Cape Peninsula
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The development of a controller for PV and wind energy for Angolan power Transmission network

by

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DECLARATION

I, Adao Francisco Catraio, declare that the contents of this dissertation represent my own unaided work, and that the dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date 15.05.2024**

ABSTRACT

The power transmission network is responsible for transporting the electrical energy from generating plants to different substations. Electrical energy has become extremely important in this current world. Companies, churches, schools, and households need more electricity to satisfy their daily needs. The increase in load demand causes several challenges to the power transmission networks. Therefore it is evident that there is a need to introduce renewables into traditional power systems to mitigate this continuous increase in load demand. However, some issues come with the introduction of renewables into traditional power systems. The output power for renewable energy such as wind and solar energy systems depends on many factors such as solar irradiance, temperature, wind speed, geographical location, air density, swept area, wind turbine configurations, and many other factors. These factors are responsible for the inconsistency and variability of the wind and solar energy systems. Therefore, it is important to develop an efficient controller that can operate in different systems such as solar and wind energy systems to maintain a stable power and continuous flow of electricity. Various controllers can be used for the renewable energy system such as Unified power flow controller, Unified Interphase Power Controller, Radial basis function (RFB) network-based single Maximum Power Point Tracking controller, Thyristor Controlled-Interphase Power Controller, or Interphase Power Controller. However, this research, focused on the Fuzzy Logic Controllers based Maximum power point tracking (MPPT) to obtain a stable output power and also to mitigate the instability of the system. This project covered the detailed development of a controller for renewable energy for the Angolan power network through the use of MATLAB/SIMULINK software. The proposed controller developed in this project was introduced into a PV system which significantly increased the performance of that PV system by enabling the PV grid to generate 30MW and also to maintain the power network stability. The proposed controller was also able to ensure that the additional voltage supplied by the PV system to the network was within the standard voltage allowable limits to keep a safe and stable operating of the system.

Keywords

Transmission network, Renewable energy system, Controller, Simulations, Wind energy, Photovoltaic energy, Maximum power point tracking, Fuzzy Logic Controllers.

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DEDICATION

This thesis is dedicated to my father, my wife, and my children. Moreover, this thesis is dedicated to my entire family and colleagues for their immense contribution and support.

GLOSSARY

PV	Photovoltaic
TCSC	Thyristor Controlled Series Capacitors
UPFC	Unified Power Flow Controller
SVC	Static VAR Compensator
STATCOM	Static Synchronous Compensator
DC	Direct Current
AC	Alternative Current
WAEMS	Wide Area Energy Management System
MPPT	Maximum PowerPoint Tracking
FACTS	Flexible Alternative Current for Transmission system
IPC	Interphase Power Controller
AVIC	Adaptive Virtual Impedance Controller
RPM	Revolutions per minute
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine
UIPC	Unified Interface Power Controller
FLC	Fuzzy Logic Controllers
SCADA	Supervisory control and data acquisition
HIL	Hardware In the Loop

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

An electric power system consists of generators, transformers, power transmission networks, and other devices. Many faults occur in the power transmission networks which can cause blackouts, power outages, and many other electrical problems. The occurrence of faults in the power network is caused by various factors and one of the main factors is the instability of the power supply (Araga & Airoboman, 2021). The power generated from different sources in the initial phase of the power system is mostly unstable. For instance, the power generated from solar, or wind energy is unstable due to the fluctuations in the solar irradiance or wind speed. The sun does not always shine at the same intensity and the wind does not always blow at the same speed, these sources of energy are highly affected by the location, the weather, and many other factors. Therefore, it is important to have a device that can control the power input and can also supply the desired power output.

In this research, a strong literature review is provided to identify the most efficient controller to be used for power stability of power networks with renewable energy sources. The Fuzzy Logic Controller was identified to be the most suitable solution for power stability. In this thesis, a controller was developed using MATLAB for a PV system that was integrated into an Angolan power network.

Fuzzy logic control is a popular technique employed in the management and optimization of solar energy systems. Solar energy systems often involve complex, non-linear, and uncertain dynamics, making them well-suited for fuzzy logic control approaches. Solar energy systems are subject to various uncertainties, such as fluctuating weather conditions, shading effects, and equipment performance variations. The Fuzzy logic controller can effectively handle these uncertainties by using linguistic variables and fuzzy rules, rather than relying on precise mathematical models. Furthermore, The Fuzzy logic controller can optimize the operation of the PV systems, such as maximizing power output, improving energy efficiency, and enhancing system reliability.

1.2 Awareness of the problem

The population around the world is increasing in such a way that the need for electricity is also increasing worldwide. Many countries such as Angola have been experiencing electrical problems for years due to failures in the power network caused by high load demand. Only one-third of the population in Angola has access to electricity under good conditions (Rinkesh, 2019).

The power networks in Angola are located in a rough environment where many types of natural disasters can occur such as earthquakes, high winds, storms, excessive heat, and rains. Therefore, developing an efficient controlling system for the PV system is important to minimize the occurrence of the failures and optimize the utilities in the power networks. The integration of the PV system with a controller into the Angolan power networks can bring significant improvement and can be a solution to the electrical problem that Angola is facing.

1.3 Problem Statement

The majority of the population in Angola has no access to electricity due to various factors and one of the major factors is the failure of the power networks. These failures have been occurring constantly in urban and rural areas of the country due to the unstable power supplied by the generation system.

Problem statement: To develop a controller for renewable energy such as PV energy to improve power stability and minimize the faults in the power network.

1.4 Research Aim and Objectives

This project aims to find an alternative solution to improve the electrical condition of Angola by developing a controller for renewable energy for Angolan power transmission networks. This controller will be able to provide a good power flow control and achieve a good stability and thereby reduces the instability in the power transmission networks.

1.4.1 Objectives

To conduct a thorough study on developing a controller for renewable energy in power transmission networks, clearly defined objectives are essential. The primary goal of this research is to enhance Angola's power transmission network.

The sub-objectives of the research are:

- To review literature done on the development of controllers for renewable energy cultivation.
- To improve the monitoring of the power transmission networks in Angola.
- To mitigate the occurrence of instability in the power networks in Angola.
- To make effective and efficient use of renewable resources in Angola.
- To perform load flow analyses to investigate the performance of the power network when disturbances occur.
- To perform load flow analyses to investigate the impacts of disturbances due to the integration of PV or Wind in the power network.

1.5 Research questions

Here are several key research questions that were considered. These questions were incorporated into the sections of the research proposal once its structure was finalized.

1.5.1. What can be done to improve the power transmission network in Angola?

The power transmission network in Angola can be improved by developing a controller that can operate efficiently in renewable energy such as a PV system.

1.5.2 What tool will be used to develop a controller for the power transmission network?

MATLAB/SIMULINK software will be used to develop the controller and perform simulations.

1.5.3 What is a unique benefit that the proposed controller can provide?

The proposed controller will have the ability to detect any instability and minimize it so that there is no or less interruption of electricity.

1.5.4 Why is that so important to improve the power network?

Improving the power network is crucial because electrical energy cannot be distributed without it. Consequently, a weak power network will result in poor energy distribution.

1.6 Motivation of the research project

The power transmission network serves as the critical link between the generation and distribution systems. However, it often faces challenges related to power stability and power losses. Ensuring the efficient performance of the power transmission network is essential for delivering high-quality, uninterrupted energy to end consumers.

To achieve this efficiency, incorporating renewable energy sources is a vital step. Implementing a controller for the renewable energy system will enable precise management of power input, ensuring a stable and reliable power output. This research project aims to develop and optimize such a controller, thereby enhancing the overall performance and stability of the power transmission network.

This research project will provide many benefits in the electrical sector of Angola considering that humans require electricity as a basic necessity. In the modern world, buildings such as homes, businesses, schools, and churches cannot function without electricity. The electrical national utility company Empresa Nacional de Distribuição de Electricidade will be able to manage and control better the flow of electrical energy efficiently and also will be able to satisfy the needs of the consumers at an affordable cost.

1.7 Hypothesis

The development of a controller for renewable energy will improve power stability and reduce the instability in the power transmission network. It will also minimize the cost involved from the generation to the distribution of electrical power.

1.8 Delimitation of research

The proposed research focuses on the development of a controller for PV energy systems for power networks with great attention to power stability and fault mitigation. The controller is to be developed and tested using MATLAB/SIMULINK software. The following points were considered in the development of a suitable controller:

- Power network case studies based on PV energy.
- Modelling of a controller in the MATLAB/SIMULINK software.
- Analyse the results after simulations.
- Compare the results of the existing controllers against the proposed controller for PV energy.

1.9 Assumptions

The following assumptions have been made to solve the research problem:

- The Load flow analysis considers the disturbances influencing the integration of renewable energies in the power network.
- The Load flow analysis considers disturbances influencing the power network.

1.10 Problem Formulation

Angola faces significant challenges in providing continuous electricity to consumers due to failures in power transmission networks, insufficient electrical power supply, and reliance on hydropower sources. Many households, companies, schools, and other institutions are forced to spend money on fuel for generators to cope with blackouts, power outages, and load shedding. This lack of reliable electricity adversely affects the daily lives of the majority of households and compromises both economic growth and the prospects of future generations.

1.11 Research methodology

Research methodology is one of the most important sections of any research because it assists a researcher in understanding which method is more suitable for the study to respond to questions asked at the study’s objectives (Fange, et al., 2007).

Qualitative methodology is used in this research through a systematic review of many papers, past reports, and journal articles available from different sources. Furthermore, some simulations, load flow analyses, and the development of some MATLAB/SIMULINK models were performed.

1.12 Thesis Chapters

This thesis is composed of six chapters and the description of what these chapters contain is as follows:

- Chapter One presents the research problem and statement. It also describes the research aims and objectives, the research methodology, the scope, and limitations.

- Chapter Two sets out the literature review. It also discusses the electricity crises in Angola. Furthermore, it describes in detail the power network, the controllers, and renewable energies. Then, the finding of the literature review is also presented.

- Chapter Three discusses the performance and operation of the Fuzzy Logic Controller.

- Chapter Four presents the load flow analysis of a Three-Phase power network in Angola
- Chapter Five presents the system development, modelling, and simulations of the fuzzy logic controller.

- Chapter SIX concludes the research. The research contributions and deliverables are presented, a summary of the research is presented and recommendations for future work are suggested.

1.13 Conclusion

The introduction lays out the foundation for understanding the critical issues within the Angolan power transmission network, emphasizing the necessity for stability and reliability during growing demand and environmental challenges. The acknowledgment of the critical role of renewable energy sources, particularly photovoltaic systems, sets the stage for the proposed solution development of a Fuzzy Logic Controller. This controller aims not only to enhance power stability but also to mitigate faults within the network, thereby addressing the overarching problem of insufficient electricity access in Angola. By employing a comprehensive research methodology encompassing literature review, simulations, and model development using MATLAB/SIMULINK, the study endeavors to contribute significantly to the improvement of Angola's electrical infrastructure. The projected outcomes of this research hold promise for bolstering economic growth, improving living standards, and fostering sustainable development in Angola. The next chapter presents the literature review conducted for this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section focuses on the literature review developed to select the most efficient controller to integrate renewable energy for an Angolan power transmission network. The development of a suitable controller for renewable can improve the electrical conditions in Angola. Various reviews have been done in the past on the development of controllers for power transmission networks, but those reviews focus more on the development of controllers for improvement of the power efficiency and obtention of a dynamic power flow control, on the protection and monitoring function of the power transmission networks.

This literature review is constructed using analyses made from current reviews to emphasize and fill the gap in the controller for the power transmission network in Angola. A literature search was performed on previous reviews done regarding solar and wind energy, afterwards, it has been observed that the integration of solar and wind energy will eliminate the problem faced in Angola and many other countries because of the good geographical location of the country, Angola can make great use of solar energy and improve the current electrical challenge. The implementation of a suitable controller will enable solar to supply efficient electrical power to the transmission networks in a way that blackouts in a country can be eliminated and the standard of living can become much better.

The current literature review is composed of many sections and each section provides specific information. Section 2.2 explains the current situation in Angola regarding electrical problems. Section 2.3 discusses the power transmission network. Section 2.4 explains the different aspects of PV and wind energy controllers. Then section 2.5 discusses PV energy and every factor included in this technology. Section 2.6 discusses wind energy and every element included in this technology. Furthermore, Section 2.7 provides information on some literature searches regarding the controller, Section 2.8 discusses the review conducted on each controller, including the challenges that have been faced by each controller, then section 2.9 gives the conclusion regarding the study and the review conducted.

2.2 The Electricity Crises in Angola

Angola is a coastal country located in Africa, bordered by the Atlantic Ocean to the west. It is the seventh-largest country in Africa, and it is also the eleventh richest country in Africa with a gross domestic profit (GDP) of 70 Billion Dollars per year (Tallungs, 2021). Despite being one of the richest countries in Africa, the country has been facing daily blackouts and a huge challenge in terms of the transmission of electricity for years. Also, the demand for electrical energy is much higher than the supply, causing most of the area in a country to live without electrical power for weeks and sometimes months or years (Vasconcelos, 2022).

The present electrical company is struggling to manage the transmission of electrical power throughout the country. This is due to many factors and one of the main factors is the failure of the power transmission networks. A failure of one of the electrical grids will cause an absence of electrical power in some areas for weeks or months. Thus, companies and houses have to spend on fuel for generators and lose productivity. Furthermore, it has been observed that Angola is well located to make use of solar and wind energy. Therefore, The integration of PV or wind energy with an efficient controller in the power transmission network will have a positive impact on the economy of the country as well as on the standard of living of many people.

2.3 Power Transmission Network

There are three phases in electricity, namely, generation, transmission, and distribution but the focus of this research is on the transmission phase. The power transmission network is located between power generation and the distribution grid. It is the middle element playing a very crucial role in electrical power. Without the transmission lines, electricity can be generated but it will not be distributed to the consumers, and it was also found that many countries are facing electrical problems due to their poor transmission of lines (Rinkesh, 2019).

Power transmission networks are interconnected lines that enable the transportation of electrical energy. Those interconnected lines are connected to the highway system to enable the transmission of electrical energy over long distances to electrical substations or to the users. The electrical energy generated at the power station is estimated to be between 11KV to 33 KV before moving to the transmission network then it is stepped up by using transformers to an estimated voltage between 100KV to 800KV, sometimes, even more, depending on the distance that the electrical energy needs to be delivered.

It is important to step up the voltage during the transmission of electricity to minimize the power losses and undesirable transfer of energy that occur when the electrical energy is being transmitted from one station to the substation. The higher the voltage, the lower the current, and the lower the power losses in the system. This process is called primary transmission. When the electrical power arrives at the substation, the voltage needs to be stepped down by the transformer to an estimated voltage of between 33KV and 66KV, then this voltage is sent to the substations closer to the urban and rural areas. When the electrical energy arrives at these substations is stepped down again to an estimated voltage of 11KV to supply electrical power to the consumers as shown in Figure 2.1. This process is called secondary transmission.

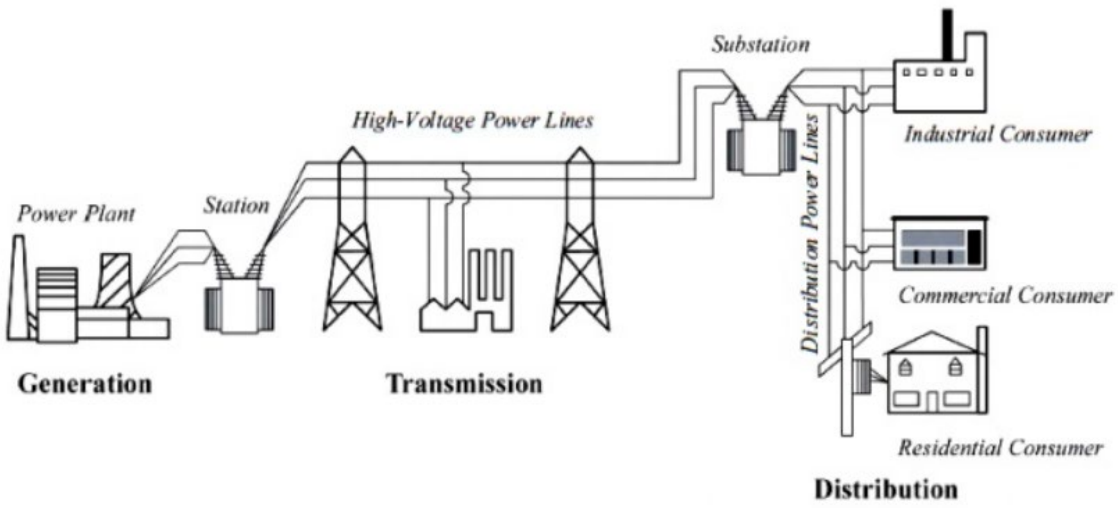

Figure 2.1: **Electric Power System** *(Deboutte & Gwenaelle, 2020)*

The power transmission network is directly connected to the substations and each substation performs four main functions in the power transmission network namely (Stojcevski, 2013).

- **Monitoring function:** This function consists of minimizing the occurrences of alarms, monitoring alerts in the SCADA, and administrating the generation and transmission of log data used in the information system
- **Control function:** This function is used to control the flow of power and also to maintain the equipment of the system
- **Protection function:** This function uses an automation system and smart tools to protect the equipment and prevent the occurrence of faults in the system
- **The recording function:** This function uses software to record any faults in the system.

In this research, the control function in the power transmission network of electricity will be the focus.

2.4 Controllers for Renewable Energy Sources

A controller is a tool for a control system that aims to reduce the deviation between the actual value and the desired value of the system to zero or the possible minimum value (Araga & Airoboman, 2021). A controller can also be used to perform different tasks such as:

- Improving the stability of a system by improving the steady-state accuracy
- Reducing all unwanted offsets generated by the system (Araga & Airoboman, 2021)

There are two main types of controllers namely:

- **Discontinuous Controllers:** Discontinuous controllers are used to measure and control dimensions, surface finish, position, velocity, acceleration, and force through the use of limit switches, photoelectric sensors, and strain gages during a period of less than a second (Colombino et al., 2019).

- **Continuous Controllers:** Continuous controllers are used to measure and control the weight, liquid volume, solid volume, pressure, temperature, and flow rate using different devices such as flow meters, thermocouples, and pressure sensors during a period that can vary from seconds to hours (Colombino et al., 2019).

After combining these modes of controllers, there are three new combinations to be considered in the control system which are:

- Proportional and Integral controllers (PI controllers)
- Proportional and derivative controllers (PD Controller)
- Proportional integral derivative control (PID controller) (Colombino et al., 2019).

2.4.1 Proportional Controllers

The controllers cannot be just used in any system, there are some conditions to take into consideration to get a great result. For instance, the proportional controllers are used on two conditions:

- **1st Condition:** The deviation between the actual value and the desired value should not be large.
- **2nd Condition:** The deviation between the input and the output value should not be sudden (Teferra & Ngoo, 2021).

In the proportional controller, the output is directly proportional to the error signal as shown in equation (1), and the complete mathematical expression is shown in equation (2).

$$A(t)\ \alpha\ e\ (t) \qquad (1)$$

$$A(t) = K_p \times\ e\ (t) \qquad (2)$$

K represents the proportional constant. For the controller to use the feedback control method to amplify the error signal, K needs to be greater than 1 as shown in **Figure 2.2.**

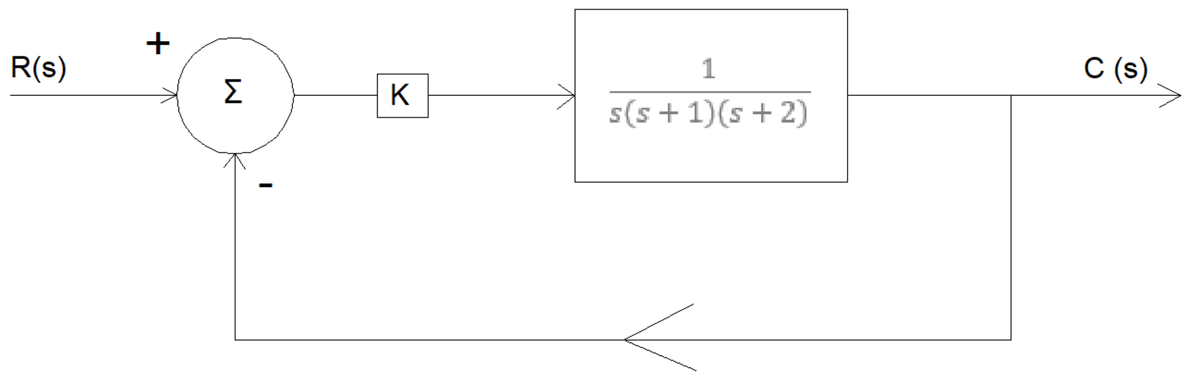

Figure 2.2: **Feedback Control System with Proportional Controller** (Teferra & Ngoo, 2021)

K in the diagram represents a proportional controller or the error amplifier and it can be represented in the form of the closed-loop characteristic presented in equation (3).

$$S^3 + 3S^2 + 2S + K = 0 \qquad (3)$$

According to the Routh-Hurwitz criterion, K can determine if the system is stable or not stable. If K>6 then the system is unstable but if 0<K<6 (less or greater than zero is the operator to use), the system is stable.

2.4.2 Integral Controllers

The output of the integration controller is proportional to the sum of the errors. The controller is also called a reset controller because it resets the controller to the actual setting. (Padmane & Rane, 2015) The mathematical expression for the integral controller is shown in Equation (5).

$$A(t) \propto \int_0^t e(t)dt \qquad (4)$$

$$A(t) = K_i \times \int_0^t e(t)dt \tag{5}$$

Ki: Represents the Integral constant

2.4.3 Derivative Controllers

Although the derivative controller's output is directly proportional to the error signal's derivative, it is unable to reduce steady-state error and exacerbates the system's noise signals. The derivative controller is also called “rate controller’’ and its mathematical expression is shown in the equation (7).

$$A(t) \propto \frac{de(t)}{dt} \tag{6}$$

$$A(t) = K_d \times \frac{de(t)}{dt} \tag{7}$$

Kd: Represents the proportional constant

2.4.4 Proportional and Integral Controller (PI Controller)

The proportional and integral controller is the combination of the output of the proportional and integral error signal as shown in the formula below:

$$A(t) \propto \int_0^t e(t)dt + A(t)\, \alpha\, e(t) \tag{8}$$

$$A(t) = K_i \times \int_0^t e(t)dt + K_p \times e(t) \tag{9}$$

The PI controller reduces the stability of the system due to the additional pole added at the origin, but reduces significantly the steady-state error, and it is one of the most used controllers in the control system. Figure 2.3 shows the schematic diagram of the PI controller with K=5.8 and Ki=0.2.

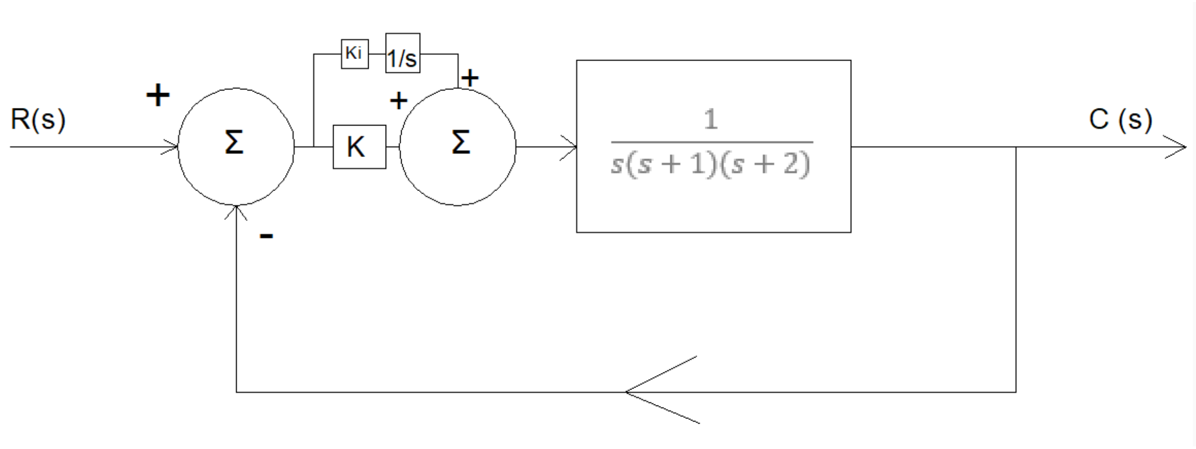

Figure 2.3: **The closed-loop control system with PI controller** (Teferra & Ngoo, 2021)

2.4.5 Proportional and Derivative Controller (PD Controller)

The proportional and derivative controller is the combination of the output of the proportional and derivative error signal as shown in the formula below:

$$A(t) \propto \frac{de(t)}{dt} + A(t)\; \alpha\; e\,(t) \qquad (10)$$

$$A(t) = K_d \times \frac{de(t)}{dt} + K_p \times e\,(t) \qquad (11)$$

It is important to understand that adding zero and pole should improve the stability of the system as shown in Figure 2.4 (Mandeng & Kom, 2020).

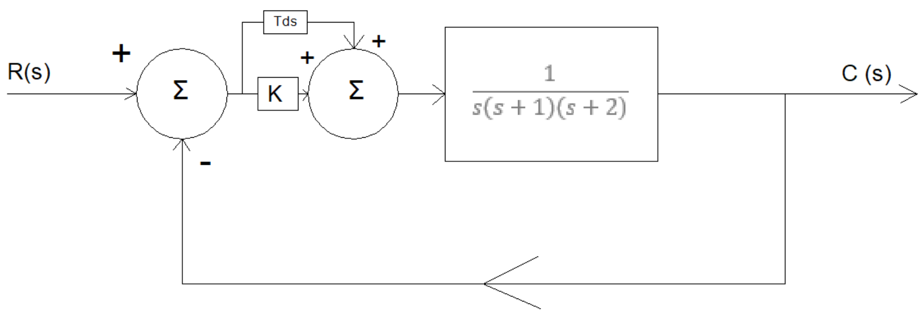

Figure 2.4: **Closed-loop control system with PD controller** (Teferra & Ngoo, 2021)

2.4.6 Proportional plus integral plus Derivative Controller (PID Controller)

In industrial control applications, the PID controller is primarily used to control process variables such as pressure, temperature, speed, and flow rate. Figure 2.5 shows the closed-loop control system with PID Controller (Mandeng & Kom, 2020).

PID controllers are the most accurate and reliable controllers because they use a feedback loop to control different processes. This controller has zero steady-state error and accepts continuous feedback.

