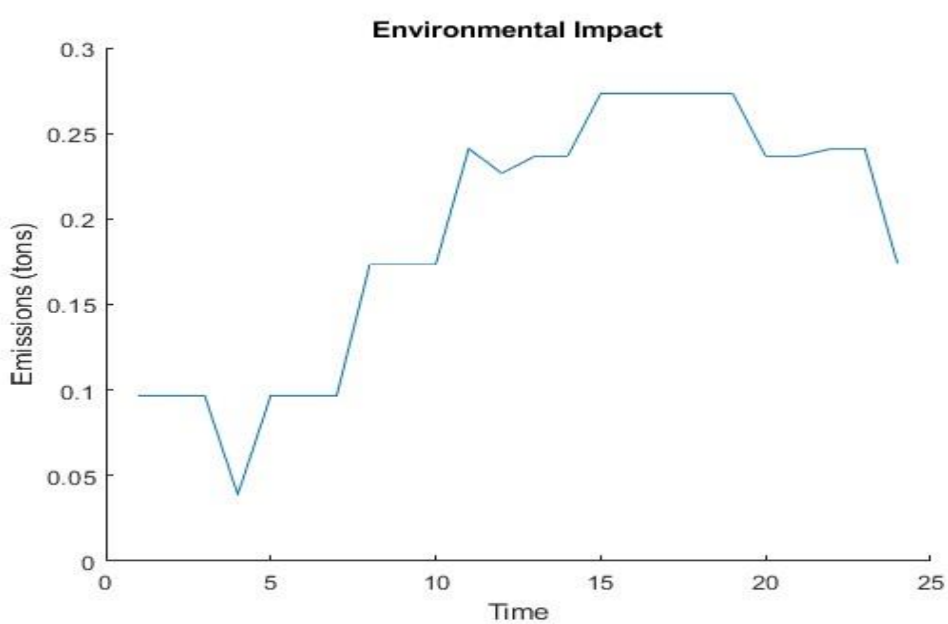

Figure 5.11: Total emission for the day after crossover.

5.3.4 Calculation Time

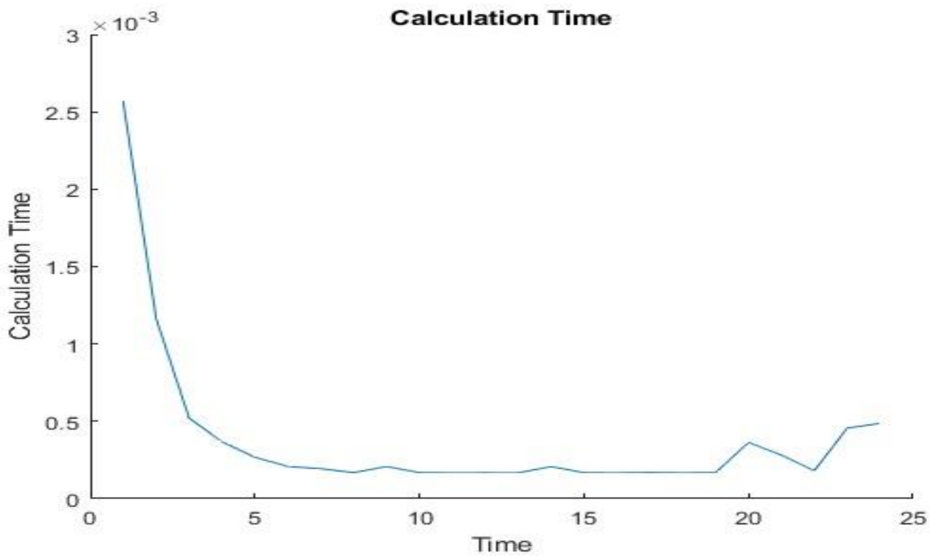

Figure 5.12: Calculation time.

5.4 COMPARISON

5.4.1 Excess Power

It can be seen that the random mutations causes an increased amount of excess power that is produced due to its random nature. Random selection also hinders the excess power even further when combined with random mutation. When mutation is paired with elitism, the results are slightly more efficient. When crossover is combined with random selection, the results are similar to mutation due to its lack of diversity. When crossover is combined with elitism, the best result are made due to only reproducing with the most elite chromosome for each generation.