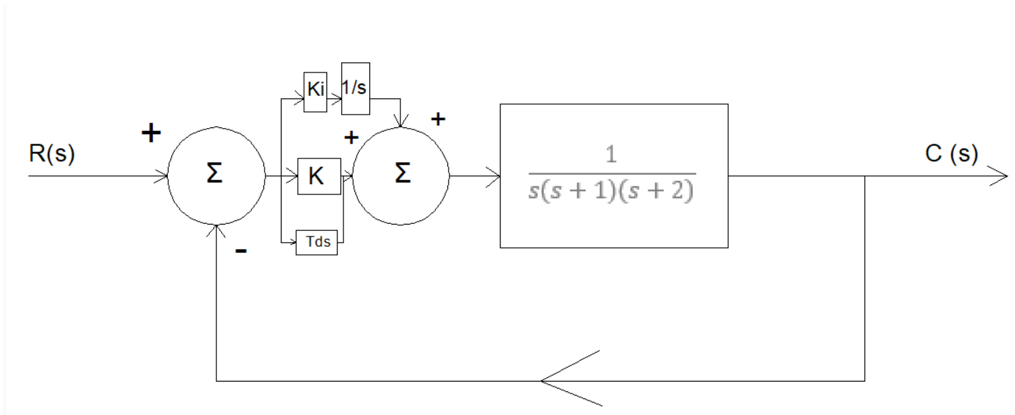

Figure 2.5: **The closed-loop control system with PID Controller** (Teferra & Ngoo, 2021)

2.4.7 Fuzzy Logic Controllers (FLC)

Fuzzy logic controllers (FLC) are used for highly nonlinear systems such as electrical systems because electrical systems have dynamic behaviors. Although FLC does not require a particular mathematical model, it can exhibit a higher degree of disturbance sensitivity than other non-linear controllers. After many studies performed by different researchers, FLC has been considered the best controller to be used for complex, nonlinear, and undefined systems (Yilmaza et al., 2018). Figure 2.6 shows the block diagram of the fuzzy logic controllers

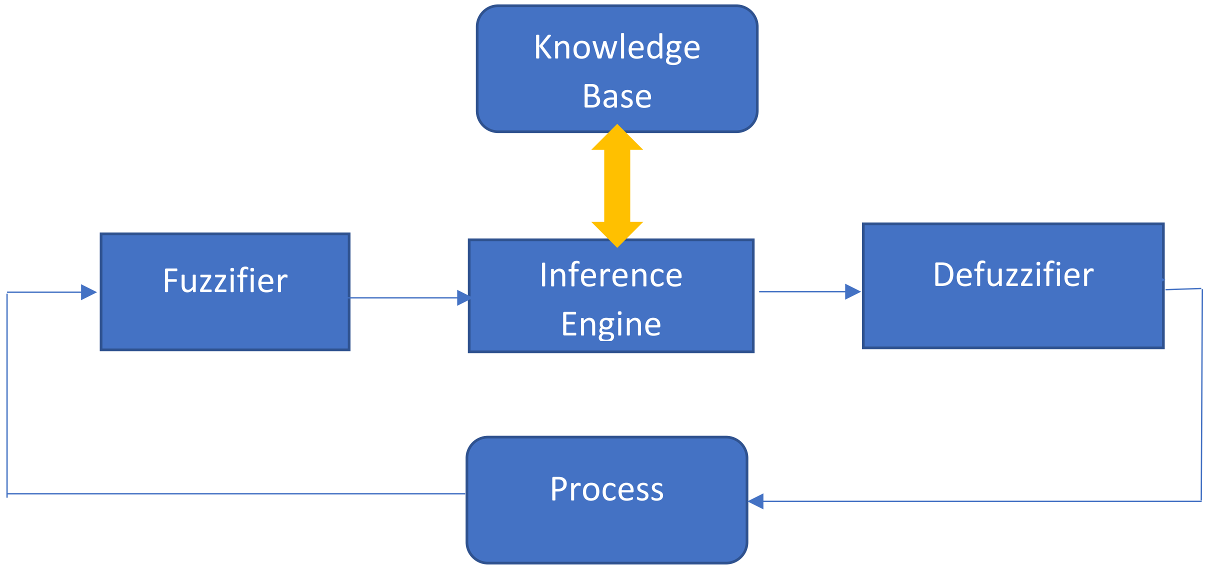

Figure 2.6: **Block diagram of the fuzzy logic controllers** (Algarin et al., 2017)

The fuzzy logic controller comprises four components: a fuzzifier, rules, an inference engine, and a defuzzifier. Those components of Fuzzy logic serve as control logic that uses degrees of input and output to simulate human reasoning by integrating rule-based implementation. This technique manipulates and manages uncertain or imprecise information or facts. Fuzzy logic controllers include connectives like conjunctions and disjunctions to handle degrees of uncertainty. Additionally, there is a set of inference rules for making decision statements. These rules help to represent a type of human expertise.

2.4.8 Interphase Power Controller (IPC)

Interphase Power Controller (IPC) is considered one of the newest concepts for controlling power flow in AC networks. IPC is suitable for short-term situations, normal situations, unexpected situations, and safety issues. It has also been shown that IPC can do unlimited work and provide reactive power to control voltage, as it does not produce harmonics and does not change variation (Padmane & Rane, 2015).

2.4.9 Unified Interphase Power Controller (UIPC)

Unified Interphase Power Controller (UIPC) is a controller made of Static Synchronous Series Compensators (SSSC) and due to the SSSC structure, the UIPC is suitable for controlling the flow of power. The FLC mechanism with UPFC can provide great stability to the system (Arouna et al., 2019).

After analysing each controller, their performance, applications, structures, and configurations, the fuzzy logic controller has been identified as the best option to be used for this project. This choice was firstly based on the system that will be studied in this project. This project consists of developing a controller for PV and Wind energy systems. These renewable energy systems produce non-linear outputs such as electricity. Thus amongst all the controllers stated above the most suitable controller for non-linear outputs is the Fuzzy logic controller. Furthermore, The PV and Wind energy systems are unstable due to the inconsistency of the sun radiation and wind flow. Therefore, the fuzzy logic controller has a great ability to control a system with sudden changes and disturbances (Yilmaza, et al., 2018).

2.5 Photovoltaic (PV) Energy

Some research has been also conducted in Angola and it has been found that more than thirteen million Angolans, or about twenty-six percent of the population, have no access to electricity, according to the International Energy Agency (IEA) (Anon, 2020).

Many areas in Angola have no electricity and the areas that have electricity can experience blackouts and load shedding almost every week (Tallungs, 2021).

As shown in Figure 2.7, from 1980 to 2018, hydroelectric power constituted 58% of Angola's energy consumption, while fossil fuels accounted for 35%, gas for 4%, and biomass energy for 3%. This indicates that solar energy has not yet been utilized in the country (Tallungs, 2021).

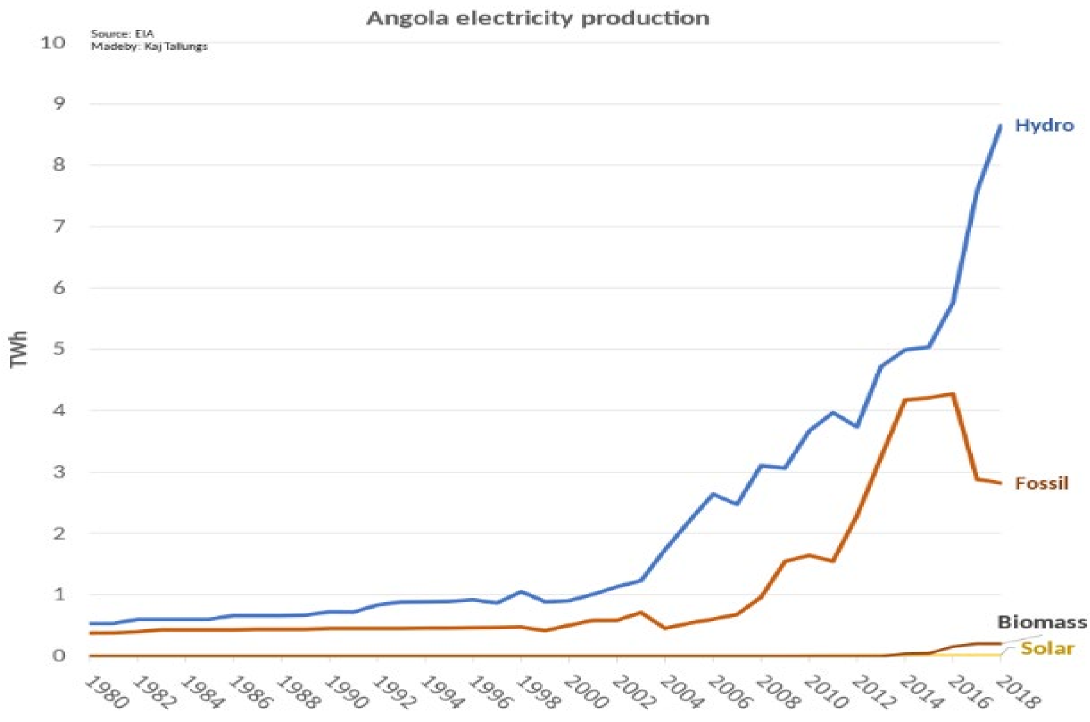

Figure 2.7: **Angola Electricity Production** (Tallungs, 2021)

Some companies and organizations such as the big French company Total have been planning to start a project regarding the implementation of a solar power plant in Angola (Deboutte & Gwenaelle, 2020). Total has a project to promote and install renewable energy sources in Angola with a capacity of about 800 Megawatts by the end of 2025, but Total is still analysing all the factors that can negatively affect the implementation of this big project in Angola (Deboutte & Gwenaelle, 2020). The company confirmed that the country has a great potential for solar energy as shown in Figure 2.8. The success of this project will highly improve the electrical conditions of the country and will also give more job opportunities to Angolans.

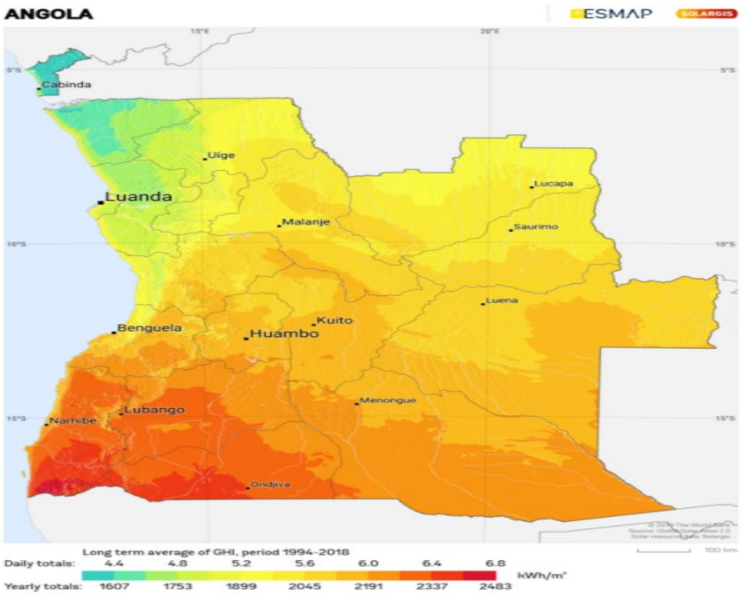

Figure 2.8: **Zone-based Solar Irradiation of Angola** (Tallungs, 2021)

An endless and free source of energy is the sun. Solar energy can meet the world's energy demands and needs if suitable technology is available. Figure 2.9 shows around 1.018 Kilo joules of solar energy reaching Earth annually (Kabira et al., 2018). Despite this, the world continues to disregard the usage of such a potential source of energy. Additionally, using solar energy can greatly reduce global current emissions, which severely impact the environment, society, and economy of many nations worldwide.

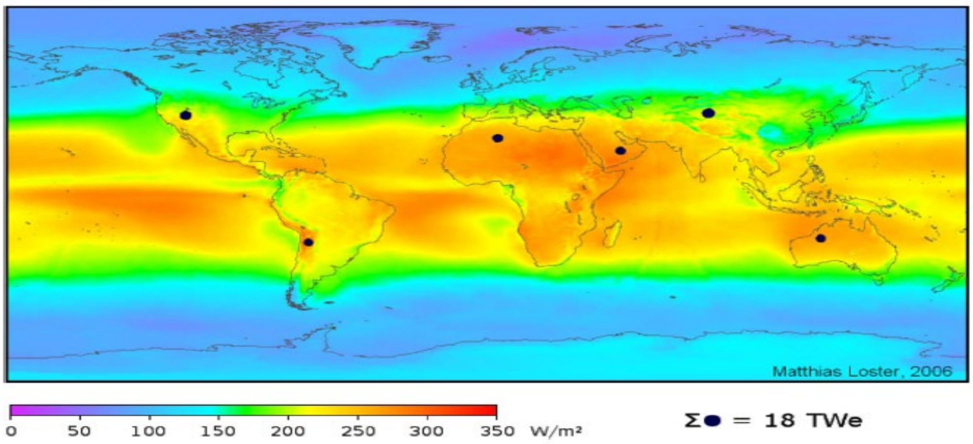

Figure 2.9: **Annual average solar irradiance distribution over the surface of the Earth** (Kabira et al., 2018)

2.5.1 Elements of Solar Energy

The radiation of the sun can produce energy called, solar energy. This energy can be used in many sunny countries, and it is composed of four elements namely; panel, inverter, and solar battery storage as shown in Figure 2.10 (Kabira et al., 2018).

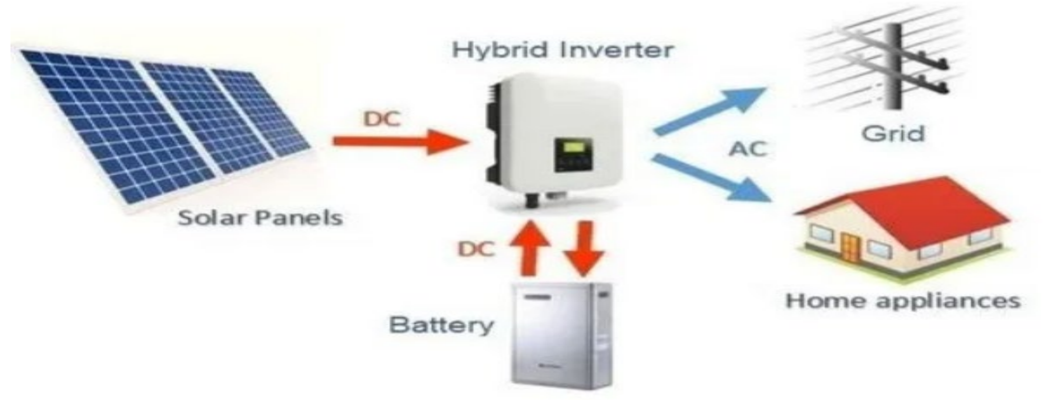

Figure 2.10: **Elements of the solar energy system** *(Gajewski & Nkowski, 2021)*

2.5.1.1 Panels

Another name for solar panels is photovoltaic modules, they are visible devices that are mostly found on the roofs of houses and buildings. These devices collect sunlight from nature and convert it into electricity. The solar panels generate DC current from solar irradiation, they are composed of six main components as shown in Figure 2.11 (Sumathi et al., 2015).

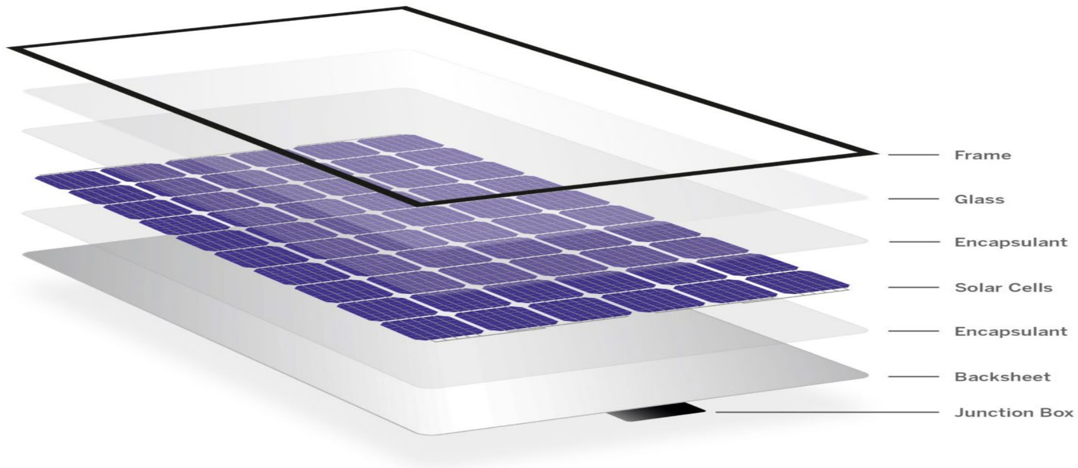

Figure 2.11: **Main Components of the Solar Panel** (Kumar et al., 2017)

- **Frame:** The purpose of this part is to secure and seal the solar panel. It is also in charge of guarding against damage and shattering of the solar cell and glass (Chad et al., 2016).
- **Glass:** This component is in charge of absorbing and reflecting the heat that the sun emits.
- **Encapsulant:** This part, which is primarily composed of polymeric materials, is in charge of fostering adhesion between the solar panel's top and bottom surfaces
- **Solar Cells or Photovoltaic Cells:** These elements produce electricity from solar energy. Figure 2.12 shows the inside functioning of solar cells.
- **Back sheet:** This part of the solar panel is in charge of providing mechanical protection as well as electrical insulation (Gajewski & Nkowski, 2021).
- **Junction box:** This part guarantees that power flows through a solar panel continuously and without interruption and acts as a home or enclosure for all of the electric components (Algarin et al., 2017).

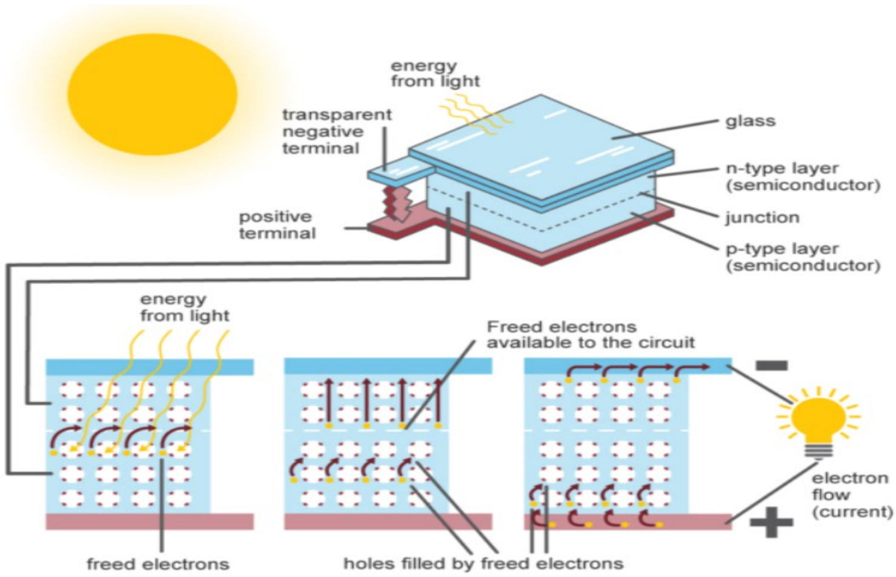

Figure 2.12: **Inside operation for a photovoltaic cell** (Sumathi et al., 2015)

2.5.1.2 Inverters

The inverter is a device that is responsible for converting the DC produced by the solar panel into AC. This device can easily get damaged, thus it is important to always purchase a high-quality inverter during the installation phase (Chad et al., 2016).

There are two types of inverters namely; the string inverter and the microinverter. The string inverter is mostly installed on a wall and converts the energy from the source into AC current and then distributes it to homes and houses. The microinverter is mostly installed on the rear of the panel to maximize the output power (Yilmaza et al., 2018).

2.5.1.3 Racking

Solar racking or mounting is a device used to hold the solar equipment in place as shown in **Figure 2.13**. This device can affect the overall performance of the solar system if bad-quality racking is used in the installation phase (Mahdi et al., 2020). Various solar companies use quantity instead of quality just to get the installation done and get money, but those companies put at high risk the houses of the consumers. It is recommended to spend more money to get a safe installation that will last for years (Algarin et al., 2017).

Figure 2.13: **Solar racking/mounting** (Sumathi et al., 2015)

2.5.1.4 Batteries

Batteries are devices used to store energy generated during the day and use it throughout the night when there is no more solar irradiation to produce electrical energy. The cost involved to include the batteries in the solar energy system is significantly high but the batteries are one of the most important keys to having a great performance of any renewable energy system (Algarin et al., 2017). Section 2.7 gives more details regarding the battery system for renewable energy.

2.5.2 Operation of the Solar Energy System

When the sunlight reaches the semiconductor material of the solar cell, it releases some electrons to the solar cells which in turn produces electrical energy. The electrical current produced in the solar panel is DC and needs to be converted into AC, this conversion is performed by the inverter. Then the AC power converted by the inverter can be supplied to the grid, the battery, and the consumers as shown in Figure 2.14 (Sumathi et al., 2015).

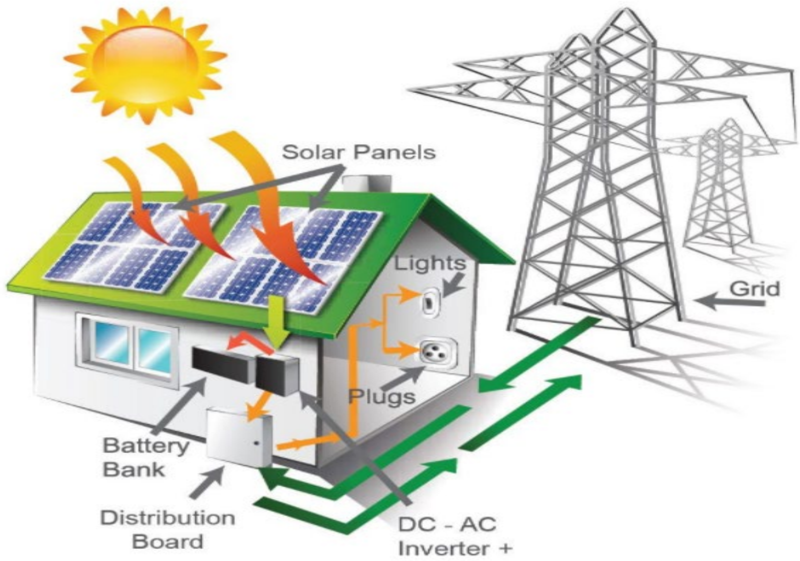

Figure 2.14: **How the solar energy system works** (Kabira et al., 2018)

2.5.3 Limitations and Benefits of Solar Energy Technologies

This renewable energy can significantly improve the electrical conditions in the world and can also positively impact the economy of many countries around the world but this renewable energy has some limitations and benefits to take into consideration (Algarin et al., 2017).

The main limitations of Solar Energy Technology that need to be always taken into consideration are the following:

- The initial installation cost is significantly high
- The efficiency of most solar panels is between 10 to 20 % and Solar panels with an efficiency bigger than 20% are expensive
- The batteries needed in solar energy technology are significantly expensive
- Few skilled people know how to install solar system
- Solar technology is exposed to dust, water, and other weather conditions that can affect the performance of the system

Every system has some disadvantages and advantages or benefits. Solar energy technology has also various benefits such as:

- The sun is abundantly available around the world, thus solar energy can satisfy the demand of the entire world.
- Solar energy is inexhaustible
- Solar energy is environmentally friendly. The worldwide range of CO2 emission per kilowatt-h generated from coal is between 0.64-1.64 kg and from natural gas is 0.27-

091 kg. Thus, CO_2 emission gases around the world can be highly reduced by using solar energy and human health can be highly improved (Ngang & Aneke, 2021).

- Solar energy technology creates job opportunities
- It reduces the number of electricity bills
- The maintenance cost is low (Mandeng & Kom, 2020).
- The implementation of solar energy technology can reduce the problems of energy security, climate change, and unemployment (Bocklisch, 2015).

2.6 Wind Energy

The energy produced from wind is called wind energy. This renewable energy has recently been used in all parts of the world (Anon, 2020). Temperature, location, and global changes all affect the availability of wind energy. Wind energy is obtained by converting the kinetic energy of the air into electrical energy through wind turbines (Bocklisch, 2015).

The wind energy system like any other system presents some advantages and disadvantages. The most important advantages of using wind energy are:

- The electricity bills can significantly decrease
- Fewer power outages occur.
- Less risks to the environment because wind energy is environmentally friendly.
- Efficient and effective use of electricity at an affordable cost.
- Less human effort because the wind turbines can operate without human intervention (Kumar et al., 2017).

On the other hand, wind energy also presents some disadvantages such as:

- The Wind energy system is very noisy.
- The wind turbines kill birds as shown in Figure 2.15.
- The success of wind turbine installation depends on the location. Few locations are suitable for wind energy.
- Wind is not reliable in nature, and due to this situation, wind turbines generally operate at about 30% capacity.
- Bad weather can harm wind turbines.
- The initial cost to install the wind energy system is extremely high (Kumar et al., 2017).

Figure 2.15: **Wind turbines killing birds** (Kumar et al., 2017)

2.6.1 Wind Turbines

Devices that transform kinetic energy into electrical energy are called wind turbines. Depending on the wind speed, the wind turbines range in height from 80 to 120 meters. The wind turbine is composed of many parts namely as shown in Figure 2.16.

- **The Blades:** The blades in the wind turbine are responsible for harnessing wind energy
- **The Wind Vane:** This part is responsible for measuring the direction of the wind to orient the wind turbines to the direction of the wind.
- **The anemometer:** This apparatus gauges wind speed and transmits wind speed information to the controller.
- **The Nacelle:** It is the cover housing for the mechanical and electrical components of the wind turbines.
- **The shaft:** It performs heavy-duty operations and carries the loads.
- **The yaw mechanism:** This device is used to turn the wind turbine rotor towards the wind.
- **The rotor:** It consists of three blades, and it is responsible for capturing the force of the wind and converting it into mechanical energy.
- **The multiplier:** It is in charge of raising the rotational speed from 35 rpm to 1500 rpm.
- **The generator:** It is the generator's job to transform mechanical energy into electrical energy.

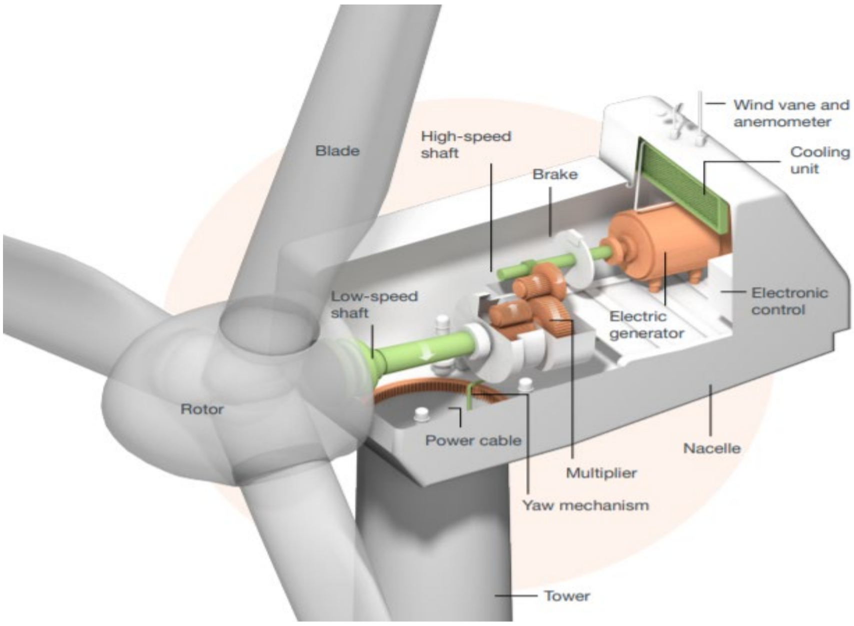

Figure 2.16: **Parts of the wind turbine** (Kumar et al., 2017)

Each year around the world the capacity of wind turbines has been increasing and according to the International Renewable Energy Agency, Wind turbines with a capacity of about 8 Megawatts have been available since 2020 (Anon, 2020).

Figure 2.17 shows an exponential global increase in the wind turbine's capacity from 2010 to 2020 (Anon, 2020).

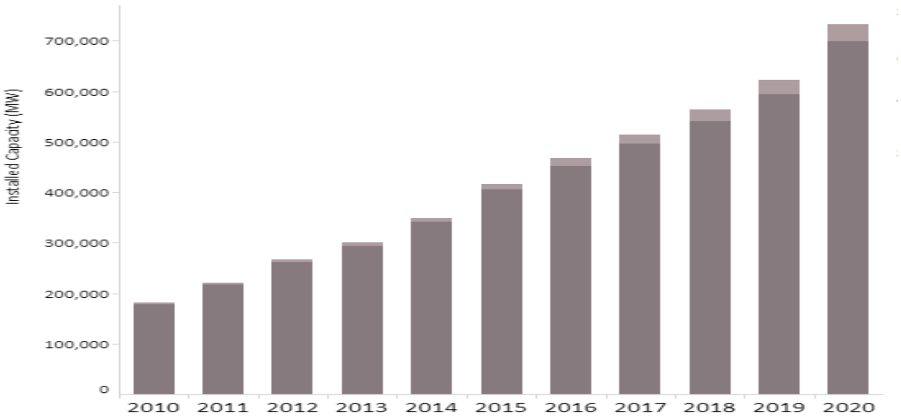

Figure 2.17:**Average Capacity of wind turbines** (Chad et al., 2016)

2.6.2 Classification of Wind Turbines

The two types of wind turbines are the Vertical Axis Wind Turbine (VAWT) and the Horizontal Axis Wind Turbine (HAWT) respectively as shown in Figure 2.18 (Baloch et al., 2016). Each of these categories of wind turbines has advantages and disadvantages. HAWT is largely used for commercial purposes and they are mainly used because they are cost-effective. On the other hand, the VAWT has perpendicular or vertical rotating axes. The configuration of the rotating axes makes the wind from every direction and does not need the yaw power to operate (Kumar et al., 2017). For the success of wind energy, it is extremely important to know the difference between HAWT and VAWT before deciding which one to install. **Ta**ble 2.1 provides more details about the difference between the HAWT and the VAWT wind turbines.

Figure 2.18: **Horizontal and Vertical axis wind turbine (Sumathi et al., 2015)**

Table 2.1: **A comparison study of HAWT and VAWT (Kumar et al., 2017)**

HAWT	VAWT
It is suitable for big wind applications.	It is suitable for small wind projects and residential applications.
It is heavy and not suitable for turbulent winds.	It is light and is suitable for turbulent winds.
It is powered by the wind in a specific direction.	It is powered by the wind coming from all 360 degrees.
It is not suitable to generate electricity from the wind speed below 6m/s and above 25m/s.	It is suitable to generate electricity from the wind at a minimum speed of 2m/s and a maximum speed of 25m/s.
HAWT cannot resist extreme weather conditions due to frost, freezing rain, or heavy snow.	VAWT can resist to extreme weather conditions.
HAWT is difficult and expensive to transport and install.	VAWT is cheaper to transport and install

2.6.3 Wind Turbine Control

For an efficient wind turbine's performance, the best control systems must be put in place. There are many control systems in wind energy technology, but the main control systems are pitch control, passive control, active stall control, and Yaw control systems (Chad et al., 2016).

2.6.3.1 Pitch Control

The pitch control consists of optimizing the blade angle to achieve the correct rotor speeds and the required power output of wind turbines. Optimizing the blade angle also protects the system when the wind speed is high (Chad et al., 2016).

The disadvantage of this method is that each blade is affected by wind turbulence. Due to this situation, there is a need for a technique that can control each blade. The pitch control systems can be hydraulic or electronic. Figure 2.19 shows how the hydraulic pitch actuator rotates a blade (Chad et al., 2016).

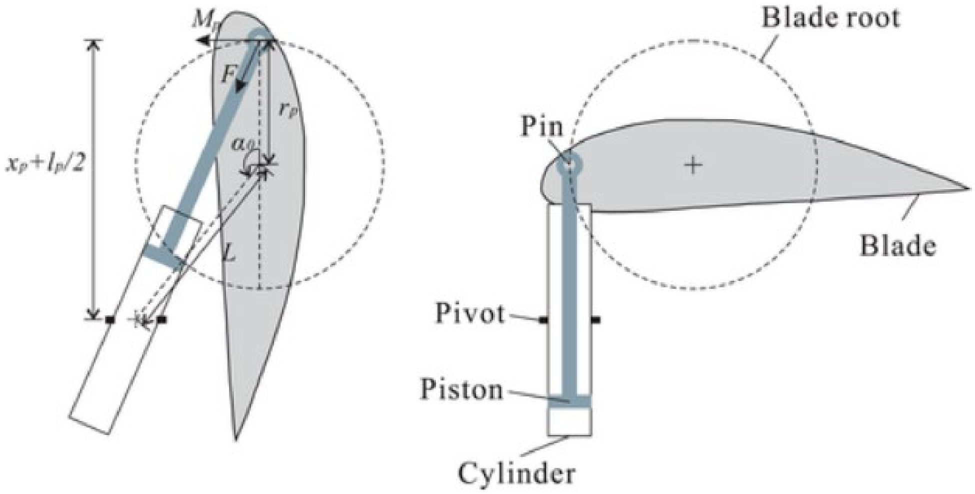

Figure 2.19: **Hydraulic Pitch (Chad et al., 2016)**

The electric pitch control systems are more powerful than the hydraulic pitch control system. Figure 2.20 shows the configuration of the engine of the electric pitch control system.

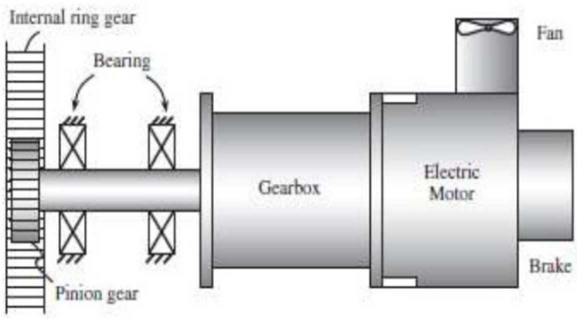

Figure 2.20: **Electric pitch control system** (Chad et al., 2016)

2.6.3.2 Stall Control

Stall control is another technique to control the wind turbine by keeping the stall-regulated wind turbine operating at a steady speed in the strong wind without generating too much power or altering the rotor shape. There are two types of stall-control systems namely; the passive stall-control system and the active stall-control system (Sumathi et al., 2015).

The passive stall control system does not make use of a complex control system. The configuration is simple and due to this simplicity, this system has a reliable control system but like any other system, this system has some disadvantages such as low performance, the need for some additional equipment, and starting devices.

2.6.3.3 Yaw Control

An essential component of the wind turbine control system is the yaw control system. Yaw error is the term used to describe the discrepancy between the wind direction and the wind turbine's position. The yaw control system consists of a gearbox electric motor, an electric bull, a windscreen, and a brake (Liu et al., 2021).

2.6.4 Wind Power Parameters

The wind A turbine gathers air energy and converts it to electrical energy. A few of the variables that impact the amount of energy extracted from the air are air density, turbine swept area, air velocity, and power coefficient (Badrana et al., 2014) as shown in the equation below:

$$P = 0.5 \times \rho \times C_p \times V^3 \times A \tag{12}$$

Where:

P represents the mechanical power in the moving air

ρ is the air density

A is the area swept by the rotor blades

V is the velocity of the moving air

C_p is the power Coefficient.

2.7 Findings from the existing literature

Some reviews and studies have been conducted regarding the controller for renewable energy for power transmission networks, but those reviews focus more on the monitoring functions and the protection functions, for instance In the agricultural sector, (Septiarini, et al., 2021) experiment over ten days to monitor a solar charging system utilizing the fuzzy logic controller.

(Septiarini, et al., 2021) also look into the Fuzzy Logic Controller (FLC)-supported autonomous battery charging system for powering a mobile manipulator. The outcomes of the experiment indicate that a solar-powered robot is feasible, and this robot is perfect for agriculture. Furthermore,(Siva & Balaraman, 2022) Established a monitoring system that uses a fuzzy logic controller to harvest solar photovoltaic system electricity in response to shifting environmental conditions the results after the experiment show that with good monitoring of the Fuzzy Logic Controller, a solar system can maximize its efficiency. (Guntupalli, et al., 2022) create protection functions for a traditional grid by employing the Constant Current Controller (CCC) to safeguard the grid. The results show that optimizing the protection capabilities of the Constant Current Controller can be achieved by integrating the 3-Φ Pulse Width Modulated Voltage Source Inverter (PWM-VSI) into the system. (Gajewski & Nkowski, 2021) explain the mathematical models of the various components of hybrid renewable energy systems and use simulations to put the Maximum Power Point Tracking (MPPT) algorithms into practice for more efficient energy conversion in renewable energy systems. Simulation results indicate that a direct-driven Permanent Magnet Synchronous Generator, photovoltaic panels, and a battery energy system can guarantee a superior control system. (Riad, et al., 2023) create a fuzzy logic controller design type 2 for a process workstation to address the issue of imprecise and uncertain data within the system. When compared to the type 1, the design's outcomes suggest that the type 2 fuzzy controller performs far better. (Yilmaza et al., 2018) create and construct a fuzzy logic controller to track a 65-watt photovoltaic system's maximum power point. MATLAB/Simulink was utilized for the design and modelling, and the outcomes show that the fuzzy logic controller is a good choice for managing power loss and oscillations in PV systems at the operating point. To enhance the performance of the air purifier, (Emenuvwe, et al., 2023) design and implement a fuzzy logic controlled-intelligent air purifier/humidifier device. The designed device's noise level is less than 40 decibels, which is the typical threshold for an air purifier, according to the data. In addition, the gadget took 68 minutes to raise the humidity in a designated area from 21% to 40%. (Kumar et al, 2017) simulated a radial basis function network-based single MPPT controller in the hybrid renewable system which consists of a 560W PV system and 500W wind energy to track the maximum power incorporated with the Boost converter and the results show that for a period of 0 to 0.3 seconds, the system gives an average power of 587W with solar irradiation of 600 W/m^2 and wind speed of 8m/s, for a period of 0.3 to 0.6 seconds the system gives an average power of 721W with solar irradiation of 800 W/m^2 and wind speed of 10m/s. Therefore, the more solar irradiation for the PV system the more power, and the more wind speed for the wind system the more power as well. (Kadia & Jamnani, 2012) developed a controller using Thyristor Controlled Series Capacitors (TCSC) and analysed various events in the power transmission network such as faults and losses on long transmission lines. The analyses conducted during the modelling confirm that the TCSC controller helps to increase the power transfer and maintain the power system stability of the power network by improving the load angle. Therefore, the TCSC controller is an efficient tool to improve the overall performance of an electrical power network. (Mandeng & Kom, 2020) discuss the Interphase Power Controller for the PV system for the power transmission. The interphase power controller is a flexible alternative current for the transmission system (FACTS) that manages fault current and stabilizes power flow, among other non-harmonic functions. The best solution for ensuring proper management and limiting fault currents in power transmission lines is to utilize IPC. (Mahdi et al., 2020) create an Adaptive Virtual Impedance Controller (AVIC) to improve wireless power transfer efficiency using MATLAB/SIMULINK simulations, It was found that an adaptive resonant controller is much more efficient than a non-adaptive resonant controller.(Chad et al., 2016) Perform the modelling and simulations of a hybrid energy system which consists of a wind generator and a photovoltaic solar system using MATLAB/SIMULINK to obtain an efficient system response and to make the system more compatible. Furthermore, the authors identify an incompatibility of the wind and PV sources in a DC coupling and propose the development of a control strategy for DC bus loads and sources by using adaptor switches. (Bocklisch, 2015) create controllers for pitch-regulated constant-speed wind turbines by researching the challenges associated with implementing feedback linearization and direct linearization techniques to account for nonlinear aerodynamics. (Muhammad Junaid, 2013) Illustrates how WAMS will provide safe and efficient energy transfers. It can also optimize the management of the grid. (Muhammad Junaid, 2013) Also demonstrates that fuses are used more in power supply, transmission networks, and associated equipment to lower the cost and provide reliable protection. (Stojcevski, 2013) pay attention to the faults of the overhead transmission lines and the distance fault error. (Stojcevski, 2013) Also discusses different types of fault locator algorithms derived from frequency, time, and high-impedance domains. Less attention is given to the development of a specific controller for PV and wind energy for power transmission networks. Therefore, this research project focuses on the development of a controller for PV and wind energy for power transmission networks.

2.8 Discussion on the reviews

Various articles and experiments have been reviewed in this literature review to find the gap in the application of the controllers. It was proved that most of the previous studies focused more on IPC for the adjustment of the voltages and flow of the power. Some studies conducted by researchers focus more on the FLC and UIPC on the control of the flow of the current and power in the system. Furthermore, a few researches also show that Artificial Neural Network controllers reduce the oscillations. The proportional controller (PI) as well as the integral controller, have been also largely used, researchers and scientists demonstrated that the proportional controller (PI) is one of the controllers that is mainly used to minimize the rise time and to increase the speed of the response. (Algarín, et al., 2017) used the proportional controller to reduce the transient period for electricity-gas integrated energy systems (IESs), but the challenge was to find the stability range of feedback systems. Furthermore, the PI controller was also unable to detect the trends in the system and adjust them while the integral controller can easily minimize the time-invariant error in the system. On the other hand, it has been also observed that many researchers and engineers have been using the derivative controller in many integrated energy systems and in cruise control systems to reduce transient errors such as overshoot and oscillations in the output of the systems.

Although the Fuzzy Logic Controller and FLC can be used to regulate an automatic fan, this approximation model of probability is inaccurate when considering the fuzzy logical operations of OR and AND as probabilities. When these fuzzy logical procedures are used, fuzzy inference may potentially fall short (Yilmaza et al., 2018)). The failure of the fan system under non-standard operating conditions or when fuzzy logic OR and AND operations are applied was the second issue that was found. Furthermore, according to (Yilmaza et al., 2018), who designed and modelled the Fuzzy Logic Controller for tracking a 65-watt PV system's maximum power point. It has been also observed that it is very challenging to select the membership function that can correspond exactly with the system being implemented or developed, a wrong choice can lead to undesired results on the output. The Fuzzy Logic Controller can require a lot of work and effort to implement. Lofti Zadeh, a mathematician and computer scientist, conducted trials with the Fuzzy Logic Controller and reported that it is variable, produces results that are impossible for a person to acknowledge, and is too complex for practical application (Emenuvwe, et al., 2023). The Fuzzy Logic Controller was also used to control the speed and the blade pitch angle of the wind energy system. The FLC was also able to improve the system responsiveness and minimize the overshoots, but the main challenge was the steady-state error that was constantly occurring in the wind energy system due to the lack of integral action of the fuzzy logic controllers. This steady-state error was causing power instability in the wind energy system (Qi & Meng, 2017). Further studies were also performed on the Fuzzy Logic Controller-based Individual Pitch Control (IPC) for the wind energy system to mitigate fatigue loads and regulate output power. The FLC was able to reduce the fatigue loads in the turbine, but the regulation of the power was not successfully achieved in the system (Han, et al., 2016).

As discussed above, each existing controller presents some strengths and weaknesses as per normal logic there is no perfect system. Therefore, it is important to identify the weaknesses that can significantly affect the performance of the controllers that will be developed in this project, bearing in mind that the controller for this project should be able to integrate solar energy into the power network to achieve power stability. After an extensive review of many articles regarding different types of controllers, it has been identified that the Fuzzy Logic Controller is the most suitable controller to be used for solar energy. Many important facts were discovered on Fuzzy Logic Controllers and scientists have tried to address most of the past and current challenges regarding Fuzzy Logic Controllers except the challenge of the power stability in the PV system and this fact has been considered as a gap.

This research project aims to address the problem of power stability in the solar energy system by developing a Fuzzy Logic Controller-based Maximum Power Point Technique and then by running a few simulations and performing a load flow analysis through MATLAB to ensure that the developed controller can achieve power stability in the solar system. The next chapter will discuss in detail the performance and operation of the fuzzy controllers' based Maximum Power Point Technique in the solar energy system.

2.9 Conclusion

In this chapter, the literature review was conducted on different types of controllers, and each of them has been discussed in detail. The controller in this research project will be integrating solar energy with the national grid to offer power stability, thus better knowledge can be achieved by conducting a literature review on these energy sources. The maximum power point technique has been identified as the best method for the Fuzzy Logic Controller to achieve power stability. Furthermore, the uses of each controller were discussed and the challenges faced in the past with these different controllers were discussed in detail to identify the gap and the most suitable controller for this project.

CHAPTER THREE

THE PERFORMANCE AND OPERATION OF THE FUZZY LOGIC CONTROLLERS BASED ON THE MAXIMUM POWER POINT TRACKING TECHNIQUE

3.1. Introduction

Fuzzy logic control is a critical thinking approach procedure introduced by Professor Lotfi Zadeh in 1965. This approach applies the concept of human thinking in the design of non-linear controllers to develop and implement control systems. They are used for highly non-linear systems such as electrical systems because they have dynamic behaviors. Fuzzy Logic Control does not need a specific mathematical model (Yilmaza et al., 2018).

The Fuzzy logic controller is composed of various components that play different functions in the system, equipment, and programming. Therefore, it is important to understand the role that each component plays to achieve efficiency and stability in the power network. The performance and the best operation of these controllers always depend on factors such as the design, the technique used, and the analysis performed. In this chapter, the advantages, and disadvantages of the fuzzy logic controller will be established, each component of the fuzzy logic controller will be discussed, then the fuzzy logic controller operation will be explained. Furthermore, the important processes such as Fuzzification and Defuzzification will also be explained in detail. The fuzzy logic controller operation and performance will also be discussed. To achieve great performance of the fuzzy logic controller the maximum power point technique will be used and the load flow analysis will also be conducted in the system. There is a good relationship between the maximum power point technique and the load flow analysis when it comes to the application and development of an efficient controller for renewable energy systems. The load flow analysis investigated in detail the flow of the power in the PV system so that the Maximum Power-Point Tracking (MPPT) Technique can be easily applied to the systems and can help the controller harvest the most power possible from PV panels to achieve good stability, even in unstable conditions.

The chapter is divided into numerous sections, each of which offers particular knowledge required to create an effective controller. In Section 3.2, the benefits and drawbacks of the fuzzy logic controller are covered. The functions of each component of the fuzzy logic controller are explained in depth in Section 3.3. Fuzzy logic control operations and processes are covered in Section 3.4. A basic description of the fuzzy logic controller-based maximum power point technique is presented in Section 3.5, and the suggested fuzzy logic controller for PV and wind energy systems is concluded in Section 3.6.

3.2. Advantages and disadvantages of Fuzzy Logic Control

Every controller has some advantages and disadvantages. Therefore, it is important to understand the benefits and limitations of the fuzzy logic controller to decide on the best design and configurations. **Table 3.1** shows the advantages and disadvantages of fuzzy logic control.

Table 3.1: Advantages and Disadvantages of the Fuzzy Logic Controller (Amira, et al., 2021).

Advantages	Disadvantages
Cheaper	Requires lots of data to operate
Robust	It is not appropriate for programs with a capacity higher than their historical data.
Customizable	Requires significant human expertise
Reliable	Needs regular updating of rules
Efficient	It requires a lot of testing for validation and verification
Easy to understand	The fuzzy rationale is not always exact.
It can perform like a human which makes it more efficient in terms of control.	
It can operate efficiently with noisy inputs.	
It works efficiently in highly non-linear systems.	
It has a very simple user interface.	

3.3. Components of Fuzzy Logic Controllers (FLC)

It is important to understand the structure of the FLC in a system. Many components are combined to enable the operation of the Fuzzy Logic Controller and the major components of the FLC are described below.

- **Fuzzifier:** This component is responsible for converting the crisp input values into fuzzy values.
- **Fuzzy Knowledge Base:** This component is responsible for storing the knowledge about all the input-output fuzzy relationships.
- **Fuzzy Rule Base:** This component is responsible for storing the knowledge about the operation of the process of the domain.
- **Inference Engine:** This component simulates human decisions during the controlling process.
- **Defuzzifier:** This component is responsible for the conversion of the fuzzy values into crisp values from the fuzzy inference engine (Haddad, et al., 2020).

3.4. Fuzzy Logic Controller Operation

The Fuzzy Logic Controller operates through its components as shown in Figure 3.1**.** The Fuzzifier enables the numerical input variables to be converted into understandable variables and then sent to the Fuzzy inference engine which in turn gets activated by the input variables received. As soon as the fuzzy inference engine is activated the fuzzy knowledge base also gets automatically activated and both produce the output fuzzy variables and send them to the Defuzzifier which in turn converts the output fuzzy sets received into a quantifiable result or value so that the controller can fully understand the received information (Riad, et al., 2023).

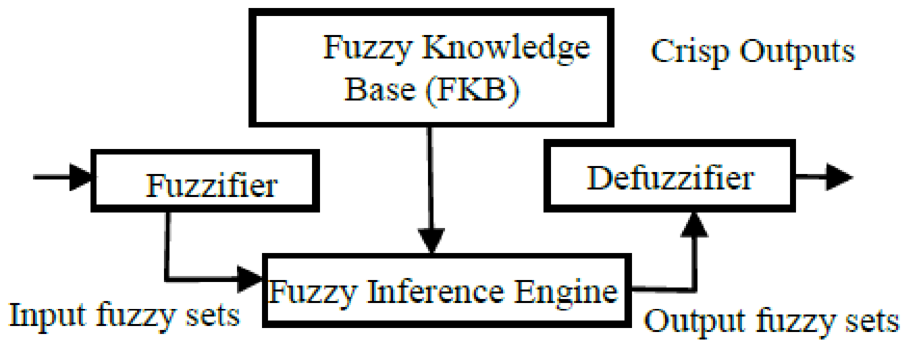

Figure 3.1*:***Operation of the fuzzy logic controller** ***(Riad, et al., 2023)***

3.4.1. Sets and Operations of a fuzzy logic controller

3.4.1.1. Sets

There are in total two important sets in the Fuzzy Logic Controller namely; the classical set and the Fuzzy set (Riad, et al., 2023).

- **The classical Set:** In a classical set, the membership of the components are allowed in the set in binary. It is demonstrated by Equation 3.1.

  A={x ϵ U| x meets some conditions} (3.1)

  Equation 3.1 can also be expressed as shown in Equation 3.2

  μ A(x)= {1 if x ϵ A; 0 if x not ϵ A} (3.2)

- **The Fuzzy Set:** In the fuzzy set can be found using Equation 3.3.

  A={x, $\mu_A(x)$| xϵU} (3.3)

Each letter in the above equations represents something for the fuzzy logic controller. “A” represents the fuzzy set, “x” represents the component of the set, “μ_A" represents the membership function, “ϵ” means belongs, and “U” stands for union.

3.4.1.2. Operations

The operations of the Fuzzy logic controller are used to determine the elements of the fuzzy system. The main set operations to consider in the Fuzzy Logic Controller are; the complement, the intersection, and the union (Siva & Balaraman, 2022).

Each letter in the equations below represents something for the operation of the fuzzy logic controller. “A” and “B” represent the fuzzy sets, “x” represents the component of the set, “μ_A" represents the membership function, “ϵ” means belongs, “U” stands for union, and “∩” stands for intersection.

- The Complement is the fuzzy set of membership functions. This operation can be performed by using Equation 3.4

$$\mu_A(x) = 1 - \mu_A(x) \qquad (3.4)$$

- The intersection is an operation in which fuzzy sets can determine how much the element belongs to two sets and the value of the membership is different in each set. This operation can be performed by using Equation 3.5

$$\mu_{A \cap B}(x) = \mu_A(x) \cap \mu_B(x) \qquad (3.5)$$

- The Union is an operation that consists of every element that is part of individual sets and the value of the membership function will be large. This operation can be performed by using Equation 3.6.

$$\mu_{A \cap B}(x) = \mu_A(x\ \mu_B) \cup (x) \qquad (3.6)$$

The membership functions for these three operations are shown in Figure 3.2.

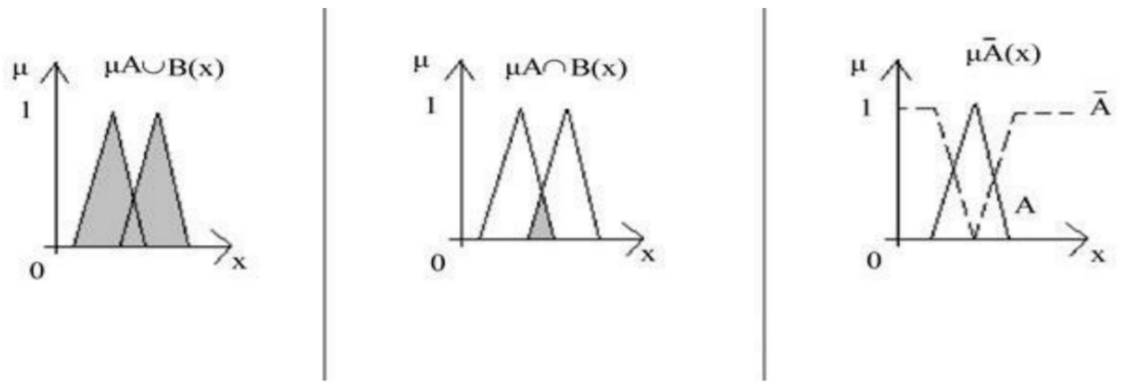

Figure 3.2: ***Membership functions of Union, Intersection, and Complement*** **(Septiarini, et al., 2021)**

3.4.2. Fuzzy Logic Controller processes

The three main processes in the fuzzy logic controller are; Fuzzification, Fuzzy Rule base and Interfacing engine, and, Defuzzification as shown in Figure 3.3 (Siva & Balaraman, 2022).

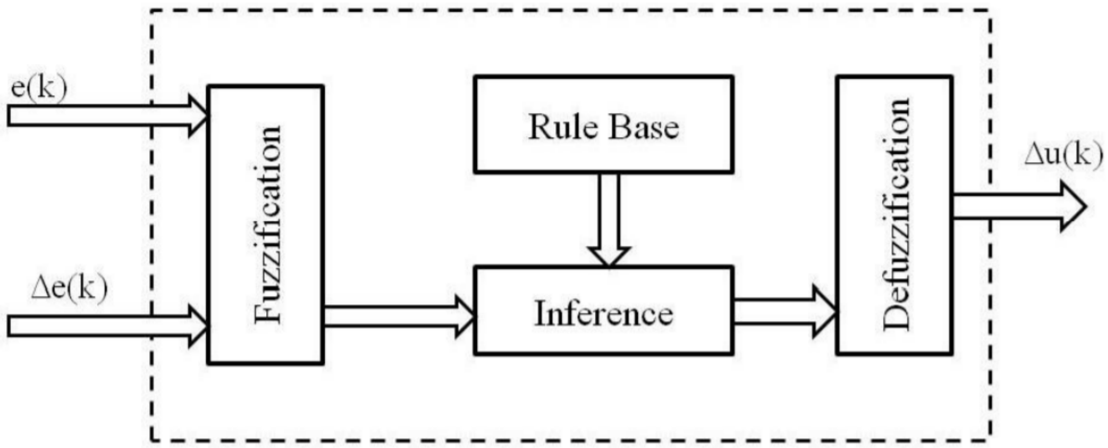

Figure 3.3: **Fuzzy Control Internal Block Diagram** ***(Siva & Balaraman, 2022)***

3.4.2.1. Fuzzification Process

It is extremely important to determine the state variables that will control the system under consideration because the fuzzification process makes use of these variables during the process of conversion. The fuzzification process consists of converting a numerical variable into a fuzzy linguistic variable (Siva & Balaraman, 2022).