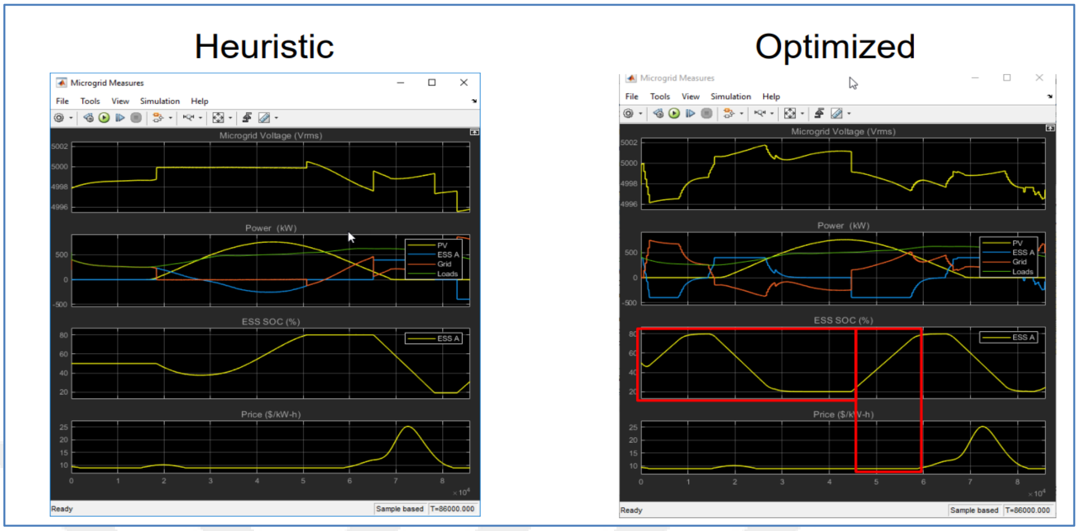

Figure 5.13: Comparison of output power between methods.

5.4.2 Cost

The cost for each method is quite similar and behaves as you might expect. The cost throughout the day typically follows the trend of the power output. The typical range for cost is $\$50 \leq cost \leq \$65$.

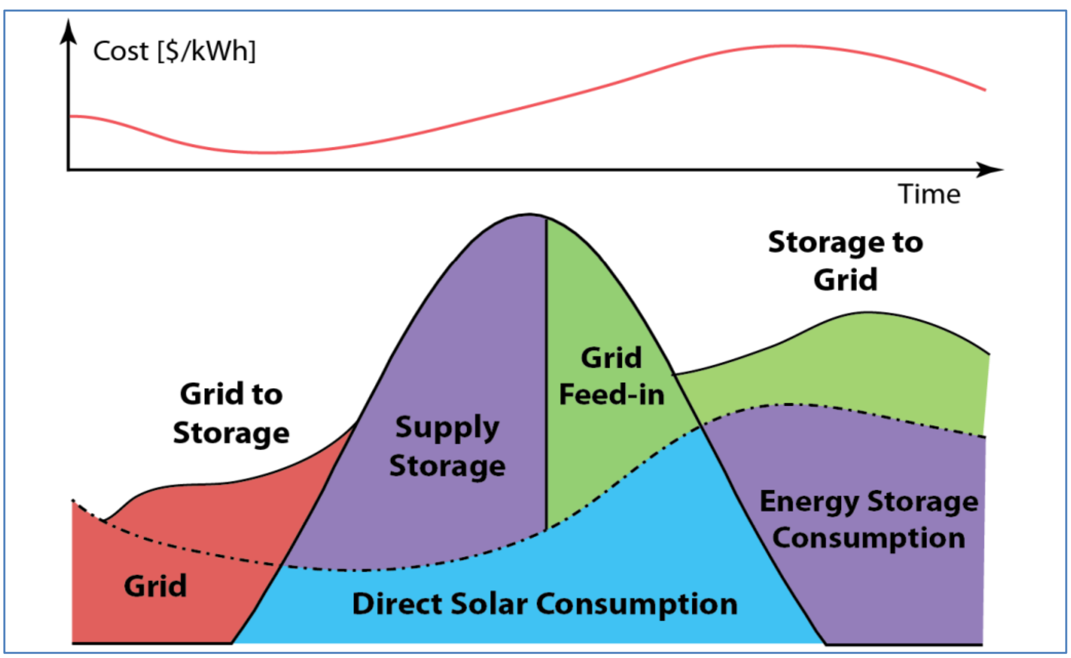

Figure 5.14: Cost estimation method.

5.4.3 Environmental Impact

The emissions also follow a similar trend to the power across all methods. Interestingly, the curve is typically a little wider than that of the power curve. Perhaps this is due to the defined weights. The range for emissions is typically $40 \leq emissions \leq 48$ tons.

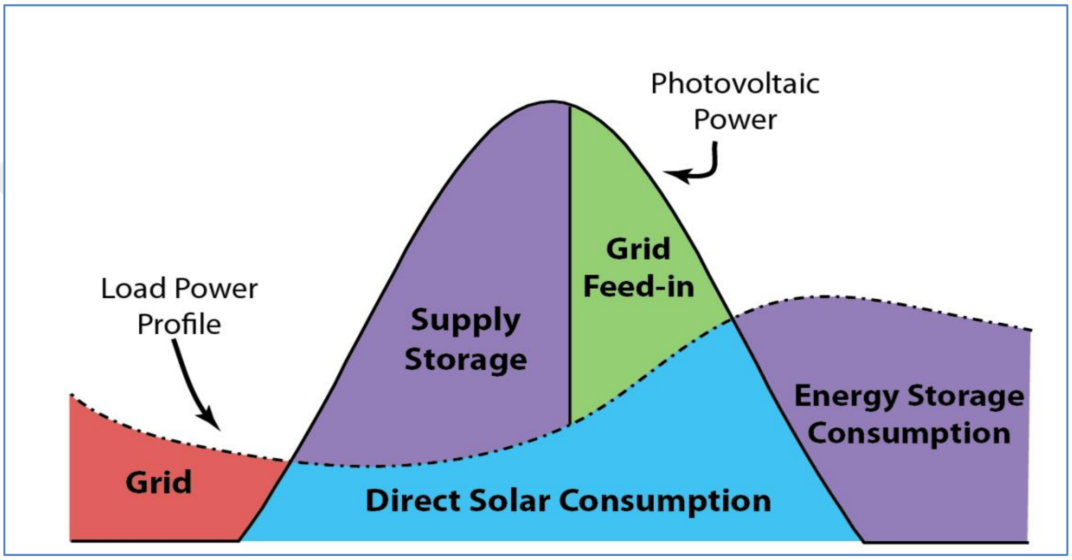

Figure 5.15: Emission estimation method.

5.4.4 Calculation Time

The time it took to generate across all methods was quite predictable. The main driving factor that hindered the calculation time was the survival method. Random selection typically took longer than that of elitism. Interestingly, the difference between mutation and crossover time was not that different as long as the crossover set received a good starting point. There are some cases where crossover is unsolvable due to lack of diversity.

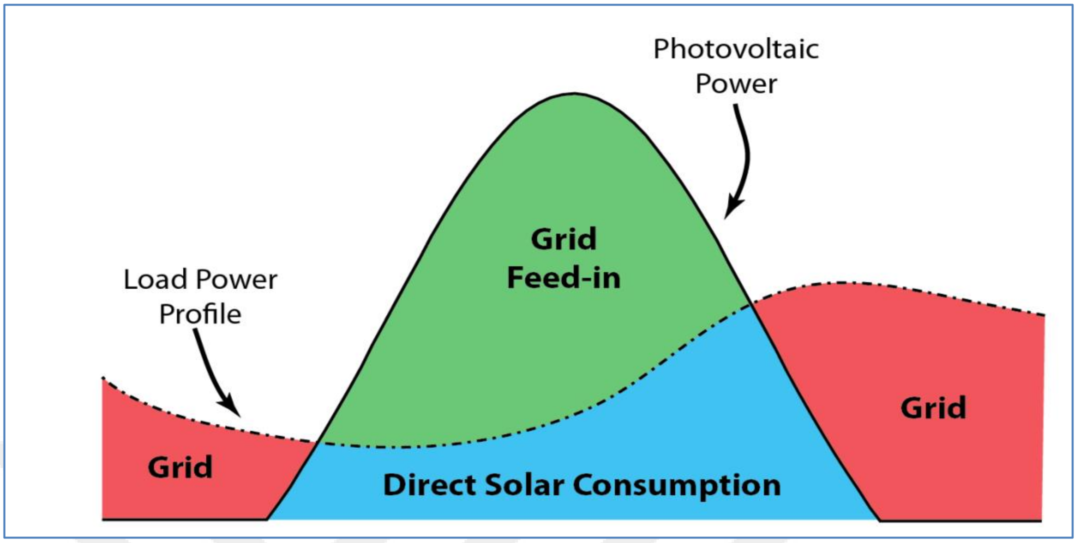

Figure 5.16: Time series prediction method.

6. CONCLUSION AND RECOMMENDATION

6.1 IMPROVEMENTS

The initial chromosome generation could be optimized to use more realistic values and diverse. Crossover benefits from larger data sets with more diversity as a starting point. If the original chromosomes were intentionally more diverse there could be better results. In the case that the good enough value is too low or the data set is not diverse enough the algorithm will run out of solutions to make it to the stopping condition.

6.2 CONCERNS TO BE ADDRESSED

One concern that is not addressed in this system is that there is no value for the maximum heat that the sources can produce before failure. With this additional constraint there may be times where it would be more logical to increase cost and/or emissions in order to cool a source that has done a lot of work. With the way the system is set up now, a source could go all day without any down time while another source doesn't do much. The lack of this information could lead to catastrophic failure.

Another concern is that there is no set limit how much extra power can be produced. With no location for storage, the system could over load the load and could potentially cause fires or explosions depending on how much excess power is sent to the load.

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