The state error, the rate at which the state error is changing, and the membership functions can have different shapes depending on the variables like the error is trapezoidal shaped, the error change is Gaussian shaped, and output is the triangular shaped as shown in Figure 3.4.

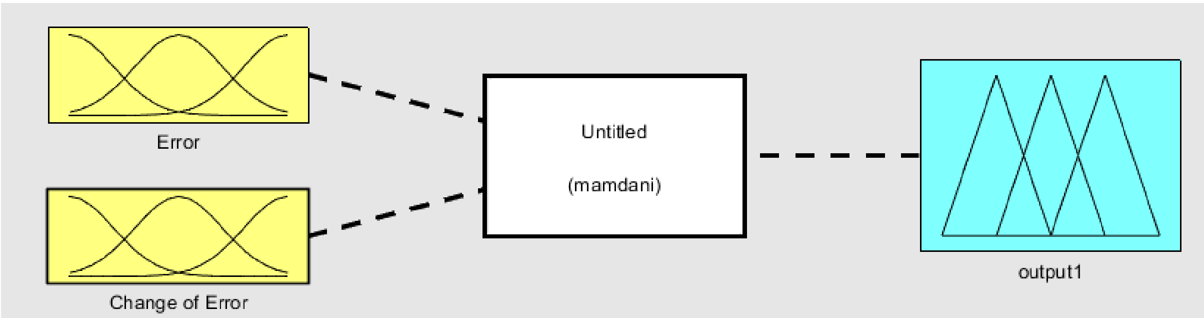

Figure 3.4: **Shapes of Membership functions of the Fuzzy Logic Controller (Septiarini, et al., 2021).**

3.4.2.2. Fuzzy Rule Interfacing Engine Process

This process is composed of two methods namely; Mamdani and Sugeno methods. The Mamdani method is the most used method developed by Ebrahim Mamdani while he was trying to control a steam engine. It consists of controlling the system with the help of a set of linguistic control rules and it is more efficient where there is only one membership function, while on the other hand, The Sugeno method can be used to generate fuzzy rules (Septiarini, et al., 2021).

3.4.2.3. Defuzzification Process

The Defuzzification process consists of converting the fuzzy values into crisp values. In general, there are three methods adopted for Defuzzification which are; The Centre of Gravity Method, The Bisector of Area Method, and The Mean of minimum Method.

- **The Centre of Gravity Method (COG):** This method is one of the most popular simple methods for the defuzzification process that can activate the membership functions.
- **The Bisector of Area Method:** This method consists of determining the center point of the fuzzy region through calculations.
- **The Mean of Minimum Method:** This method allocates weight to each membership function in the output (Riad, et al., 2023).

3.4.3. Fuzzy Control System

A Fuzzy control system can be considered under different aspects. It can be observed as a non-linear controller defined by linguistic rules or as the implementation of the control strategy of a human expert. Therefore, it is important to understand the logic and the control theory of the fuzzy control system such as the information processed within the system and its interaction with the components of the automatic control system.

This system is the most active control system used for renewable energy systems, industrial process control, biomedical instrumentation, and securities. The steps needed to be followed to design the controller are described in Figure 3.5

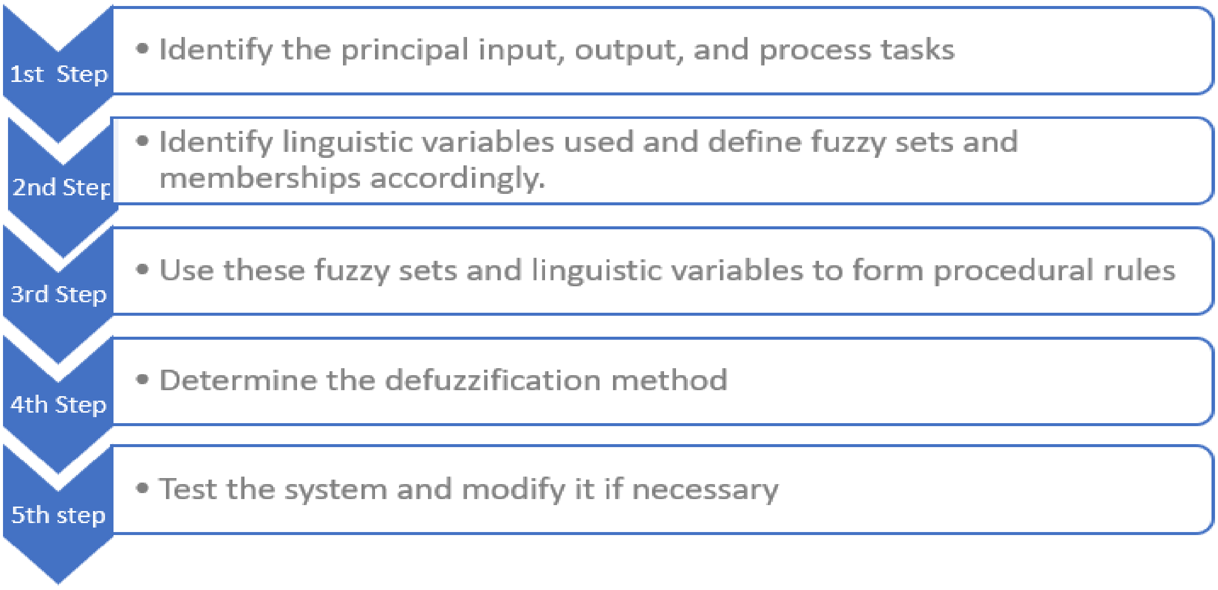

Figure 3.5: Steps to design the fuzzy Control System *(Riad, et al., 2023)*

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3.4.4. Fuzzy Controller Design

Fuzzy logic is a numerical technique that allows various input and output variables. The plan of technique begins with the input. There are three linguistic variables chosen for the fuzzy controller design which are; Positive (P), Negative (N), and Zero (Z) (Siva & Balaraman, 2022).

The design of the fuzzy logic controller is a very crucial factor in achieving the efficiency of the controller. Therefore, the steps in designing the FLC need to be the following:

- **Identification of variables:** In this step, the three important variables must be determined for the system that is being developed.
- **Fuzzy subset configuration**: In this step, the information is established into the number of fuzzy subsets.
- **Obtaining membership function**: This step consists of getting the membership function for each fuzzy subset considered for the system.
- **Fuzzy rule base configuration**: This step consists of formulating the fuzzy rule base by allocating a connection between the fuzzy variables.1
- **Fuzzification:** This step consists of converting the numerical input variables into linguistic variables.
- **Combining fuzzy outputs**: This step consists of locating the fuzzy outputs and merging them.
- **Defuzzification:** Finally, the defuzzification process starts at this stage to form a crisp output.

3.5.Fuzzy Logic Controller System Performance

The effectiveness of the Fuzzy Logic Controller is contingent upon the methodology and system design employed. In this project, the FLC was developed to control the PV energy system. Therefore, some techniques need to be implemented and some analyses need to be conducted to achieve high performance. The Maximum Power-Point Technique (MPPT) was implemented and the load flow analysis was conducted to ensure high performance and an efficient design of the Fuzzy Logic Controller.

3.5.1. The Maximum Power-Point Tracking (MPPT) Technique

Numerous natural variables affect the efficiency of renewable energy, and the power, voltage, and current produced by these renewable sources are unstable because of the sun's and wind's erratic behavior. One of the key strategies for overcoming these renewable systems' volatility and inefficiency is Maximum Power-Point Tracking.

Renewable energy generation results in nonlinear characteristics in their current and voltage outputs. They are influenced by various environmental conditions, including temperature, air density, sun irradiation, and more. The variations in power, voltage, and current are caused by these external sources. Thus, it is critical to make sure renewable energy systems are running at their Maximum Power point to maximize their efficiency. In unstable situations, MPPT is employed to extract the greatest power available (Guntupalli, et al., 2022). MPPT control in a PV system is shown in Figure 3.6.

As it can be observed in Figure 3.6, The PV panel supplies the electrical power that was generated from the sun to the DC-DC Boost which in turn acts as a link between the solar panel and the load. The Ipv and Vpv supplied by the PV panel are used to feed the MPPT control and the DC-DC Boost (Guntupalli, et al., 2022).

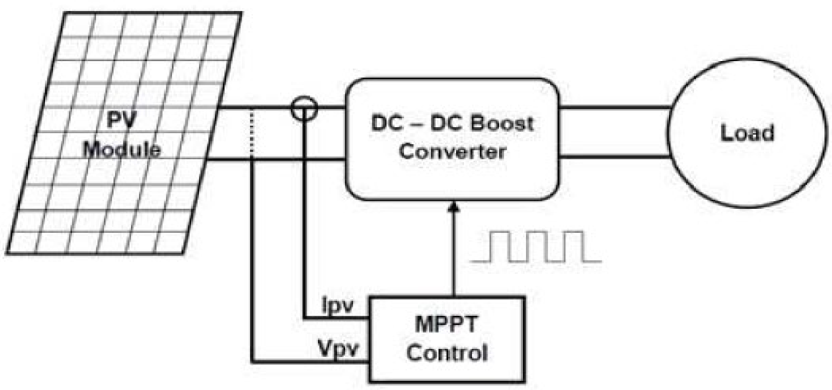

Figure 3.6: **Diagram of MPPT in PV System** ***(Guntupalli, et al., 2022)***

Maximum Power-Point Tracking (MPPT) is a crucial technique also used in wind energy systems to extract the maximum available power from the wind turbine under varying wind conditions. The main objective of MPPT is to continuously adjust the operating point of the wind turbine to match the changing wind speed and load conditions, ensuring that the system operates at its maximum power efficiency. In a wind energy system, the power output of the wind turbine is a non-linear function of the wind speed and the electrical load as shown in ***Figure 3.7***. The power coefficient (Cp) of the wind turbine, which represents the efficiency of the conversion of wind energy to electrical energy, varies with the tip speed ratio (λ), which is the ratio of the blade tip speed to the wind speed (w).

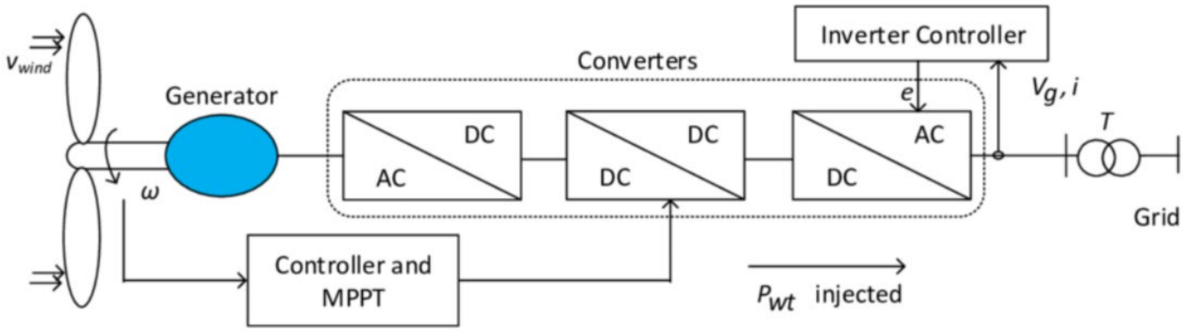

Figure 3.7: Diagram of MPPT in Wind Energy System *(Qi & Meng, 2017)*

The design of the wind turbine, the qualities of the generator, the capabilities of the power converter, and the complexity of the MPPT algorithm are some of the variables that affect how effective the MPPT approach is in wind energy systems. The goal of ongoing MPPT technology research and development is to raise the overall effectiveness and performance of wind energy systems, particularly when dealing with quickly varying wind conditions.

3.5.2. Types of Maximum Power-Point (MPPT) Tracking Techniques

A system may employ a variety of MPPT algorithms, including the extreme seeking control (ESC), incremental conductance, open circuit voltage (OCV), short circuit current (SCC), fuzzy logic control, hybrid methods, and the Perturb and Observation (P&O) technique. Below is a discussion of the Technique's specifics. Since each technique has a variety of applications some are used for complicated systems, while others are used for simpler systems, it is crucial to comprehend each one to determine which one will work best for the system under study (Guntupalli, et al., 2022).

3.5.2.1. Perturb and Observation (P&O) Technique

The most widely used MPPT technique is this technique. Using this method, the system is forced to operate in the direction that renewable energy systems' output power increases. The P&O technique's power shift is depicted in Equation 3.7. The flowchart of this technique is shown in **Figure 3.7.**

$$P = P_K - P_{k-1} \tag{3.7}$$

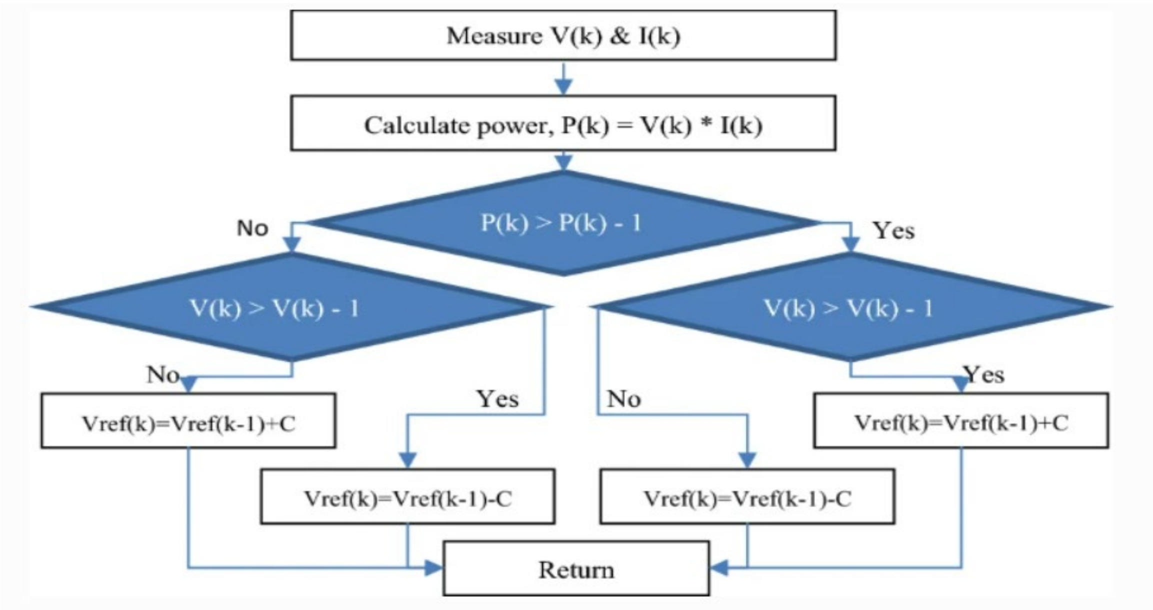

Figure 3.8: **Flowchart of the Perturb and Observation Technique** ***(Guntupalli, et al., 2022)***

Each parameter stated in the flow chart has been described in **Table 3.2.**

Table 3.2: Parameters of the Perturb and Observation Controller (Guntupalli, et al., 2022)

Parameters	Meaning
V(k)	The current value of the PV output voltage
V(k) – 1	The previous value of the PV output voltage
I(k)	The current value of the PV current
P(k)	The current value of the PV output power
P(k) – 1	The previous value of the PV output power
Vref	The reference output voltage of the P&O controller.

3.5.2.2. Fuzzy Logic Control (FLC) Technique

This method's excellent performance and straightforward design have made it highly recommended. There is no particular model required for the FLC approach. There are three stages to FLC:

- **Fuzzification:** During this stage, the variables are converted into linguistic variables
- **Decision making:** This stage consists of specifying the rules in terms of IF-THEN statements to define the controller behavior
- **Defuzzification:** This stage consists of providing A signal to control the power and take the operating point to the maximum power point (Teferra and Ngoo, 2021)

Figure 3.8 illustrates that the fuzzy logic controller receives two inputs: an error (E) and a change in Error. The inaccuracy can be caused by temperature and solar irradiance for PV systems. The output variables can be the maximum power point voltage or the duty cycle.

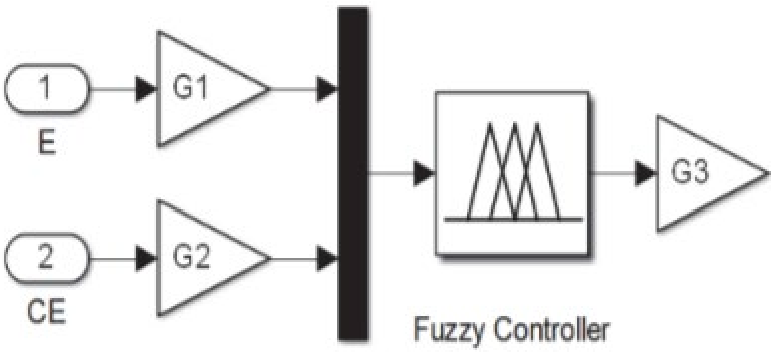

Figure 3.9: **Fuzzy Logic Controller Technique** ***(Siva & Balaraman, 2022)***

3.5.2.3. Open circuit voltage (OCV) method

This method results in power losses in the system since it is unable to precisely follow the maximum power point and requires frequent load shedding to measure the VOC as shown in Figure 3.9. Pilot cells must be used to determine VOC to prevent these power outages (Siva & Balaraman, 2022).

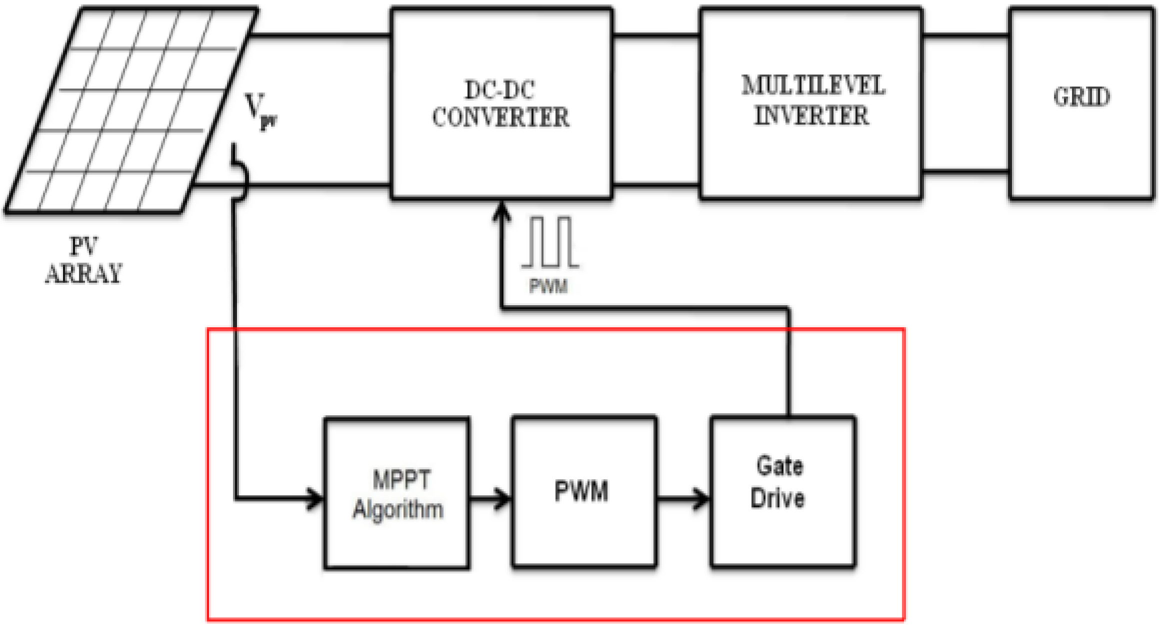

Figure 3.10: Open Circuit Voltage Method *(Siva & Balaraman, 2022)*

3.5.2.4. Short circuit current method (I_{SC})

The short circuit current approach, which compares the current with other protective devices in the system to ascertain how much current the system can give, is shown in Figure 3.10. During the short circuit current measurement, there is a load interruption, which prevents I_{SC} from providing the output power to the load (Siva & Balaraman, 2022).

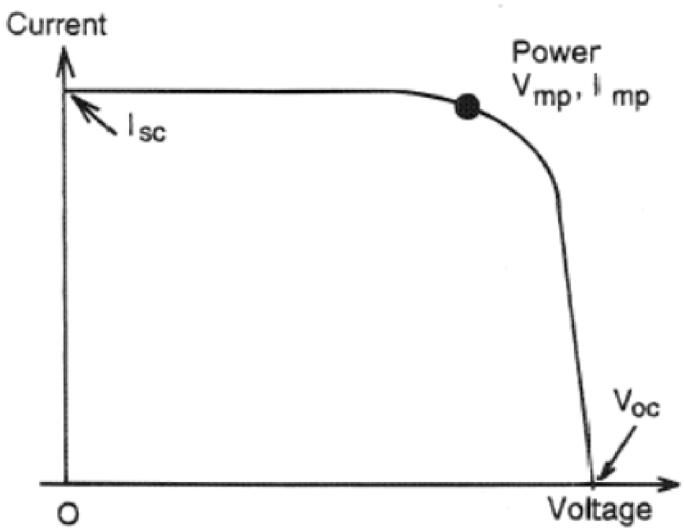

Figure 3.11: Short Circuit Current (I_{SC}) *(Siva & Balaraman, 2022)*

3.5.2.5. Extremum seeking control method (ESC)

This approach, which uses real-time optimization, is more suited for tracking vehicle targets, maximizing vehicle traction, and reducing aircraft power (Emenuvwe, et al., 2023).

3.5.3 Load flow analysis

One of the processes needed to have power stability in a system is the load flow analysis and this analysis was performed to enable the FLC to control and achieve power stability in the system. Load flow analysis is the steady state analysis of any system that determines the operating state of the system. Load flow analysis helps to analyze the system's operating conditions. One of the main objectives of the power flow analysis is to understand the behavior of the system subject to various operating conditions. It is also important to perform the load flow analysis to determine which controller is the most suitable for the power system (Padmanaban et al., 2019).

3.5.3.1 Importance of load flow analysis

Load flow analysis is extremely important for any electrical system because it investigates many important aspects of a system. In this project, the load flow analysis investigated the following points:

- The behavior of the power network when it is subjected to various operating conditions such as peak and unbalanced load conditions.
- The behavior of the power network without and with the controller integrated into the PV system.
- The flow of the power in the power network.
- Running conditions and load distribution to develop an efficient fuzzy logic controller.

3.5.3.2 Steps for Load Flow Analysis

The Load flow study consists of three steps as shown in Figure 3.11.

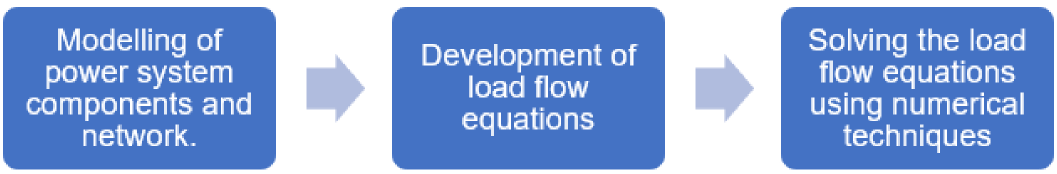

Figure 3.12: **Steps of Low Flow Analysis** ***(Teferra & Ngoo, 2021)***

3.5.3.3 Bus or Busbar

It is any structure of a conductor that plays a crucial role in connecting two or more circuits. Buses are meeting points of various components, these components can be a transformer, generator, or load. In PV systems, there are copper busbars that separate the solar cells. In load flow analysis, four parameters are determined for each bus or busbar as stated in Table 3.3.

Table 3.3: Parameters of Busbar (Emenuvwe, et al., 2023)

Parameters	Symbols
Real Power	(P)
Reactive Power	(Q)
Voltage Magnitude	(|V|)
Voltage Phase angle	δ

3.5.3.4 Bus or Busbar classification

Generally, the buses will be classified into three types; the load buses, the voltage buses, and the slack buses as shown in Figure 3.12.

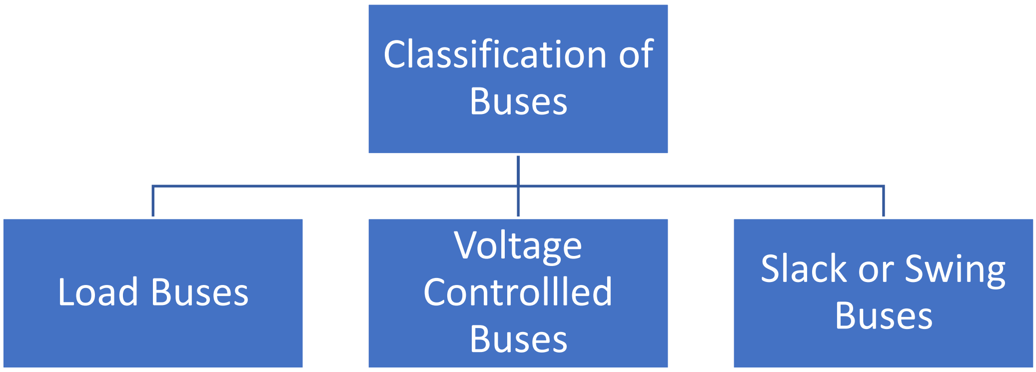

Figure 3.13: Classification of Buses *(Haddad et al., 2020)*

The load buses are known as the PQ buses, the voltage buses are known as the generator or PV buses and the slack buses are known as the reference buses.

3.5.3.4.1 Load Bus (P-Q bus)

This is the bus where the magnitude and the phase angle of the power network are determined. The active and reactive power of the system being analysed can also be found at the load bus (Haddad et al., 2020).

3.5.3.4.2 Generator or Voltage-controlled Bus (P-V bus)

This is the bus where the generated voltage and the true power of the power network are specified. The reactive power and the angle of the bus voltage will have to be configured based on depending on the system configuration (Haddad et al., 2020).

3.5.3.4.3 Slack or Reference Bus (V- δ bus)

The slack Bus emits active and reactive power from the system. This bus transport has no load and can be established using equations and calculations (Haddad et al., 2020).

It is important to determine the equation of the power flow because it helps to identify the bus voltage and the amount of current flowing in the power transmission network.

Before starting to solve a load flow problem, It is important to identify the known variables and the unknown variables of each element of the load flow analysis. Table 3.4 shows the known and unknown variables of each element.

Table 3.4: Types of elements with their variables (Emenuvwe, et al., 2023)

Types of elements	Known variables	Unknown Variables
Generator	Real power and voltage magnitude	Reactive power and voltage angle
Load	Real and reactive power	Voltage magnitude and voltage angle
Slack	Voltage magnitude and voltage angle	Real and reactive power

The correct formulation of the equation will help in determining the unknown variables stipulated in Table 3.4. The calculations will be performed in a per-unit system and the base impedance is the first to be determined by using the formula as shown in Equation 3.8.

$$Z_{base} = \frac{kV^2{}_{Base}(phase)}{MVA_{base}(1-\emptyset)} \quad (3.8)$$

The second element to be determined is the base admittance by using the formula in Equation 3.9

$$Y_{base} = \frac{1}{Z_{base}} \quad (3.9)$$

The admittance or Y- matrix shows the voltages and the currents in all the branches of the system as shown in the formula below.

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ \cdots \\ \cdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & \cdots & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & \cdots & \cdots & Y_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Y_{n1} & Y_{n2} & \cdots & \cdots & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdots \\ \cdots \\ \cdots \\ V_n \end{bmatrix} \quad (3.10)$$

I= Represents the positive sequence current that flows

V= Represents the voltage at the nodal terminal

Y= Represents the nodal admittance matrix

The current flowing at any node or bus k can be calculated using the formula in Equation 3.11

$$I_k = \frac{(P_k + jQ_k)}{V_k} \quad (3.11)$$

$\boldsymbol{P_k}$**=** Represents the power at the bus

$\boldsymbol{jQ_k}$**=** Represents the imaginary reactive power bus k

$\boldsymbol{V_k}$**=** Represents the phase voltage at the node or bus k

$\boldsymbol{I_k}$**=** Represents the phase current at the node or bus k

The equation below shows the phase current in relationship with the phase voltage.

$$I_k = V_k Y_{kG} + \sum_{\substack{m \\ m \neq k}} \frac{V_k - V_m}{Z_{km}} \quad (3.12)$$

Y_{kG}= This is the total number of admissions linked to buses that reach the ground.

Z_{km}= This represents the series impedance of the connected buses

The negative inverse of the series impedance between two buses is represented by the equation below.

$$Y_{km} = -\frac{1}{Z_{km}} \tag{3.13}$$

The larger the power system network the more complex will be the formulas and equations to analysis the load flow. Therefore, the admittance matrix is not a suitable option for large and complex networks.

Two methods that can be used to solve the power flow problems, namely:

- Gause-Seidal
- Newton-Raphson

3.5.3.5 Gauss-Seidel method

The Gauss-Seidel method is also known as the displacement method which provides solutions to the non-linear equation and the values of the parameters such as real or reactive power and current can be calculated by assuming the starting values for those parameters. Equation 3.14 shows the formula to determine the values of the voltage.

$$V_i^{(k+1)} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^*} + \sum Y_{ij} V_i^{(k)}}{\sum Y_{ij}} \qquad j \neq ii \tag{3.14}$$

To calculate the values of the active and reactive power the formula in the two equations below will be used.

$$P_i^{(k+1)} = Real\left[V_i^{*(k)}\left\{\sum_{i=0}^{n} y_{ij} - \sum_{ji}^{n} V_i^{(k)}\right\}\right] \qquad j \neq ii \tag{3.15}$$

$$Q_i^{(k+1)} = Imaginary\left[V_i^{*(k)}\left\{\sum_{j=1}^{n} y_{ij} - \sum_{ji}^{n} V_i^{(k)}\right\}\right] \qquad j \neq i \tag{3.16}$$

The load flow is developed in the form of a matrix and Equation 3.17 shows the voltage equation using the bus admittance matrix elements.

$$V_i^{(k+1)} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^*} + \sum Y_{ij} V_i^{(k)}}{\sum Y_{ii}} \qquad j \neq i$$

(3.17)

The real and imaginary power through bus admittance matrix elements are expressed as shown in **Equation 3.18** and **Equation 3.19**.

$$P_i^{(k+1)} = Real \left[V_i^{*(k)} \left\{ V_i^{*(k)} Y_{ii} + \sum\nolimits_{i=1,j=1}^{n} Y_{ij} V_j^{(k)} \right\} \right] \qquad j \neq i \tag{3.18}$$

$$Q_i^{(k+1)} = Imaginary \left[V_i^{*(k)} \left\{ V_i^{*(k)} Y_{ii} + \sum\nolimits_{i=1,j=1}^{n} Y_{ij} V_j^{(k)} \right\} \right] \qquad j \neq i \tag{3.19}$$

3.5.3.6 Newton-Raphson Method

This method is fast and more suitable for large power networks but the disadvantages of this method are it takes more time than the Gauss-Seidel method and it requires a large computer memory to operate efficiently. The voltage and the angle of the system can be found by using the power balance equations of this method as shown in the equation below (Teferra & Ngoo, 2021).

$$\sum_{k=1}^{n} |V_i||V_k|(G_{ik} cos\theta_{ik} + B_{ik} sin\theta_{ik}) - P_{Gi} + P_{Di} = 0 \tag{3.20}$$

Therefore, The real and the reactive power will be:

$$P_i(x) = \sum_{k=1}^{n} |V_i||V_k|(G_{ik} cos\theta_{ik} + B_{ik} sin\theta_{ik}) \tag{3.21}$$

$$Q_i(x) = \sum_{k=1}^{n} |V_i||V_k|(G_{ik} sin\theta_{ik} + B_{ik} cos\theta_{ik}) \tag{3.22}$$

The formulas above will lead to the final power balance equations below:

$$P_i(x) - P_{Gi} + P_{Di} = 0 \quad (3.23)$$

$$Q_i(x) - Q_{Gi} + Q_{Di} = 0 \quad (3.24)$$

3.6. Discussion

The Maximum Power Point Technique and the load flow analysis have been identified to be two important tools to achieve a good performance of the fuzzy logic controller for renewable energy systems such as the PV system which is an unstable energy due to the inconsistency of sun in nature. Therefore, it is important to understand the flow of the power under these unstable conditions and the load flow analysis can investigate in detail the flow of the power in a renewable energy system. After analysing the flow of the power, critical information can be collected such as the behaviour of the power when there is less sunlight and then the Maximum Power Point Technique can be applied to the controller to extract the available maximum power in the system.

3.7. Conclusion

The Fuzzy Logic Controller's performance has been covered in this chapter. Based on the literature review it was found that the Fuzzy Logic Controller may operate at a high level using a variety of strategies and tactics. Angola's power network may greatly benefit from the proper design and development of the controller, which would enable the efficient use of renewable energy sources. The Maximum Power-Point Method is one of these techniques. Chapter 4 discusses the load flow analysis of a three-phase power network in Angola.

CHAPTER FOUR

LOAD FLOW ANALYSIS OF A THREE-PHASE POWER NETWORK IN ANGOLA

4.1. Introduction

One essential step for ensuring power stability within a system involves conducting load flow analysis. Load flow analysis is the steady state study of any system that determines the functioning state of the system. Analysis of the system's operational circumstances is aided by load flow analysis. Understanding the behavior of the system under various operating situations is one of the primary goals of the power flow analysis. It is also important to perform the load flow analysis to determine which controller is the most suitable for the power system (Padmanaban et al., 2019).

The three-phase power network in the province of Huila has been analyzed in detail using the load flow analysis conducted through simulations in MATLAB. The purposes of the simulation activity discussed in this chapter are based on analysing the power network to understand its behaviour so that performance improvement steps can be taken accordingly. The simulations were based on the power network in Angola modelled in MATLAB software.

Section 4.2 discusses the methodology and steps needed to achieve the load flow analysis. Section 4.3 consists of the case study implementation based on the Angolan power network as well as the load flow analysis conducted to understand the behaviour of the power network so that the correct controller can be developed for the system. Section 4.4 discusses and analyse the results after load flow analysis. Section 4.5 discusses the challenges and limitations faced during and after simulations.

4.2. Methodology and steps needed to achieve the load flow analysis.

A procedure was conducted to evaluate and analyse the three-phase power network in Angola. The first activity was to conduct the load flow analysis of the Angolan power network. The simulation model focused on the province of Huila power network. This electrical grid comprises three transmission lines spanning a distance of 200km each, along with two lines covering a distance of 150km each.

The load flow analysis of the chosen power network involved the following steps:

- **1st Step) Modelling of Slack Bus, Loads and Generators:** The main elements needed for a load flow analysis were constructed to determine the crucial parameters of the power network such as the true power, the apparent power, the reactive power, and the total power losses.

- **2nd Step) Modelling of the Buses:** The three main buses were modelled to allow the connection of components of the power network

- **3rd Step) Determine the Parameters of each branch:** The parameters of each branch were determined such as the resistance, Inductance, Voltage, Power, and Frequency.

- **4th Step) Analysis and discussion of load flow results:** The results before and after simulations will be analysed in detail by taking into consideration the parameters of each element of the Slack bus, the load bus, and the generator bus as shown in ***Table 4.1*** and ***Table 4.2.***

Several crucial factors were accounted for during each of these tasks. In the load flow analysis, variations in voltage were carefully assessed. Additionally, details regarding the power network, including both real and reactive power, were taken into consideration to assess and regulate the network's performance.

4.3. Case study implementation based on the Angolan power network

The increasing demand for electricity in Angola is much greater than what has been generated, resulting in the transmission network being heavily loaded and stressed beyond permissible limits. Therefore, the load flow analysis is the best tool to use to understand better the Angolan power network as well as to find the best alternative solution to mitigate instability in the power network. Figure 4.1 shows the location of these transmission lines.

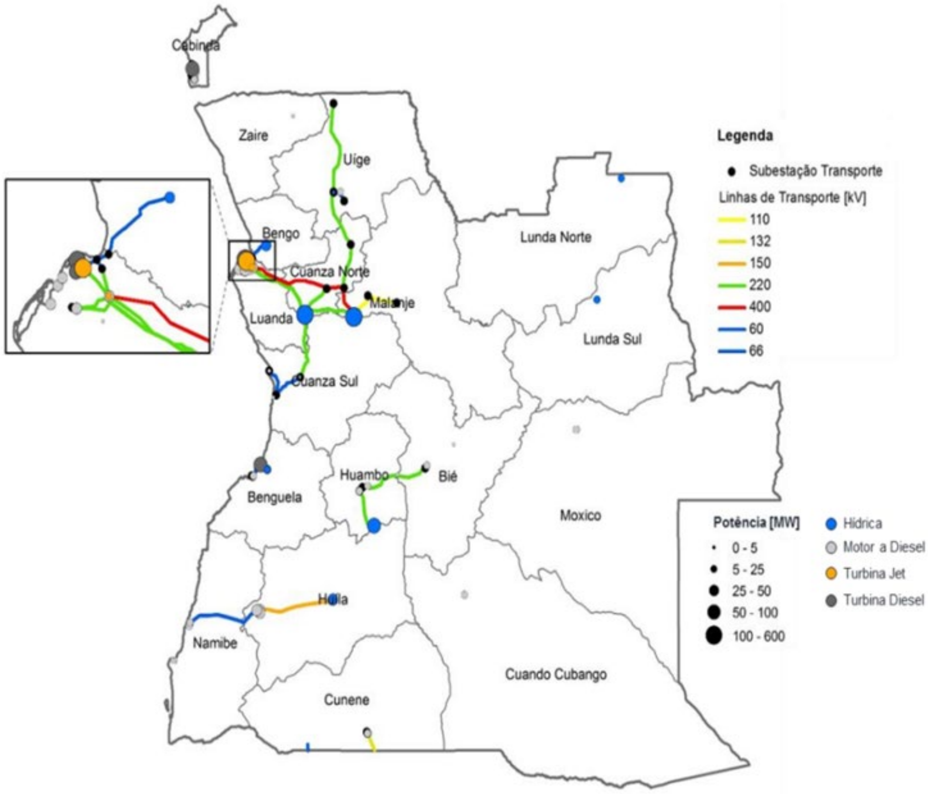

Figure 4.1: Shows the location of these transmission lines under study

A case study has been considered to understand better the behaviour of the Angolan power transmission network when it is subjected to various operating conditions.

The load flow analysis was performed through MATLAB/SIMULINK. The selected Angolan power network for this project consists of three buses that are connected through three 150 kV transmission lines 200 km, 150km, and 150km long corridor from Queve towards Namibia in the south going through the province of Huila as shown in **Figure 4.2.**

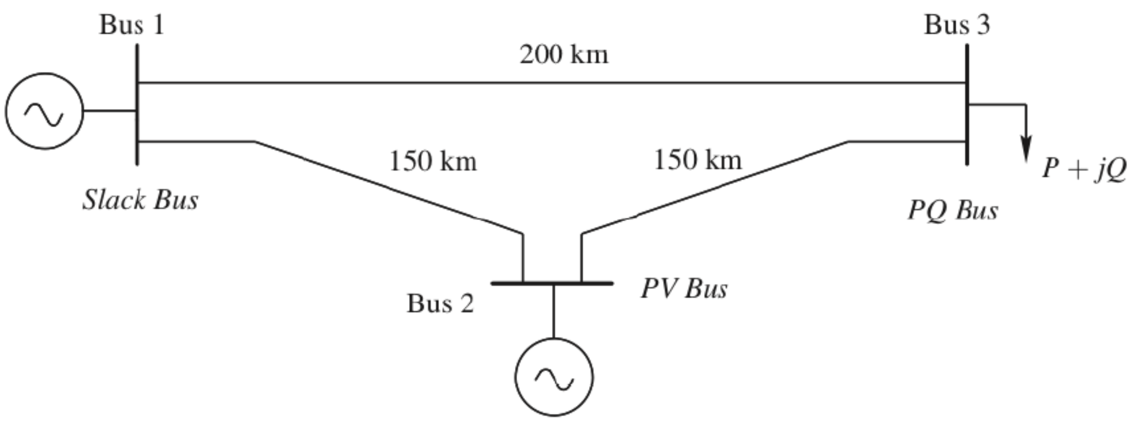

Figure 4.2: **A Three-bus system**

Prior to conducting the load flow analysis, crucial information had to be identified, including the load demand and supply in the particular area within Huila province, as well as the specifications of the Angolan 150 kV transmission lines, which are outlined below.

A. The loads demand in HUILA

Angola's energy consumption has grown dramatically over the last ten years, with an annual growth rate of more than 15%, as a result of rising living standards, greater government initiatives to enhance access to electricity, and increased generation capacity. With the province and city of Luanda as well as the biggest concentration of businesses, services, and people, the northern region continues to be the center of consumption. The current load demand in the country has been estimated to be 3.9 GW (3900MW). The load demand is expected to grow at a substantial rate, with the overall system load reaching 7.2 GW (7200MW) in the country. This is intimately related to the nation's industrialization goals. Energy-intensive operations like mining and iron exploration will be important growth drivers for the sector, which is expected to account for 25% of overall consumption by 2025 even though it only represents 9% of the demand for energy at the moment. According to the Angolan National Electricity Distribution Company (ENDE), the current total demand in the province of Huila is **50MW**.

B. The supply to the load in HUILA

Angola's total installed power capacity was 22,30 MW in 2014. This was an increase of 3,15% over the previous year. According to the National Electrical Company (ENDE) in Angola, the total generation in the province of Huila has been estimated to be **36MW.** This confirms the power supply in the province is less than the load demand.

C. The parameters of 150kV transmission lines

The transmission line analysed in this project consists of three buses which are the Slack bus, PV bus, and PQ bus. Each bus consists of parameters such as the voltage and the angles. Appendix 4.1, Appendix 4.2, and Appendix 4.3 show the parameters for bus 1, bus 2, and bus 3. The other necessary parameters for each branch of the transmission line needed for the load flow analysis to be performed are specified in Appendix 4.5.

Case study 1: This situation involves analyzing the power flow of three 150 kV transmission lines in Huila Province, Angola. These lines are 200 km, 150 km, and 150 km long, respectively. The analysis excludes consideration of the PV system and the proposed controller, which will be discussed in Chapter 5. In this network, the load demand is 50MW, while the power supply is only 36MW, indicating that the demand exceeds the supply.

Figure 4.*3* below shows the simulation of the load flow analysis for the power system of three 150KV transmission lines 200 km, 150km, and 150km long in a small province of Angola. The slack Bus is responsible for providing or absorbing the true and apparent powers to and from the transmission line. The load bus, sometimes referred to as the P-Q bus, is where active and reactive power is added to the network. This bus is not linked to a generator. The generator bus, also referred to as the P-V bus, comes next. This bus displays the voltage magnitude linked to the generating voltage.

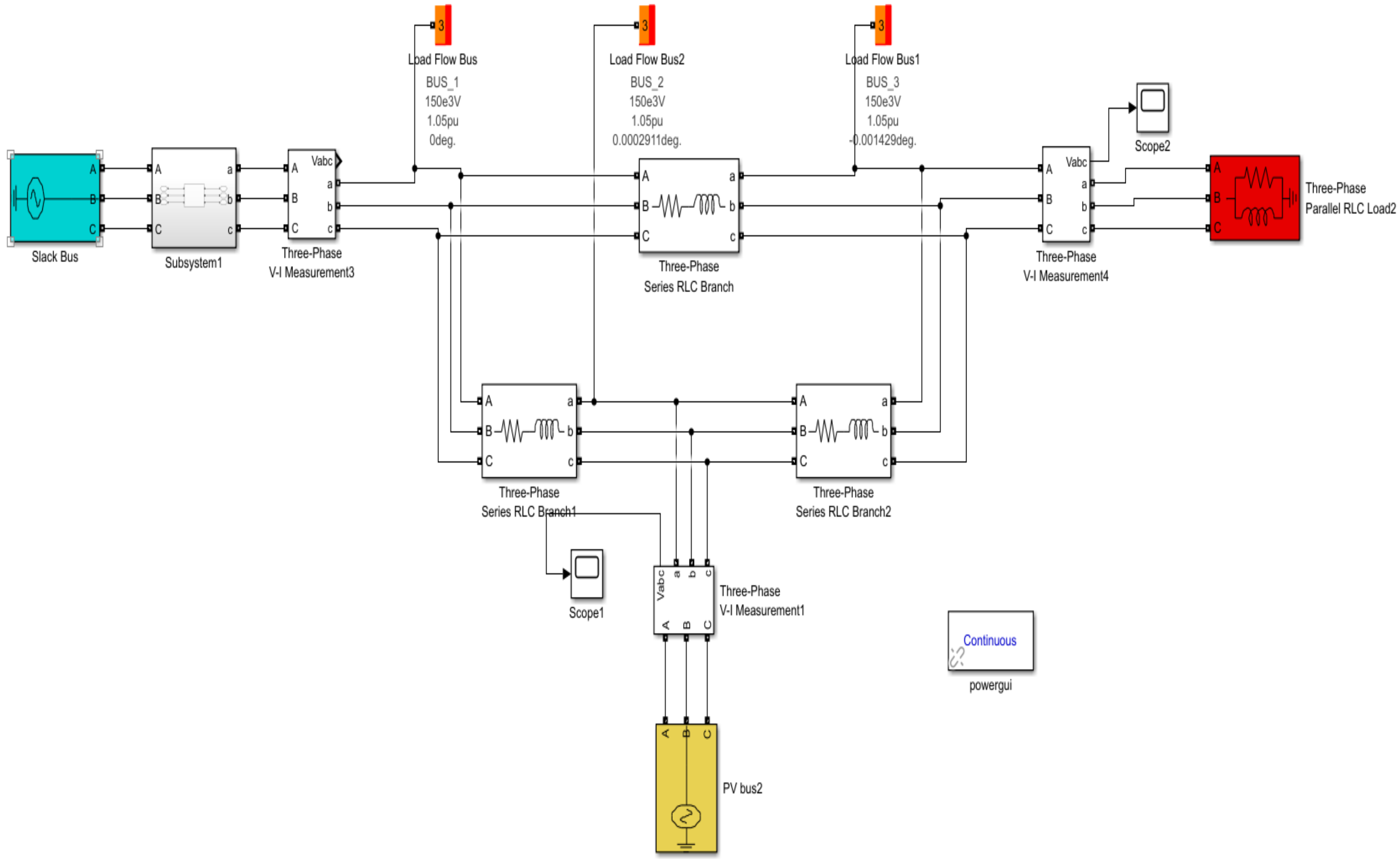

Figure 4.3: Load flow analysis for the Power System of three 150kV transmission lines without the Proposed Controlled and the PV system)

4.3.1. Results of case study 1

Table 4.1 shows the parameters for all the buses and other components before load flow simulations through MATLAB/SIMULINK. It can be observed that the voltage drop on each feeder, the voltage magnitude, the phase angle at each bus, the real and reactive powers flowing in all branches in the system are only determined after running the simulations. Bus 1 in this power network represents the slack bus and it can be observed in ***Table 4.1*** that the slack bus is not generating power because there is a malfunction or disruption in the generator that is acting as a slack bus. This indicates a fault condition at the slack bus which results in a zero power injection at that bus. There is only one generator bus operating in this power network which is Bus 2 and Bus 3 is the load bus.

Table 4.1: **Parameters of Buses, Load, and Generator before Load Flow Simulation**

Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)
BUS_1	150.0000	1.0500	0	0	0
BUS_3	150.0000	1.0000	0	50.0000	15.0000
BUS_2	150.0000	1.0400	0	36.0000	0

Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (MVA)
0	0	0	0	0	0
-Inf	Inf	0	0	0	0
0	0	0	0	0	0

After load flow simulations, the unknown parameters were determined as shown in ***Table 4.2***

Table 4.2 was extracted from MATLAB/SIMULINK with all the results after simulation for the real power (MW) and reactive power (MVA) as well as the voltage angles. After load flow analysis it was observed that the generator bus 1 was still injecting zero power into the network because it is a faulty bus that is unable to supply or absorb any power.

Table 4.2: **Parameters of Buses, Load and Generator After Load Flow Simulation**

Bus ID	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (MVA)
BUS_1	1.0500	0	0	0
BUS_3	1.0500	-0.0014	50.0000	15.0000
BUS_2	1.0500	0.0003	36.0000	0.0000

In this scenario, the power network located in Angola operates with the load demand higher than the power supply. The load demand represented by Bus 3 is 50MW, while the power supply represented by Bus 2 is 36MW. The power supplied into the power network is not sufficient to satisfy the needs of the consumers and due to this situation, the system power network is unstable as shown in **Figure 4.4.a** and **Figure 4.4 b**. The voltage per unit at the load bus (Bus 3) and the generation bus (Bus 2) is not within the standard voltage permissible limit of ± 5 %. The standard allowable voltage range is between 0.95 p.u and 1.05 p.u, anything above or below this range is considered a non-permissible voltage for the power network because it will cause disturbances and instability in the power network which will directly have a negative impact on the consumers. In this power network, the voltage profile value is 0.921 p.u for all three phases at the load bus (Bus 3) and is 0.93 p.u for all three phases at the generation bus (Bus 2) as shown below in **Figure 4.4.a** and **Figure 4.4 b**. The x-axis in the graphs below represents the time and the y-axis represents the voltage per unit. Furthermore, it can also be observed that the voltage angles for each bus were also determined after load flow analysis. The angle at Bus 1 is 0 degrees, at Bus 2 the voltage angle is -0.0014 degrees, and at Bus 3 is 0.0003 degrees as shown in Table 4.2.

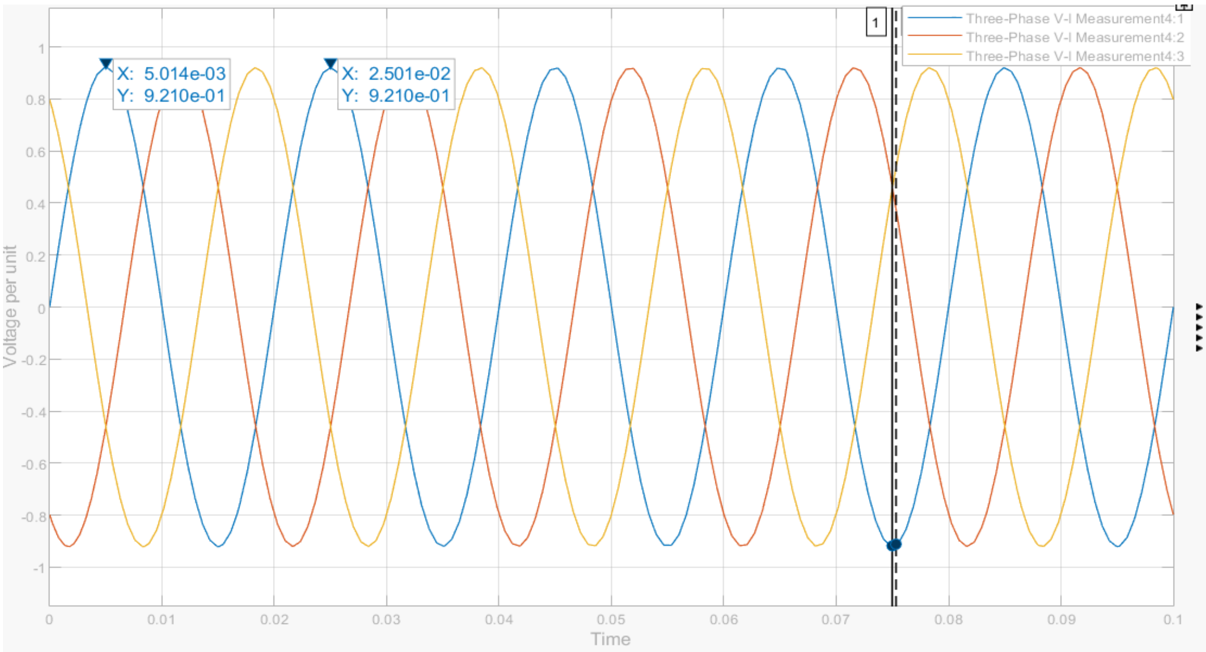

Figure 4.4a: **Per Unit Load Voltage Profile at Bus 3 (PQ-Load) when the load demand is higher than the load supply.**

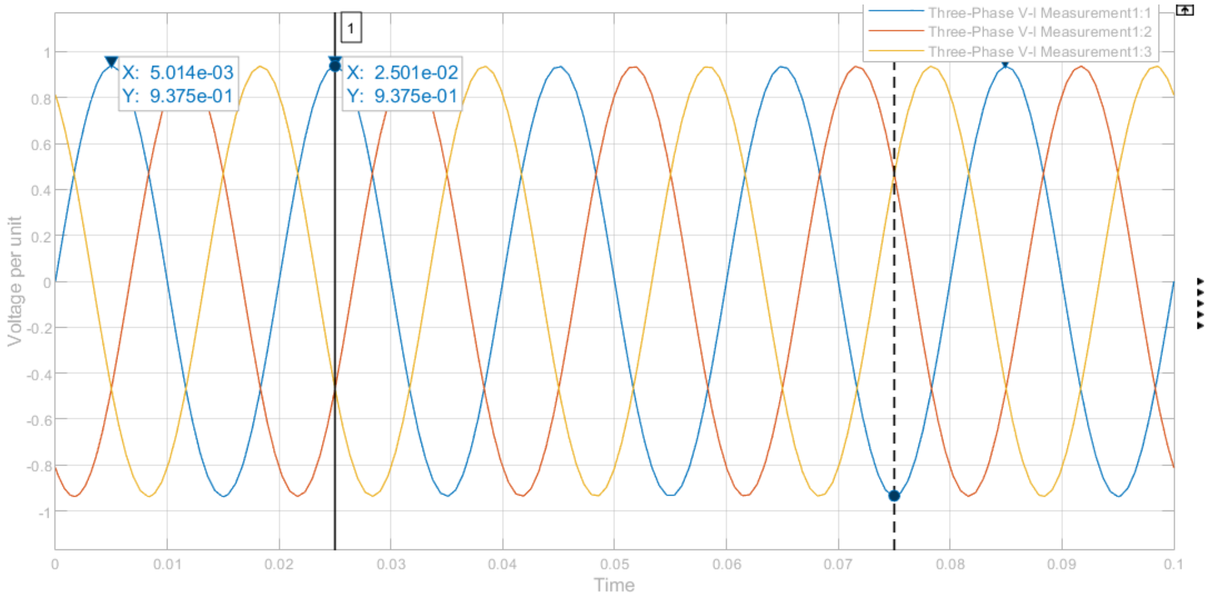

Figure 4.4.b: **Per Unit Load Voltage Profile at *Bus 2 (PV-Generation)* when the load demand is higher than the load supply.**

If the demand for electricity continues to rise in the future, the disruptions and instability within this power network will exacerbate. Hence, integrating a PV system into the network is crucial as a contingency measure to bolster its resilience. In analyzing the system's response to potential contingencies, such as increased voltage requirements due to demand surpassing supply, introducing a PV system can regulate voltage within the permissible range outlined in the grid code. This ensures the safe operation of the power transmission network.

4.4. Discussion and Analysis

The Angolan power network developed in this project is unstable and poorly performing due to the load demand that is higher than the power supply, and the population in the province of Huila is expected to increase more in the upcoming years. This increase in the population will also increase the load demand which will decrease the voltage per unit in the power network because in a power system, when the load demand increases, the voltage decreases, and when the load demand decreases, the voltage increases. The results in Figure 4.3.a and Figure 4.3 b show that the per unit load voltage profile for each bus is not within the standard allowable voltage range. This situation can cause many issues such as disturbances in the power network, power outages, blackouts, damage to the consumer's electrical appliances, and damage to the power network's electrical components. Therefore, a supportive system needs to be developed and integrated to support the power network by providing additional power and voltage required to keep the system stable.

Renewable energy systems can be the most efficient solution to solve the problem of this power network because renewable energy such as solar energy is an inexhaustible resource in nature and it is always environmentally friendly. This means that by using renewable energy as a solution, the level of air pollution in the province of Huila will decrease which will also have a positive impact on people's lives. Globally, grid-connected photovoltaic installations are expanding at an exponential rate, as Figure 4.5 shows. In year 2020 solar PV shatter yet another record, with a projected 126 GW of new installations. In terms of on-grid capacity, this raised the total to an anticipated 705 GW globally (Elomari, et al., 2022) and the figure is continually rising. The International Renewable Energy Agency (Meza, 2022) projects that by 2030, there will be 2840 GW of installations worldwide, and by 2050, there will be 8519 GW. (Elomari, et al., 2022). PV installations have historically outperformed expectations, but there are also some important points to consider when integrating the PV system into the power network such as the intermittency of solar energy in nature (Elomari, et al., 2022). Numerous review papers, like that of (K.Noussi, et al., 2020), focus only on solar PV integration. They discuss system management challenges and utility concerns for PV grid integration and offer a thorough analysis of PV inverters for grid-connected PV applications. A thorough analysis of the technical effects of the high PV penetrations in the electricity network is given in (Wongsathan, 2020). These review papers mentioned two common points; controlling the PV system while supplying the necessary power required and keeping the PV system operating at the maximum power point.

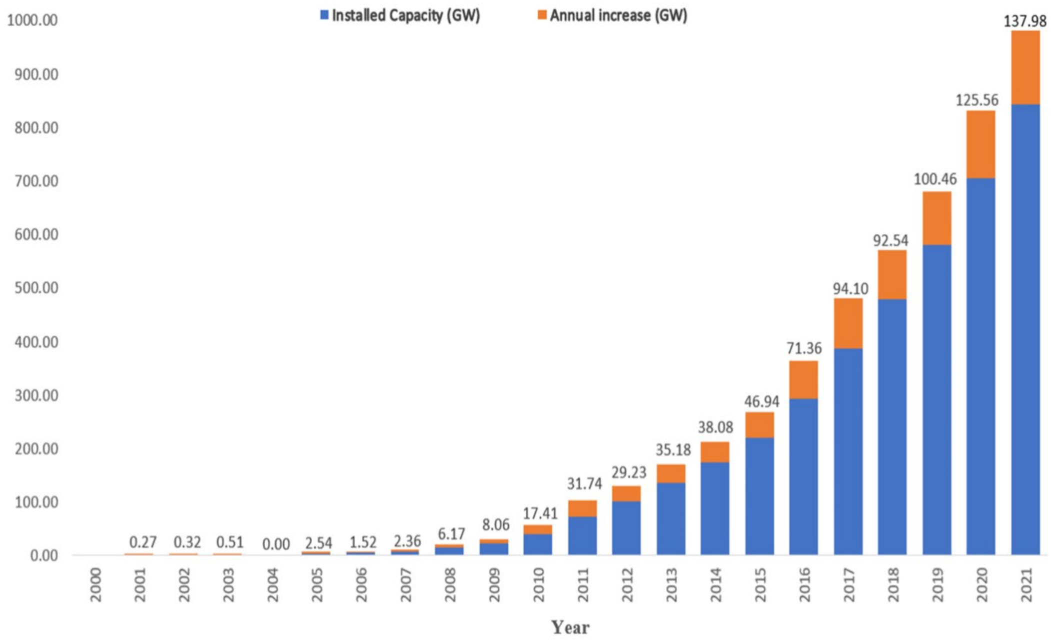

Figure 4.5: **The installed capacity of solar PV has evolved over the past 20 years, with an annual increase (Wongsathan, 2020).**

4.5. Limitations and Challenges

There were some limitations and challenges faced to achieve the activity required in this chapter. During the load flow analysis, the bus base KV was out of range from the bus nominal KV caused by the wrong voltage inputs that were entered and the load flow simulations did not run until the correct input voltage was entered into the buses.

The next chapter will discuss the system development, modelling, and simulations of the fuzzy logic controller for renewable energy such as the PV system. The best solution to supply additional power to the power network discussed in this chapter to satisfy the needs of the consumers is to integrate the PV system. This PV system must be able to supply enough power to meet the load demand. But for good performance of the PV system, a controller must be connected to ensure that the PV system is stable while operating at its maximum power. The fuzzy logic controller will be developed and designed to control the PV system that will be integrated into the power network discussed in this Chapter.

CHAPTER FIVE

SYSTEM DEVELOPMENT, MODELLING, AND SIMULATIONS OF THE FUZZY LOGIC CONTROLLER TO INTEGRATE THE RENEWABLES INTO THE POWER GRID

5.1 Introduction

The intermittent nature of sunlight and wind causes renewable energy sources such as solar and wind power, to provide unstable power. Because of this discrepancy, the system is unable to function at its maximum power point (Grant & Altermatt, 2021). To maintain system stability, a fuzzy logic controller based on the Maximum Power Point approach must be used to direct the renewable energy system to generate the most amount of energy possible during extreme weather circumstances. Because it increases system power, enables series connection of PV modules to raise system voltage, and improves system economy, the fuzzy logic controller-based maximum power point controller is an essential component of renewable energy systems. On the other hand, because the conventional controllers are directly linked to the batteries, the PV modules must function at a voltage lower than the maximum power point. Therefore, the traditional controllers cannot maximize the energy delivered by the system. Renewable energy such as the PV system without a controller does not have the same performance.

In Chapter 4, the load flow analysis was conducted on the Angolan power network which was experiencing voltage and power instability due to the load demand which was higher than the load supply. In this Chapter, the PV system was integrated to support the power network by supplying more power to satisfy the load demand. This PV system was integrated with and without a fuzzy logic controller. The design and modelling of the PV system were performed, and then the design and modelling of the fuzzy logic controller-based maximum power point was later introduced to the system. Furthermore, the PV energy system without a controller was compared to the one with the proposed controller. MATLAB software was used for all of the simulations in order to monitor and analyze the outcomes. The goal of the simulation exercises covered in this chapter was to create an effective controller design and incorporate it into the PV system in order to enhance performance, offer power stability, and reduce power failures in the power transmission network.

The simulations were based on the power network in Angola modelled in MATLAB software. Then, the proposed controller was also designed in the MATLAB platform. Afterwards, simulations were performed to analyse the performance of the PV system without and with the proposed controller. Then the results were compared.

Section 5.2 describes the methodology and the activities conducted in this chapter to evaluate the performance of the proposed controller. The design and modelling of PV systems and the fuzzy controller are covered in Section 5.3. In Section 5.4, the performance of the power network with and without the suggested controller is analyzed and shown through simulation results. Section 5.5 discusses and analysis the results. Section 5.6 discusses the limitations and challenges faced during simulations, the behaviour of the power systems with the controller and the power stability and power losses of the system with the proposed controller.

5.2 Methodology for designing the proposed controller

Three procedures were executed to formulate and assess the efficacy of the recommended controller and they were as follows:

5.2.1 Procedure number one:

It involved figuring out the PV systems' specifications as well as creating the converter and fuzzy logic controller that were then incorporated into the PV system. The actions listed below will be taken in order to fulfil the conditions of this experiment:

- **1st Step) Compute and ascertain the PV system's parameters:** The PV system's parameters, including the switching frequency, inductor, capacitor, voltage and current at MPPT were determined.

- **2nd Step) Modelling of DC-DC Converter:** For the PV system, a DC-DC converter was created using MATLAB to keep the inductor's current from dropping to zero throughout the allotted period. Resistors, capacitance, and inductance made up this converter.

- **3rd Step) Development of the Fuzzy Logic Controller:** This step consists of determining the variables of the controller to achieve efficiency and high performance of the controller for the PV system.

- **4th Step) Modelling of the Fuzzy Logic Controller:** The proposed controller was modelled through MATLAB/SIMULINK. This controller was developed and designed in such a way that the Maximum Power-Point Tracking can be reached so that power stability can exist in the PV system.

5.2.2 Procedure number two:

It was to model the PV system with the Fuzzy Logic Controller based on the Maximum Power Point Technique. This PV system was tested under different solar irradiances of $1000\ W/m^2$ to analyse in detail the impact of the proposed controller and to ensure the power stability of the PV system.

5.2.3 Procedure number three:

It was to conduct the load flow analysis of the Angolan power network with the PV system and without the proposed controller.

5.2.4 Procedure number four:

It was to conduct the load flow analysis of the Angolan power network with the integration of the proposed controller and the PV system.

Numerous vital factors required careful attention throughout each of these processes. In the load flow analysis, it was imperative to account for the impacts of voltage variations. Moreover, details concerning the transmission line and the distribution of power losses across the system had to be factored in for the assessment and management of the power system's performance. Because the sun is inconsistent in nature, temperature changes and solar irradiation had to be taken into account while modelling renewable energy sources, such as photovoltaic systems. Additionally, selecting the right inverter and controller is crucial to guaranteeing the PV energy systems operate at peak efficiency.

5.3 Design and Modelling of the PV System and Fuzzy Logic Controller

The PV system must first be simulated to better understand the system before developing and designing an effective controller. The block diagram of the PV system which consists of the PV module, DC-DC converter, and Maximum Power Point Technique (MPPT) algorithm was created for this project and is displayed in Figure 5.1 As a result, each component needs to be modelled

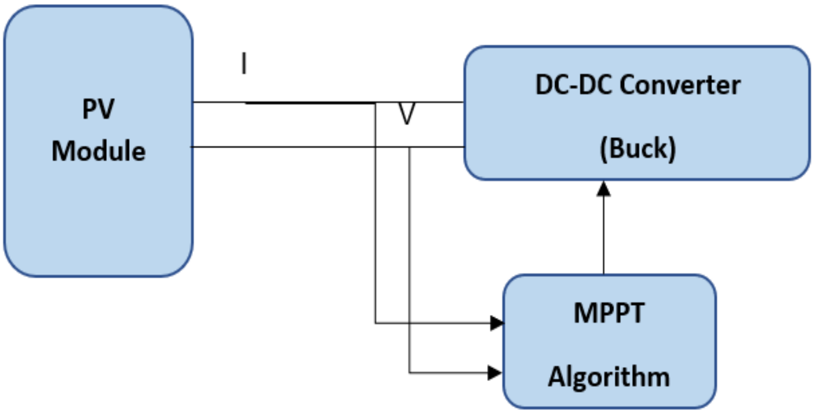

Figure 5.1: **Block Diagram of the photovoltaic (PV) system**

(K.Noussi, et al., 2020)

The diagram in Figure 5.1 shows the main configuration of the PV system that was used in this project, the DC-DC converter was introduced in a PV system to regulate the voltage and current levels, allowing the PV panels to operate at their MPP despite variations in environmental conditions such as temperature and solar irradiance.

5.3.1 Modelling of the PV Module

Using the mathematical model in Equation 5.1, the PV system's curve fitting parameter was decided.

$$I\,(V) = \frac{I_X}{1 - e^{\left(\frac{-1}{b}\right)}}\left[1 - e^{\left(\frac{V}{bV_x} - \frac{1}{b}\right)}\right] \qquad (5.1)$$

Vx= Represents the open circuit voltage

Ix= Represents the short circuit current

The open circuit voltage mathematical model, which takes temperature and sun irradiation into account, is displayed in Equations 5.2 and 5.3 below.

$$V_X = s\frac{E_i}{E_{iN}}\,TC_V\,(T - T_N) + sV_{max} - s(V_{max} - V_{\min})e^{\left(\frac{E_i}{E_{iN}}\ln\left(\frac{V_{max} - V_{OC}}{V_{max} - V_{mIN}}\right)\right)} \qquad (5.2)$$

$$I_X = p\frac{E_i}{E_{iN}}\,[I_{sc} + \,TC_i\,(T - T_N)] \qquad (5.3)$$

The equations above combine the effect of solar irradiance, temperature, and other performance factors to estimate the output current of a PV module. They are used for the evaluation of the module's performance and behaviour of the PV module under different operating conditions (Grant & Altermatt, 2021).

Table 5.1: **Parameters of PV Module**

Parameters	Description
S	The number of PV modules connected in series
p	The number of PV modules connected in parallel
Ei	The effective irradiation of the PV modules
EiN	The irradiation constant of 1000W/m^2
T	The temperature of the PV modules
TC_V	The temperature coefficient of the voltage
TC_i	The temperature coefficient of the current
T_N	The temperature constant
Vmax	The maximum voltage
Vmin	The minimum voltage
I_{sc}	The short circuit current
V_{OC}	The pen circuit voltage 3

For this project, the PV module data and all the specifications of the PV system are shown in Table 5.1.

When selecting a specific photovoltaic (PV) module for a solar energy system, there are several factors to consider to have an efficient PV system such as the PV module data and DC-DC Converter as shown in Table 5.2. Each PV module data has its parameters depending on the manufacturers. The PV module data selected for this project consists of temperature coefficients that are as close as possible to zero for both Voc and Isc. The reason for this selection is that a lower temperature coefficient close to zero for Isc means that the module's current will decrease less as the temperature rises. This is beneficial because it helps minimize the loss of current output due to temperature, enabling the module to maintain a higher current and maximize power production. Also, A lower temperature coefficient for Voc means that the module's voltage will decrease less as the temperature rises. This is desirable because it helps mitigate the voltage drop caused by temperature, allowing the module to maintain a higher voltage output and maximize power production (Ramos-Paja, et al., 2022).

A DC-DC converter in this project was used to regulate the voltage and current levels, allowing the PV panels to operate at their MPP despite variations in environmental conditions such as temperature and solar irradiance. The DC-DC converter frequency selected in this project has a frequency of 20 kHz as shown in Table 5.2 because Higher switching frequencies can lead to improved converter efficiency and also can help reduce output voltage ripple. As the switching frequency increases, the ripple frequency also increases, making it easier to filter and attenuate. This results in a smoother and more stable output voltage.

Table 5.2: **Specification of a PV system**

Parameter	Value
PV module data	
The voltage at the maximum power point (VMPP)	38.6 V
Current at the maximum point (IMPP)	9.33 A
Short-circuit current (I_{sc})	9.98 A
Open circuit voltage (V_{oc})	47.7 V
Temperature coefficient of voltage (Tcv)	-0.36099 %/°C
Temperature coefficient of current (TIsc)	0.102%/°C
DC-DC Converter	
Inductor	0.0063 H
Capacitor	0.056183 μF
Switching Frequency	20kHz

Figure 5.2 below shows the behaviour of the PV module in a subsystem in various solar irradiance to understand better the impact of the sun on the PV module used in the project. The solar irradiances used in this analysis were 0.1 kW/m^2, 0.5 kW/m^2, and 1 kW/m^2. Understanding the behaviour of the PV module involves considering the strong relationship between solar irradiance, voltage, current, and power. Therefore, analyses were conducted on solar irradiances in relation to voltage (0 to 30 Volts) and current (0 to 10 Amperes), as well as voltage (0 to 7000 Volts) and power (0 to 30 MW). The analysis reveals that higher solar irradiance results in increased current and power. Consequently, the fuzzy logic controller developed in this project must be capable of adjusting to variations in solar irradiance to maintain a stable supply of current and power to consumers.

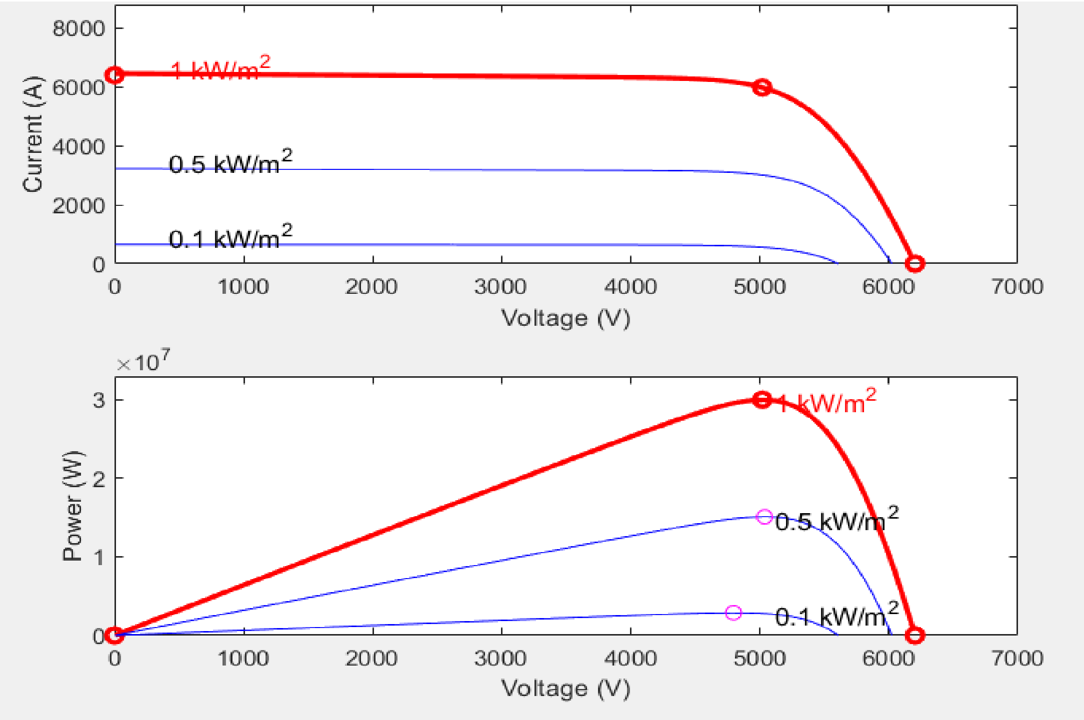

Figure 5.2: **PV module under various solar irradiance**

The process involved in getting the graphical results illustrated in Figure 5.2 consists of the following four main steps:

- Inserting the parameters for the PV system specified in Table 5.2 such as the maximum power, the open circuit voltage, the short-circuit voltage, and the temperature coefficient of the voltage and the current into the PV array block through MATLAB software.

- Inserting into the PV system different solar irradiances from 100 W/m^2 to 1000 W/m^2 because the sun is not always available in nature with the same intensity.

- Setting the solar irradiance variations in terms of 100, 500, and 1000 W/m^2 to one specific temperature of 25 degrees Celsius.

- After introducing all the parameters of the PV system and the solar irradiances, the next step was simulating MATLAB software.

The PV module in a subsystem was modelled and presented using the circuit design below in Figure 5.3 , which was tested for various temperatures and solar irradiance levels. The solar irradiance, temperature, and input voltage make up this circuit.

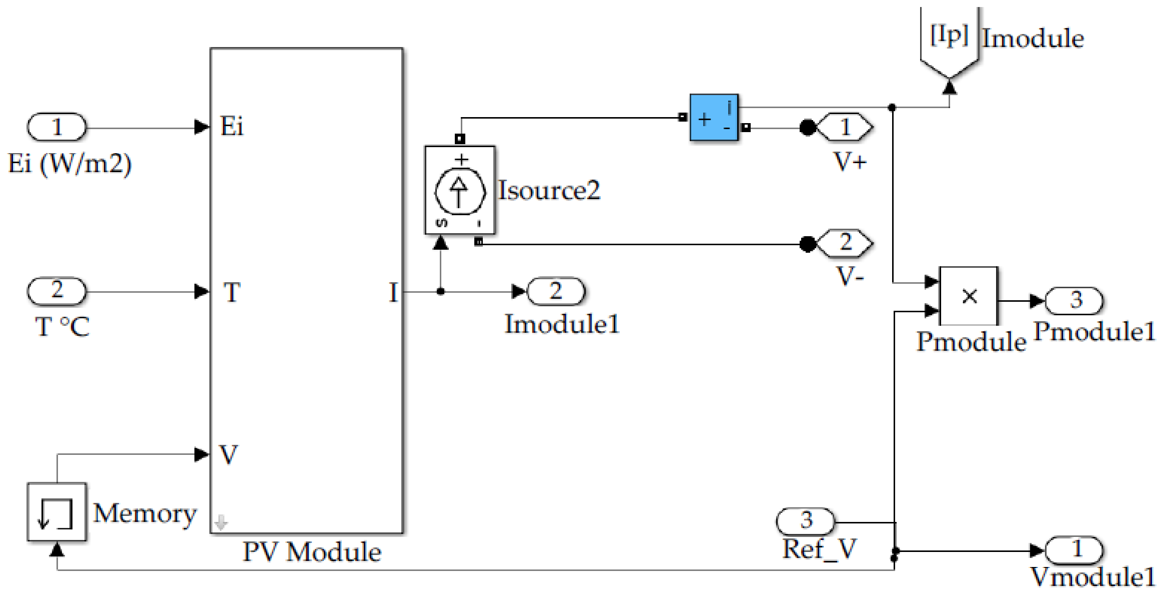

Figure 5.3: Circuit Diagram of the PV system

5.3.2 DC-DC Converter Model

The DC-DC converter was constructed in the manner depicted in Figure 5.4 in order to operate in continuously conduction mode. During the design phase, the DC-DC converter was employed as a control mechanism to prevent the inductor's current from dropping to zero (K.Noussi, et al., 2020). The DC-DC converter was essential for controlling the continuous output of the solar cells under a variety of operating conditions and preserving the efficiency of the conversion process with the fewest possible fluctuations. Furthermore, the study project's DC-DC converter helped to maximize the solar energy generated by the photovoltaic system. The way to do this is via Maximum Power Point Tracking.

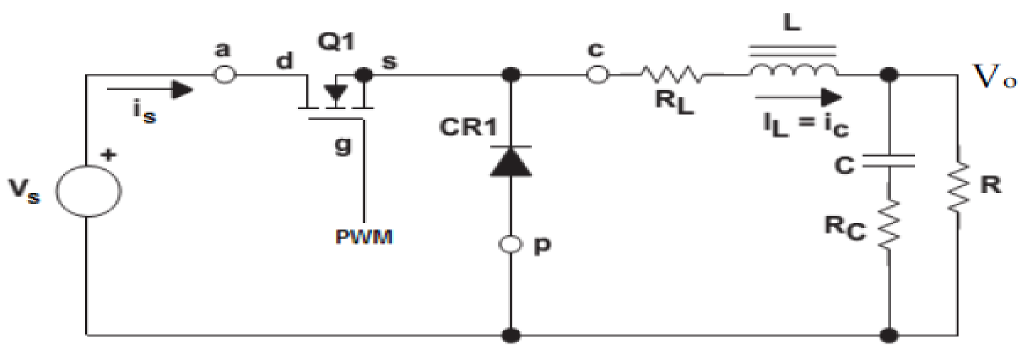

Figure 5.4: DC-DC Converter Circuit

(K.Noussi, et al., 2020)

The ripple of the inductor was calculated using Equation 5.4.

$$V_L = \frac{L\Delta I_L}{\Delta t} \quad (5.4)$$

Equations 5.5 and 5.6 below show the positive and negative changes during off-state.

$$\Delta I_L(+) = \frac{(V_o - V_{DS} - I_L R_L) - V_o}{L} T_{on} \quad (5.5)$$

$$\Delta I_L(-) = \frac{(V_o + (V_d + I_L R_L)}{L} T_{off} \quad (5.6)$$

The following equations will be used to calculate the inductor current of the DC-DC converter.

$$\Delta I_L(+) = \frac{(V_s - V_o)}{L} T_{on} \quad (5.7)$$

$$I_L(-) = \frac{V_o}{L} T_{off} \quad (5.8)$$

The duty cycle was calculated using the Equation 5.9 as shown below

$$D = \frac{T_{on}}{T_s} = \frac{V_o}{V_s} \quad (5.9)$$

5.3.2.1 Inductor Design of the DC to DC converter

To maintain the power system's balance and reduce system disturbance, it is crucial to make sure the inductor is designed efficiently. The system may provide an unstable DC output and cease to function in Continuous Conduction Mode (CCM) if the wrong inductor is chosen Equation 5.10 refers to the critical output current. The critical output current represents the maximum current that the DC-DC converter can deliver while maintaining its specified performance and safety limits (Wongsathan, 2020).

$$i_o(crit) = \frac{\Delta I_L}{2} \quad (5.10)$$

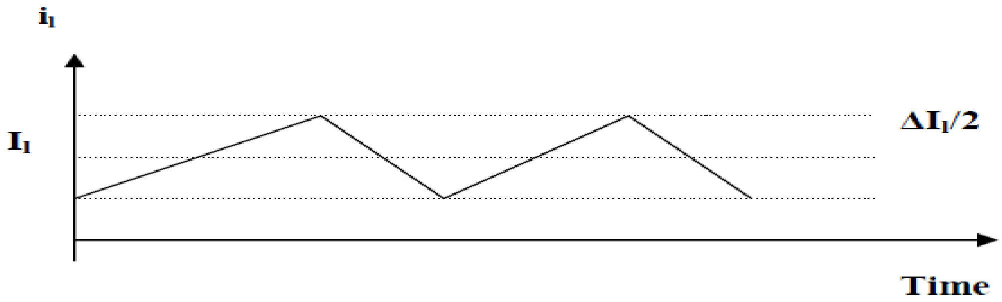

Figure 5.5: **Inductor Currents for Continuous Conduction Mode (Wongsathan, 2020)**

Figure 5.5 above shows how the maximum and the minimum inductor current can be obtained. In the Continuous Conduction Mode (CCM) of a DC-DC converter, the inductor current never falls to zero during a switching cycle. The inductor current waveform is continuous, and it remains positive throughout the cycle. Therefore, the inductor was obtained using Equation 5.11.

$$L_{min} \geq \frac{V_o\left(1-\frac{V_o}{V_s}\right)T_s}{2i_o(crit)} \quad (5.11)$$

Using the 10% ripple value and the PV module specifications listed in Table 5.2, the maximum power and voltage were determined based on the maximum power point. In Equation 5.12, the maximum output power is determined.

$$\Delta I_L = 0.1 \times \ i_o(max) = 0.541\ A \quad (5.12)$$

The minimum value of the inductor is calculated in Equation 5.13

$$L_{min} \geq \frac{12\ \times\left(1-\frac{17}{17.71}\right)\times 50}{2\times 0.2705} \geq 0.0063\ H \quad (5.13)$$

5.3.2.2 Capacitor Design of the DC-to-DC converter

The current in the capacitor can be found using Equation 5.14.

$$i = \frac{\Delta Q}{\Delta t} = C\frac{\Delta V_c}{\Delta t} \quad (5.14)$$

The variation of the load can be found using Equation 5.15**.**

$$\Delta Q = \frac{\Delta I_L T_s}{8} \quad (5.15)$$

The design of the capacitor is obtained using Equation 5.16.

$$C \geq \frac{\Delta I_L T_s}{8\,\Delta V_c} \tag{5.16}$$

Equation 5.17 can be found by using a ripple value of 0.1%

$$\Delta V = (0.001) \times V_o = 0.012\,V \tag{5.17}$$

The minimum value of the capacitor can be found using Equation 5.18

$$C \geq \frac{\Delta I_L T_s}{8\,\Delta V_c} \geq 0.056183\ \mu F \tag{5.18}$$

5.3.2.3 Modelling of DC-DC Converter

MATLAB/Simulink was used to model the DC-DC converter used in this research, as seen in Figure 5.6.

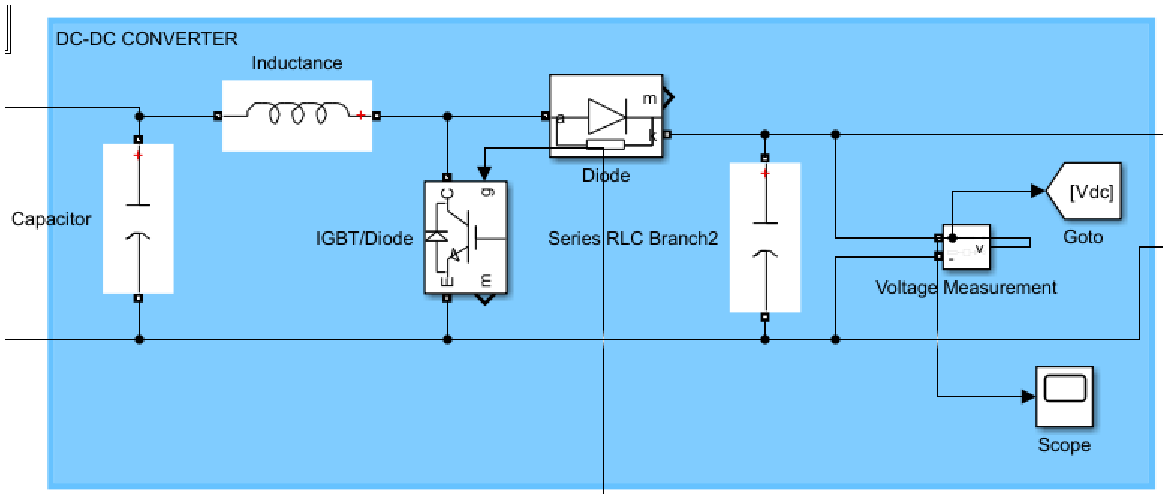

Figure 5.6: **DC-DC Converter modelled in Simulink**

The DC-DC converter shown in Figure 5.6 above has been constructed using the fundamental building blocks of MATLAB/Simulink. This converter comprises components such as a resistor, inductor, capacitor, diode, and voltage measurement. The voltage measurement is in charge of taking measurements and distributing the voltage between two electric nodes. The diode stops current from flowing in the opposite direction while allowing current to flow in one direction in the DC-DC converter. When electricity travels through the Buck converter, the inductor is in charge of storing the energy in a magnetic field.

5.3.3 Fuzzy Logic Controller Development

The Fuzzy Logic Controllers (FLC) are used for systems that are non-linear such as electrical systems because electrical systems have dynamic behaviours. FLC does not need a specific mathematical model. The inference mechanism of the FLC consists of ensuring that the understanding of the data is performed according to the rules and the membership functions (Srinvasan, 2021). There are two input variables in the Fuzzy Logic Controller which are Error (E) and Change of Error (CE) as shown in **Equation 5.19** and **Equation 5.20** (K.Noussi, et al., 2020)**.**

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} = \frac{\Delta P}{\Delta V} \quad (5.19)$$

$$E(k) = E(k) - E\,(k-1) = \Delta E \quad (5.20)$$

The CE(k) input consists of defining exactly the motion operating point in the Maximum PowerPoint direction. This process is represented in **Equation 5.21**.

$$\mathrm{D}(k) = D\,(k-1) + \Delta D\,(k) \quad (5.21)$$

5.3.3.1 Membership Functions

The membership functions were used for the fuzzification process. The variable inputs Error (e), Change of Error (ec), and the output Duty cycle (D). The following 7 membership functions were used in this project.

- NB (negative big)
- NM (negative Medium)
- NS (negative small)
- Zero (Zero)
- PS (positive small)
- PM (positive medium)
- PB (positive big)

The range for error, change of error, and the duty cycle are shown in Figure 5.7.

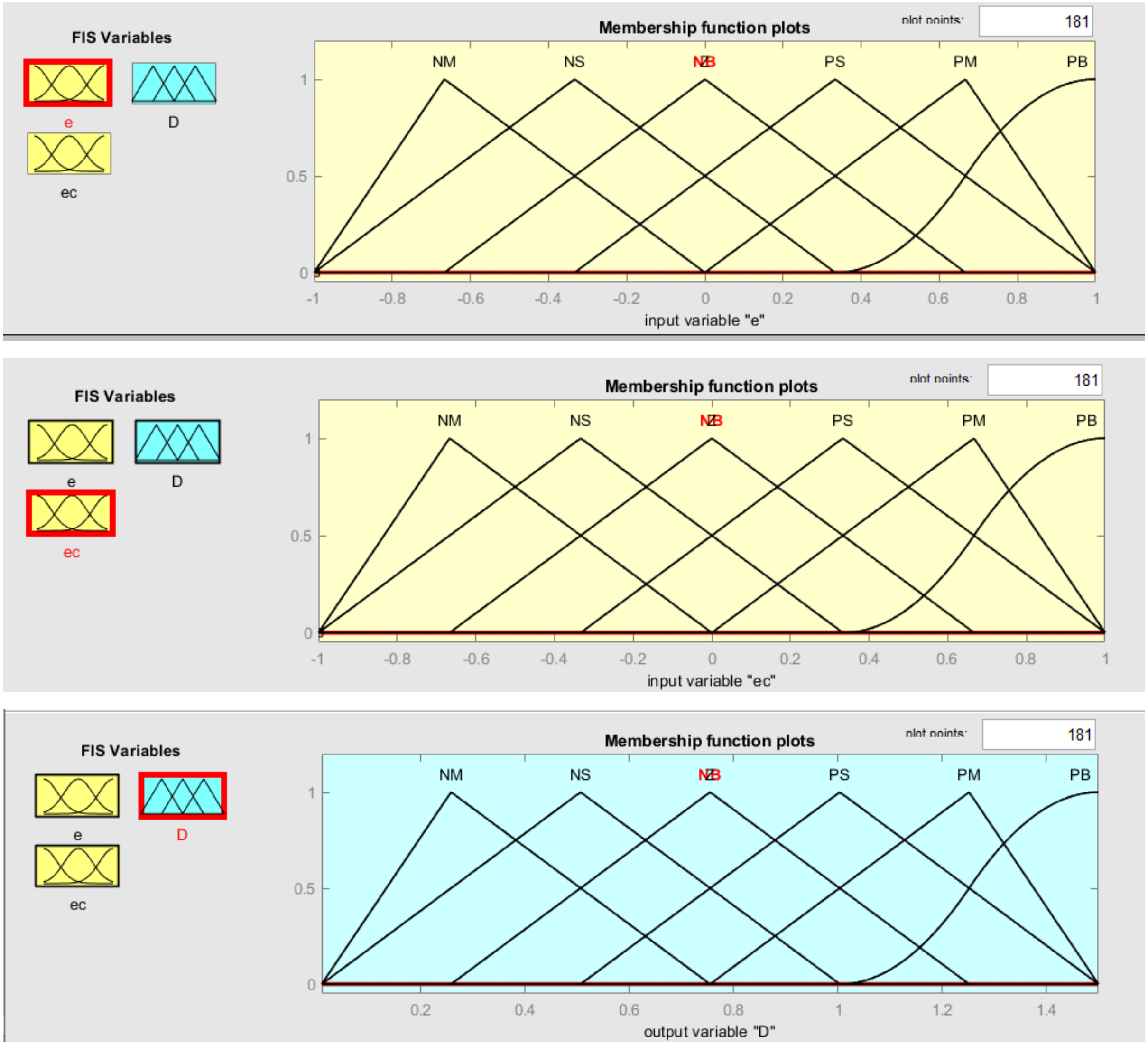

Figure 5.7: **Membership Functions. (Error; Change of Error and Duty Cycle)**

5.3.3.2 Fuzzy Rules

The proposed controller developed in this project consists of 49 fuzzy rules. Figure 5.7` shows the graphic representation of the error, change of error, and duty cycle for the 49 fuzzy rules (Molina & Marcelo, 2017).

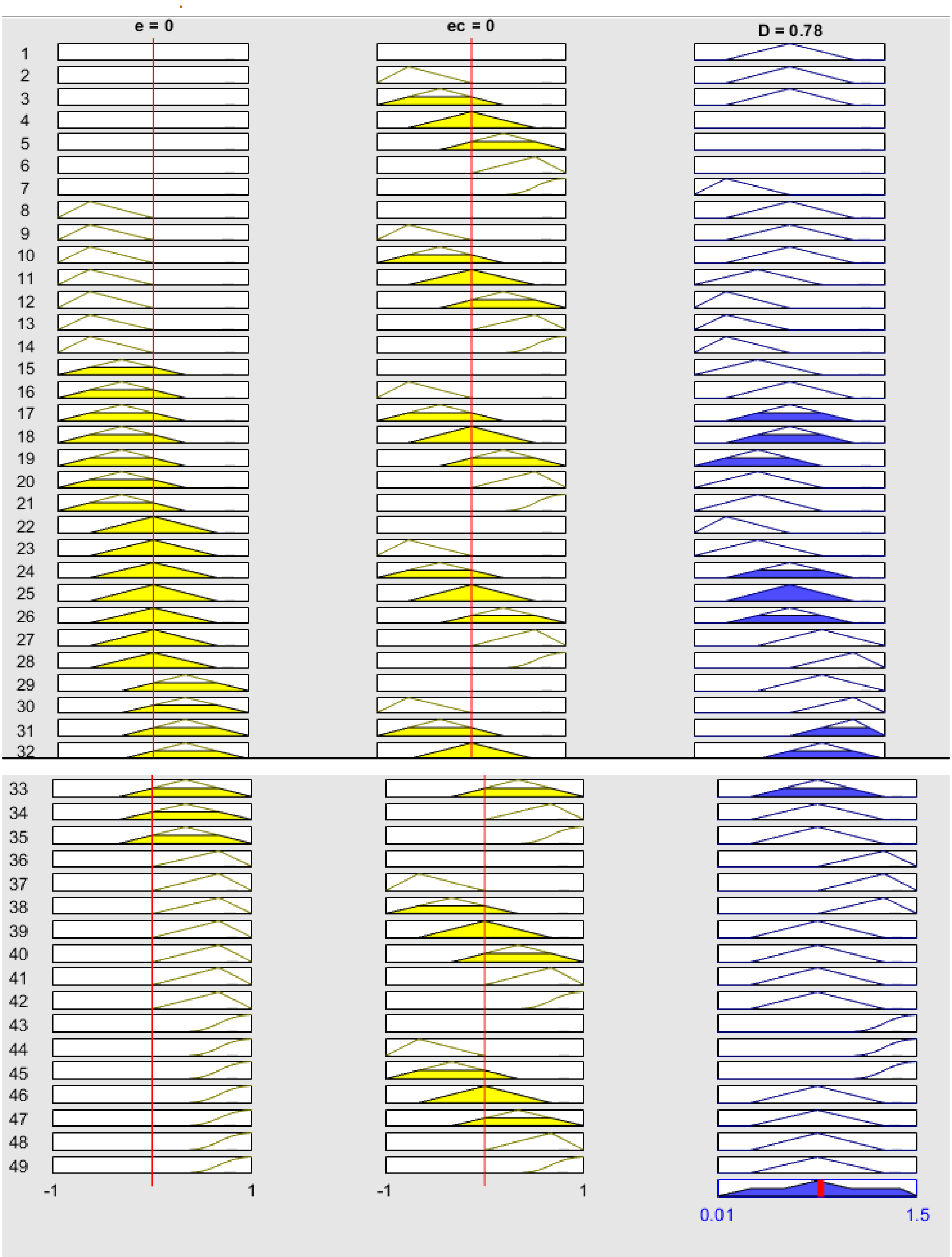

Figure 5.8: Graphic representation of the error, change of error, and duty cycle

The process to get the graphical results illustrated in Figure 5.8 consists of the following steps:

- Open the Fuzzy Logic designer window in MATLAB software

- Add a new input to have two inputs (Error and Change in Error) and one output (Duty Cycle)

- Set the fuzzy rules for the controller which consists of the combination of NB, NM, NS, Z,PS, and PB..

- Allocate the fuzzy rules to each input to observe the results on the output.

- Set the membership functions based on the fuzzy rules through MATLAB software

- Simulate through MATLAB software.

The circuit diagram illustrated in Figure 5.9 was used for the graphical results of the Fuzzy. It can be observed that the fuzzy rules contribute directly to the process of fuzzification and defuzzification of the fuzzy logic controller. Fuzzification consists of converting the numerical input variables into linguistic variables and Defuzzification consists of preparing the output variables of the fuzzy logic controller.

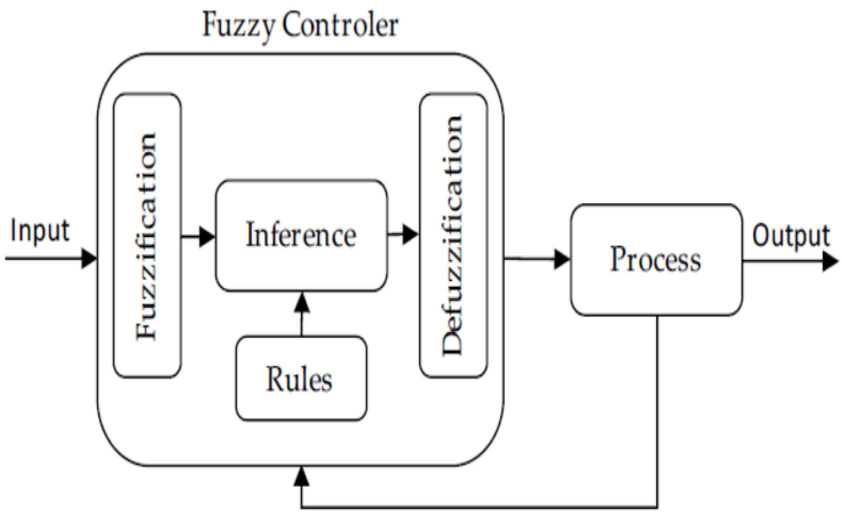

Figure 5.9: **Circuit Diagram for the Fuzzy Controller**

(Zsiborács, et al., 2019)

5.3.3.3 Fuzzy Logic Controller Modelling

Figure 5.10 below shows the Fuzzy logic Controller-based maximum power point technique that was modelled using MATLAB/SIMULINK. ΔV and ΔP are calculated through this modelling. This controlled development was used for the PV system to provide stability. The input Vpv represents the input photovoltaic voltage of the fuzzy logic controller and the input Ipv represents the input photovoltaic current of the fuzzy logic controller. Then, the input voltage and the current go to the memory blocks which hold or delay these inputs by one major integration time step. The product block in its turn multiplies the two inputs which are the voltage and the current, then sends the output of this operation to the next section which is the sum block. This block is responsible for converting the data received into its accumulator data type and sending the output to the division and multiply block which is then sent to the bus creator block which is responsible for combining a set of input elements into a bus. The combination of these input elements is then sent to the saturation block, which creates an output signal that is the input signal's value bounded to the upper and lower saturation values, after the fuzzy logic controller block implements a fuzzy inference system.

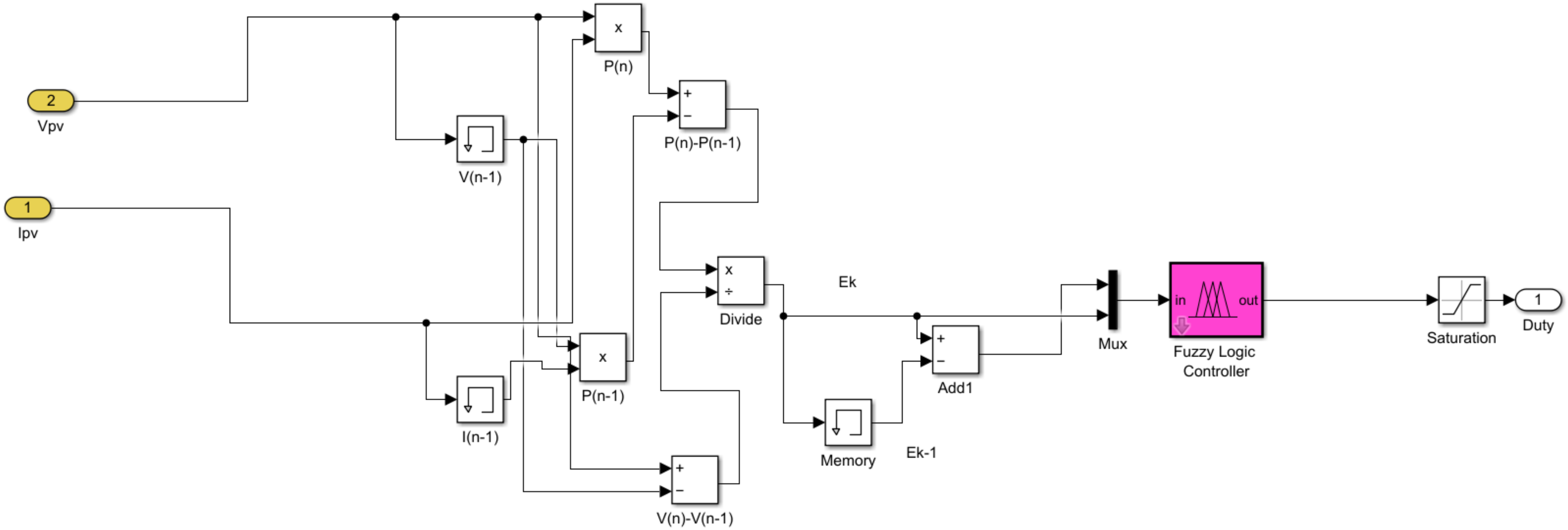

Figure 5.10: **Fuzzy Logic Controller-based maximum power point technique**

5.3.4 PV System Modelling

The PV system developed consists of the PV module, the DC-DC converter, and the fuzzy logic controller-based maximum power point technique as shown in **Figure 5.11.**

Figure 5.11 shows below the PV system modelling done through MATLAB/SIMULINK. The two inputs supplied in the PV array are the temperature and the solar irradiance. The PV array consists of 60 cells per module, with an open circuit voltage (Voc) of 47.7 Volts and a short-circuit current (Isc) of 9.98 Amperes as described previously in Table 5.2**.** Furthermore, the voltage at the maximum power point (Vmp) in the PV array is 38.6 Volts and the current at the maximum power point is 9.33 Amperes to evaluate the controller performance. The temperatures used in the PV array block of the PV system vary between 0 to 100°C and the solar irradiances used vary between 0 to 1000 W/m^2 or 0.1 kW/m^2. The same PV module is connected to both, the DC-DC converter and the fuzzy controller so that the PV system can achieve the maximum power point and can achieve high performance. The DC-DC converter on the right side in the blue block consists of the capacitor, inductance, resistor, and frequency which have been calculated systematically to operate efficiently. The fuzzy logic controller has been incorporated below the DC-DC converter, then at the bottom on the right side, there are the grid and inverter which convert direct current to alternating current. It then injects the voltage RMS at 50Hz into the electrical power grid. The other blocks in this PV system represent the measurement components of the PV system outputs such as the current, the voltage, and the power.

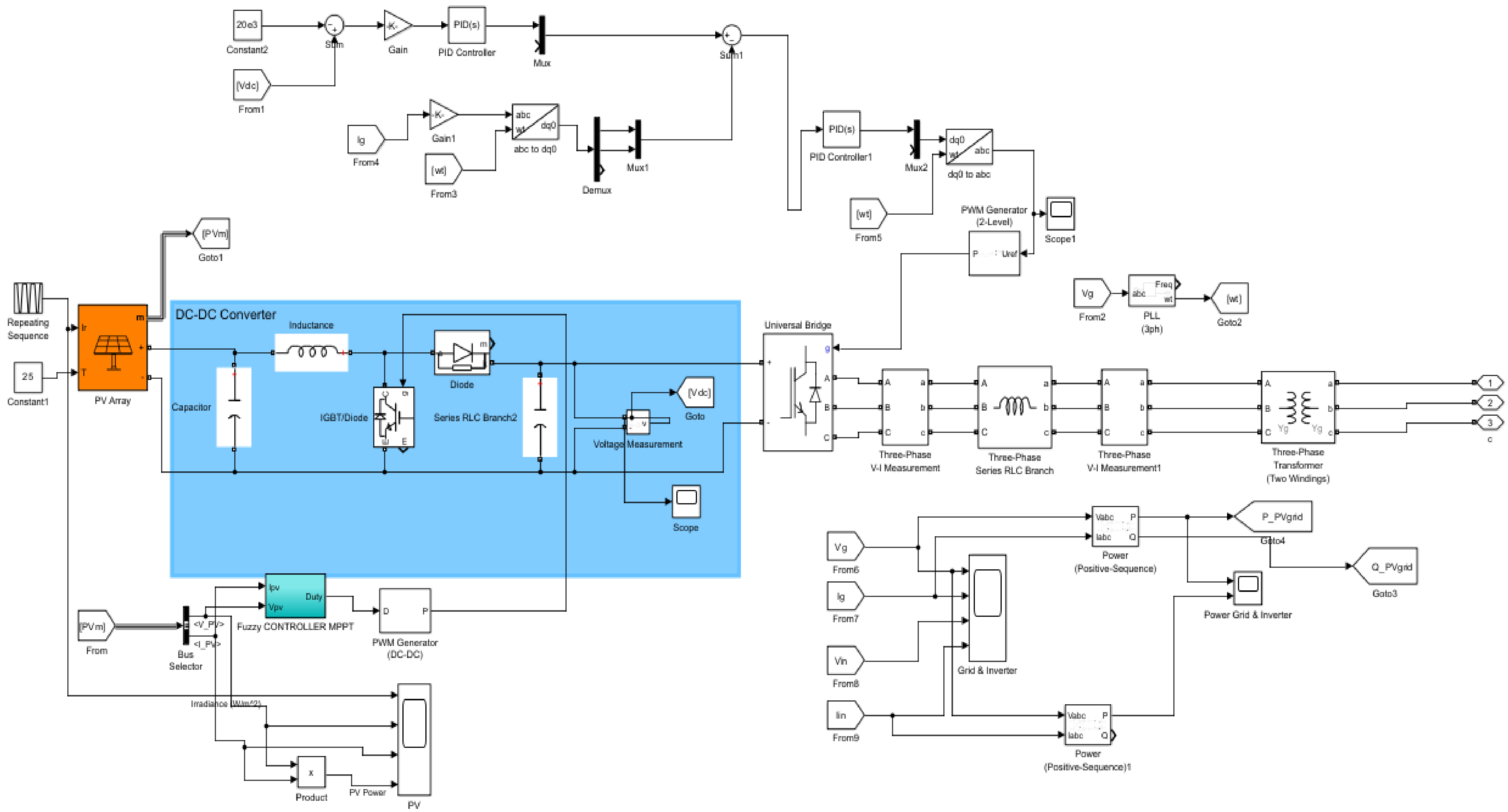

Figure 5.11: PV System Modelling With Fuzzy Logic-based MPPT Controller

5.4 Implementation of the chosen experiments and their results

- In the initial scenario, the Angolan power network, incorporating the PV system, underwent analysis without employing the suggested controller. This analysis was conducted using MATLAB/Simulink through load flow analysis.
- In the second scenario, the Angolan power network, incorporating the PV system, underwent analysis with the implementation of the recommended controller. This analysis was carried out using MATLAB/Simulink through load flow analysis.

Both scenarios were considered for the case that the load demand is higher than the supply. In all scenarios, the following parameters were considered: a 30MW PV grid, an inductor of 0.0063 H, and a capacitor of 0.0561 μF; with a frequency of 20 kHz for the dc-dc converter.

Scenario 1: This scenario consists of the same Angolan power network that was discussed in Chapter 4. It was observed in Chapter 4 that the power network was experiencing voltage instability due to load demand that was higher than the power supply. In this scenario, The PV system is introduced without a controller to support the power network to keep it stable and to satisfy the load demand needed as shown below in Figure 5.12.

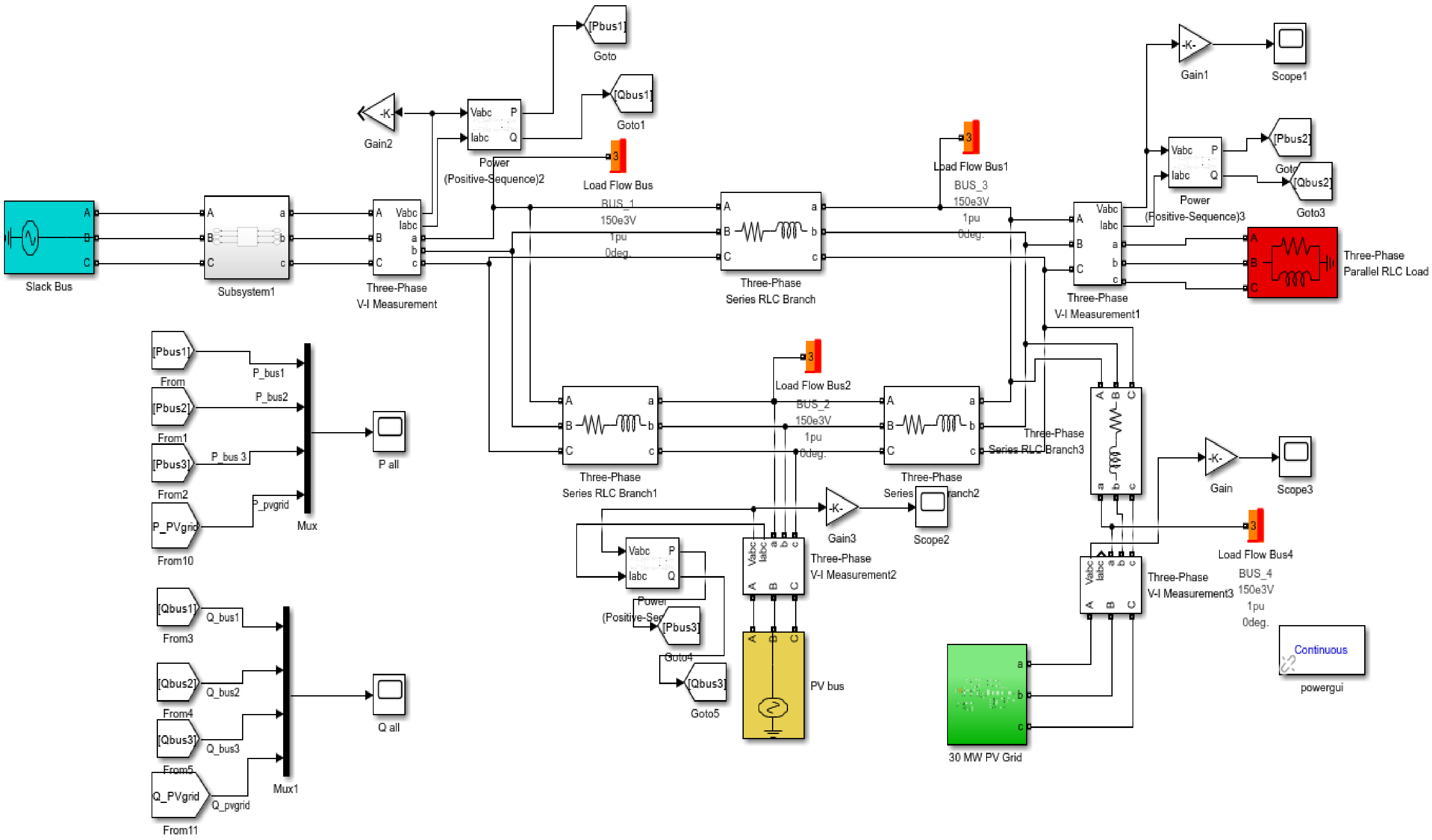

Figure 5.12: Angolan's Power Network with the PV system but without the Proposed Controller

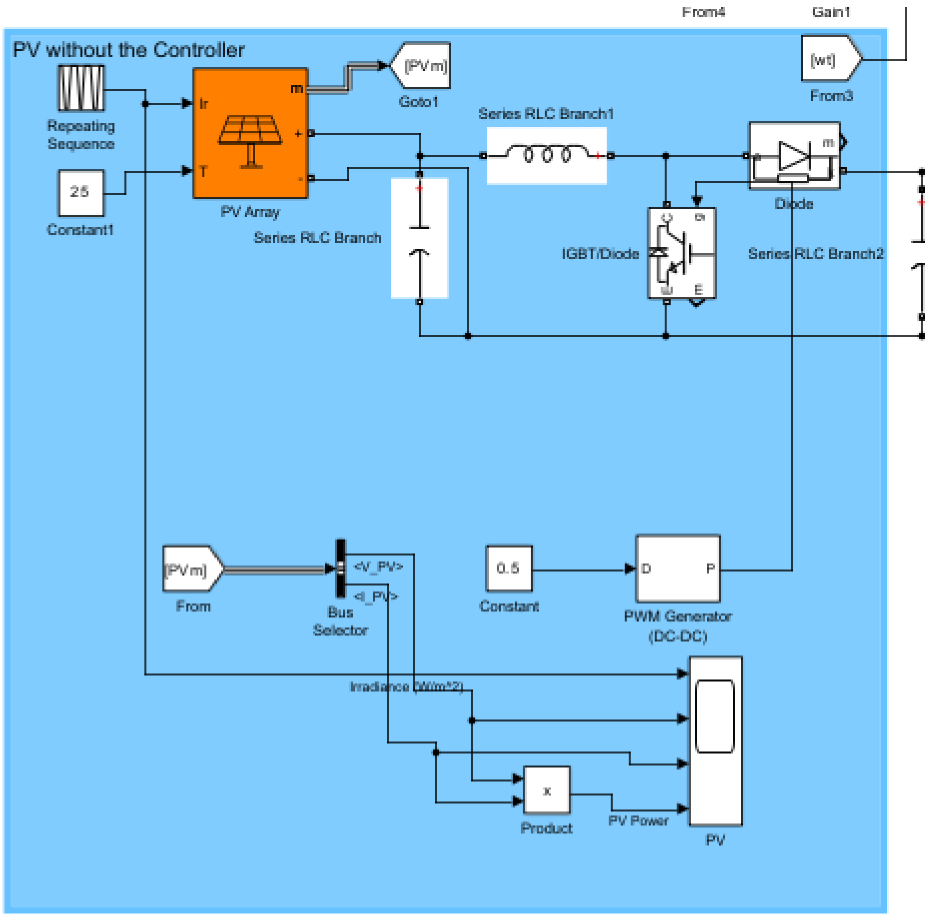

Figure 5.13: **Partial Inside setup of the 30MW PV Grid without the Proposed controller**

Figure 5.12 shows the PV system which is connected to the same three 150 KV power networks in Angola that was discussed in Chapter 4, but with additional components such as the 30MW PV grid in green, the "P all" block which represents the results of the true power, the "Q all" block which is represents the results of the reactive power, the others "From" and "Goto" blocks have been used to determine and analyses other parameters of the network such as the voltage and the current in the generation and the load buses. The inside setup of the 30MW PV grid without the proposed controller is shown in **Figure 5.13,** but the full description of the PV System is shown in **Figure 5.12.**

The load demand is still 50 MW as described in Chapter 4. The integration of the PV system had an impact on the total power network by increasing the power at Bus generation (Bus 3) from 36 MW to 50MW after a period of 0.03s, the total generation is now 50MW which is exactly the load needed to satisfy the load demand as shown below in **Figure 5.14.** Therefore, the load supply is now equal to the load demand and the power network is now capable of supplying the required load demand. It is also important to note that the PV system introduced in this power network is capable of generating 30MW when it is operating at maximum power point with a controller, but in this scenario the PV grid was only generating and supplying 2.8MW during the transient period between 0.02s and 0.03s because it is not operating at maximum power point and there is no controller to keep the power its maximum level.

Results for Scenario 1

Furthermore, it can be observed in **Figure 5.16** that the solar irradiance in the system is 1000 W/m^2. There is an increase in PV voltage to 6kV then a decrease in PV current from 6000 A to 44.9A, and then a decrease in power from 26MW to 0.15MW. The decrease in PV voltage and PV Current is because the system is not operating at the maximum power point and also there is no controller to maintain the system stability at a certain point. **Figure 5.17** shows that the grid and inverter have been operating at 2.8MW at a period of 0.025s, then there is a significant drop from 2.8MW to 1.2KW. This drop in power in the grid and inverter is also due to the absence of a controller operating at the maximum power point.

The integration of the PV system in the Angolan power network has increased the voltage per unit in Bus 2 (PQ load) and BUS 3 (Generation Bus) to 1 p.u on for all three phases as shown in **Figure 5.18 and Figure 5.19,** but there is a risk of having an excessive voltage in the system if the load demand decreases exponentially during a certain period of the day because when the load decrease the voltage increases. It is important to understand that the load demand is never the same during the day. There are periods of the day with higher load demand and periods of the day with less load demand. Therefore, a controller can be a good tool to control this change in load demand and to ensure that the system is operating at a safe operating voltage range and maximum power point.

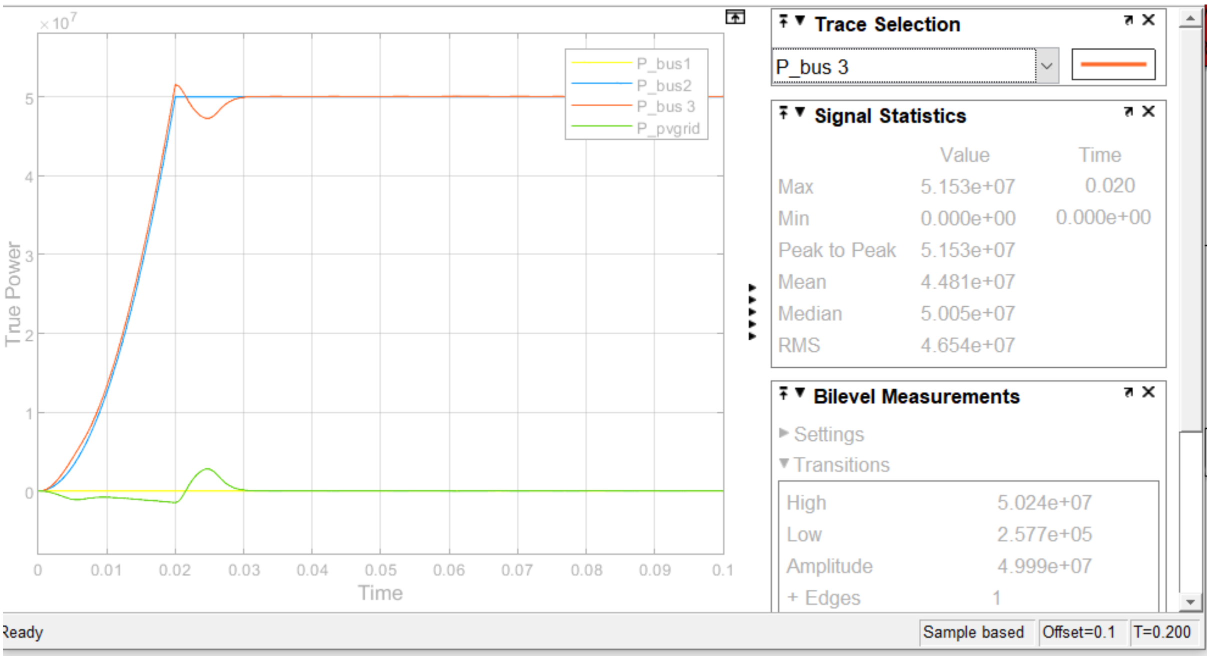

Figure 5.14: True Power of the power network with integration of the PV system

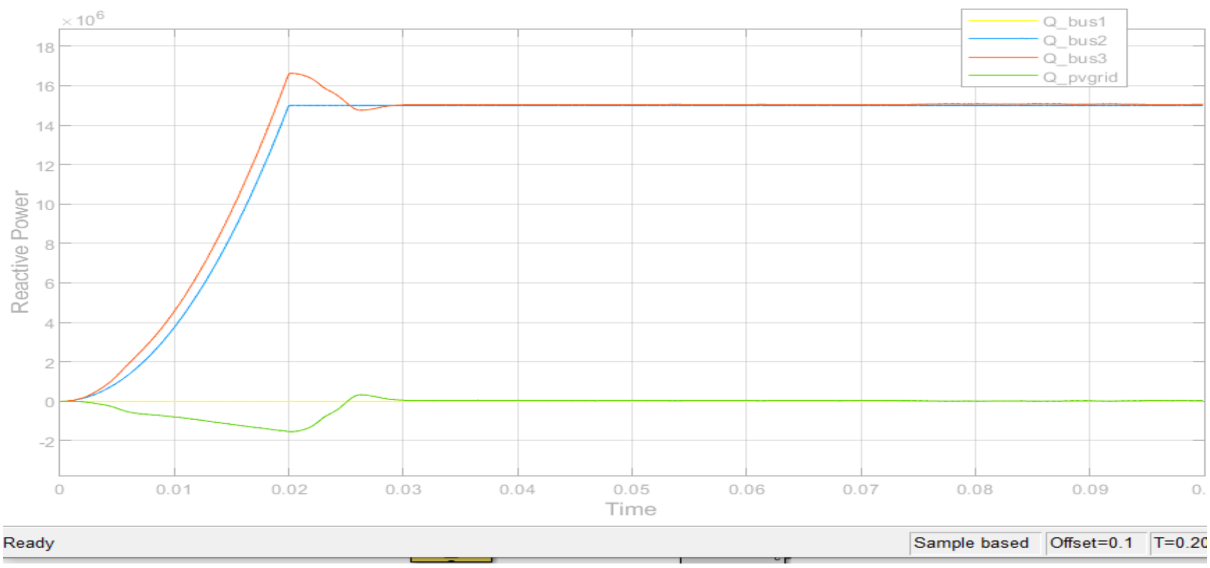

Figure 5.15: Reactive Power of the power network with integration of the PV system

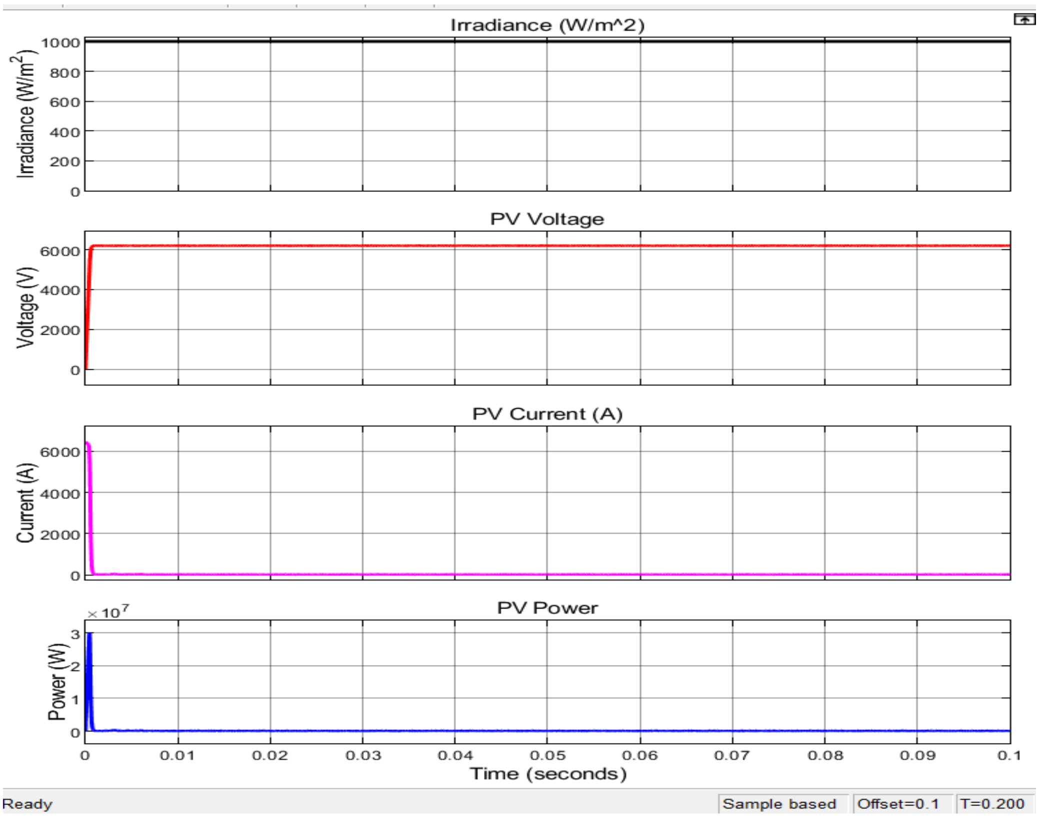

Figure 5.16: Solar Irradiance, PV voltage, PV current, and PV power of the PV grid system

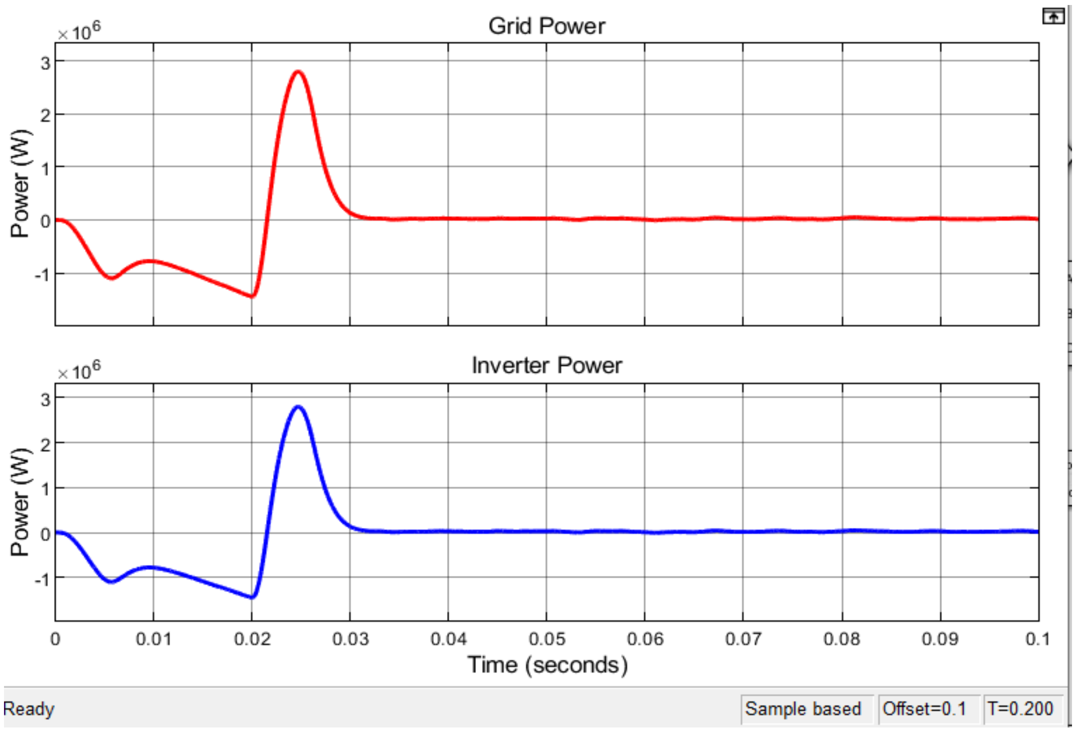

Figure 5.17: Power for the Grid & Inverter

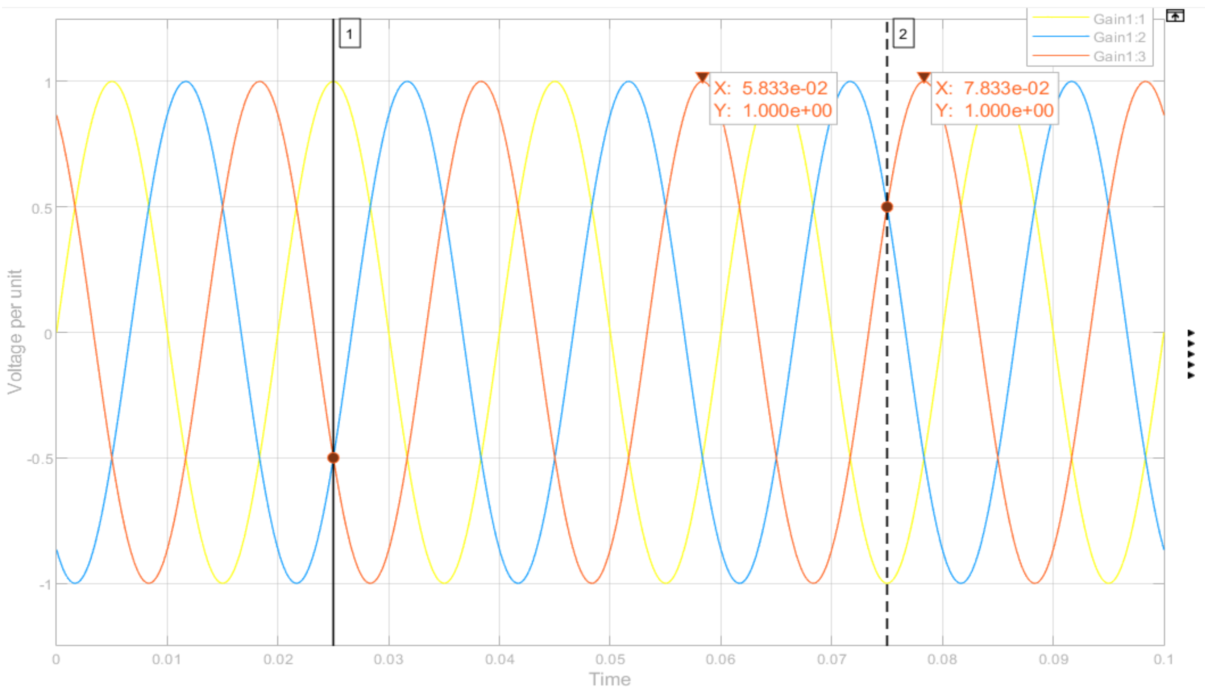

Figure 5.18: Per Unit Load Voltage Profile at Bus 3 (PQ-Load) when the load demand is higher than the load supply with the PV system but without the controller

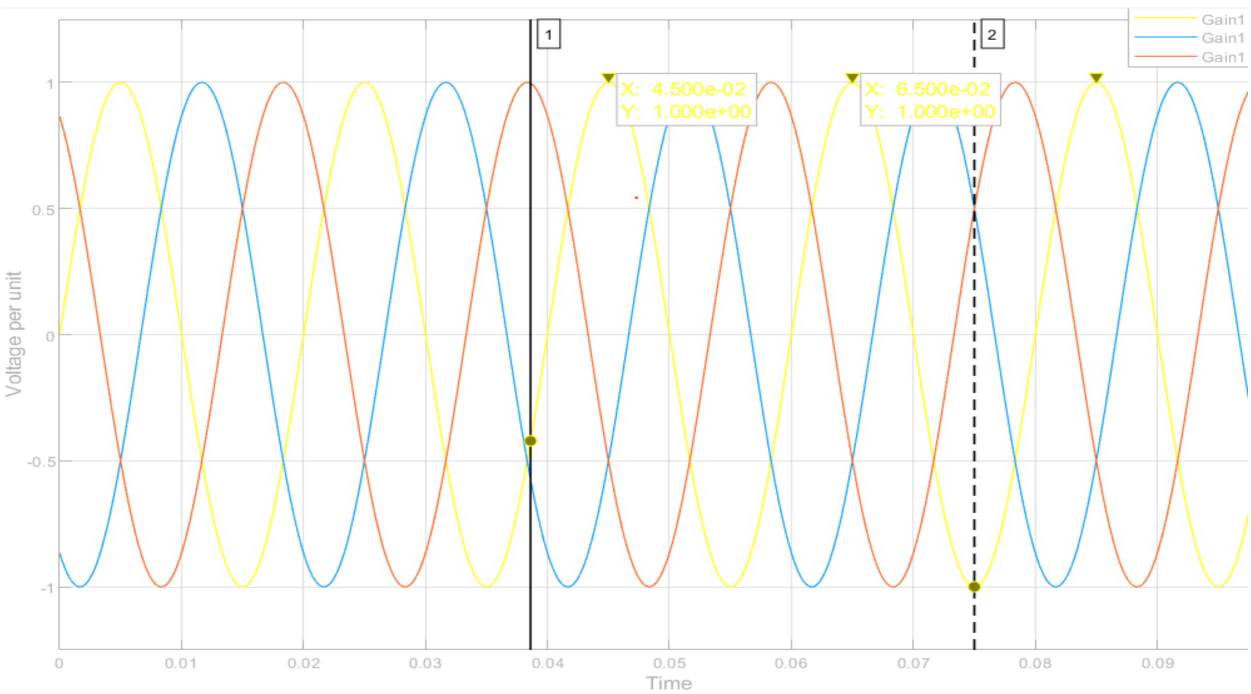

Figure 5.19: Per Unit Load Voltage Profile at Bus 2 (PV Generation) when the load demand is higher than the load supply with the PV system but without the controller

Scenario 2: This scenario consists of the same Angolan power network with the PV system and the proposed controller when the load demand is at 50 MW and the load supply is at 36 MW as shown in **Figure 5.20.**

It was found in the first scenario that there was a significant decrease in PV voltage and PV current. Furthermore, it was found that the PV grid was only generating 2.8MW while the PV grid developed in this project can generate 30MW when it is operating at the maximum power point. Therefore, the contingency plan was to have a controller integrated into the PV system so that it can control the system and enable it to operate at its maximum power point. The proposed controller was also able to control the PV system to supply a voltage that is within the standard voltage allowable limit as well as to ensure that additional power supply in the system is not excessive.

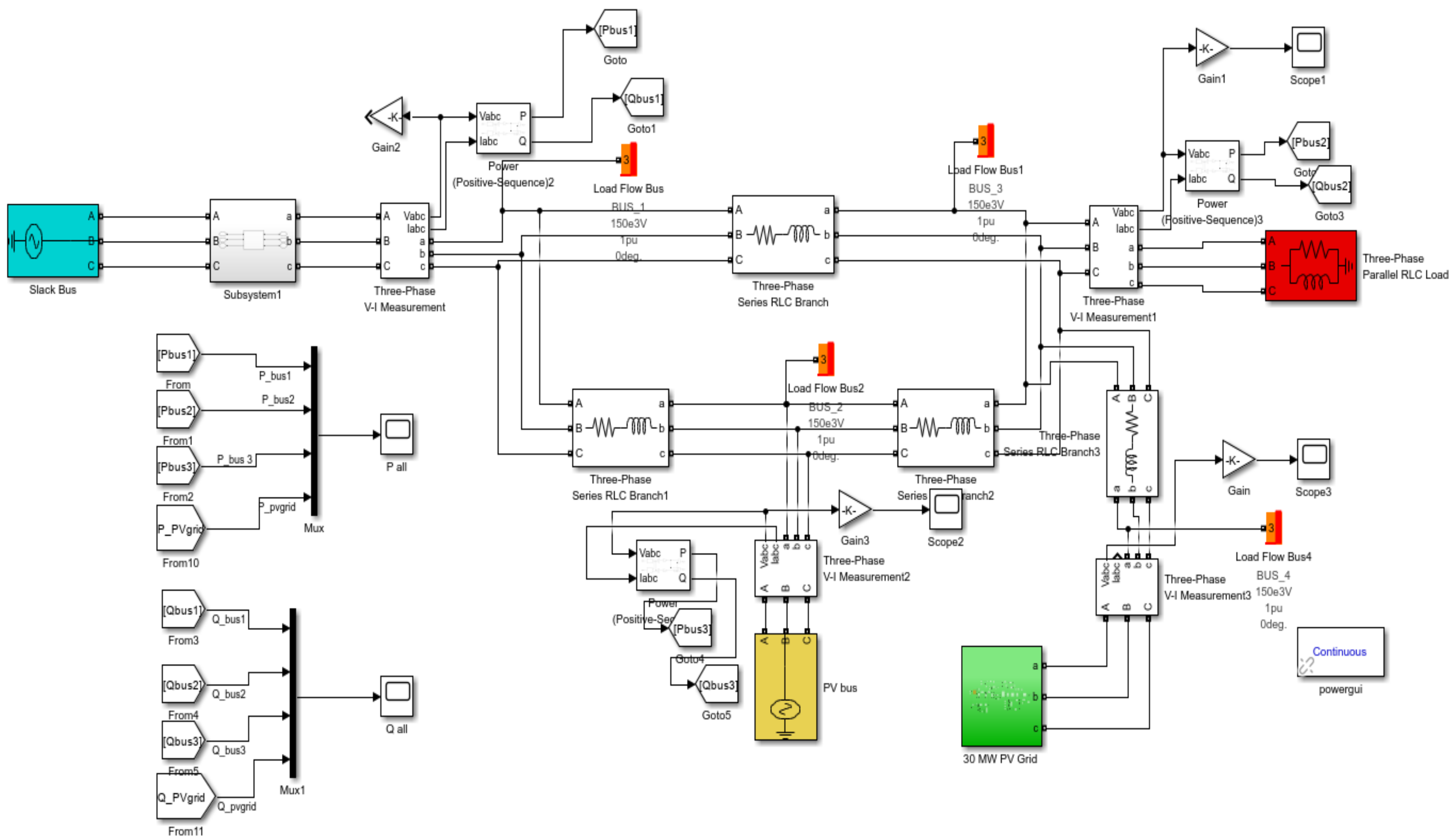

Figure 5.20: Angolan's Power Network with the PV system and the Proposed Controller

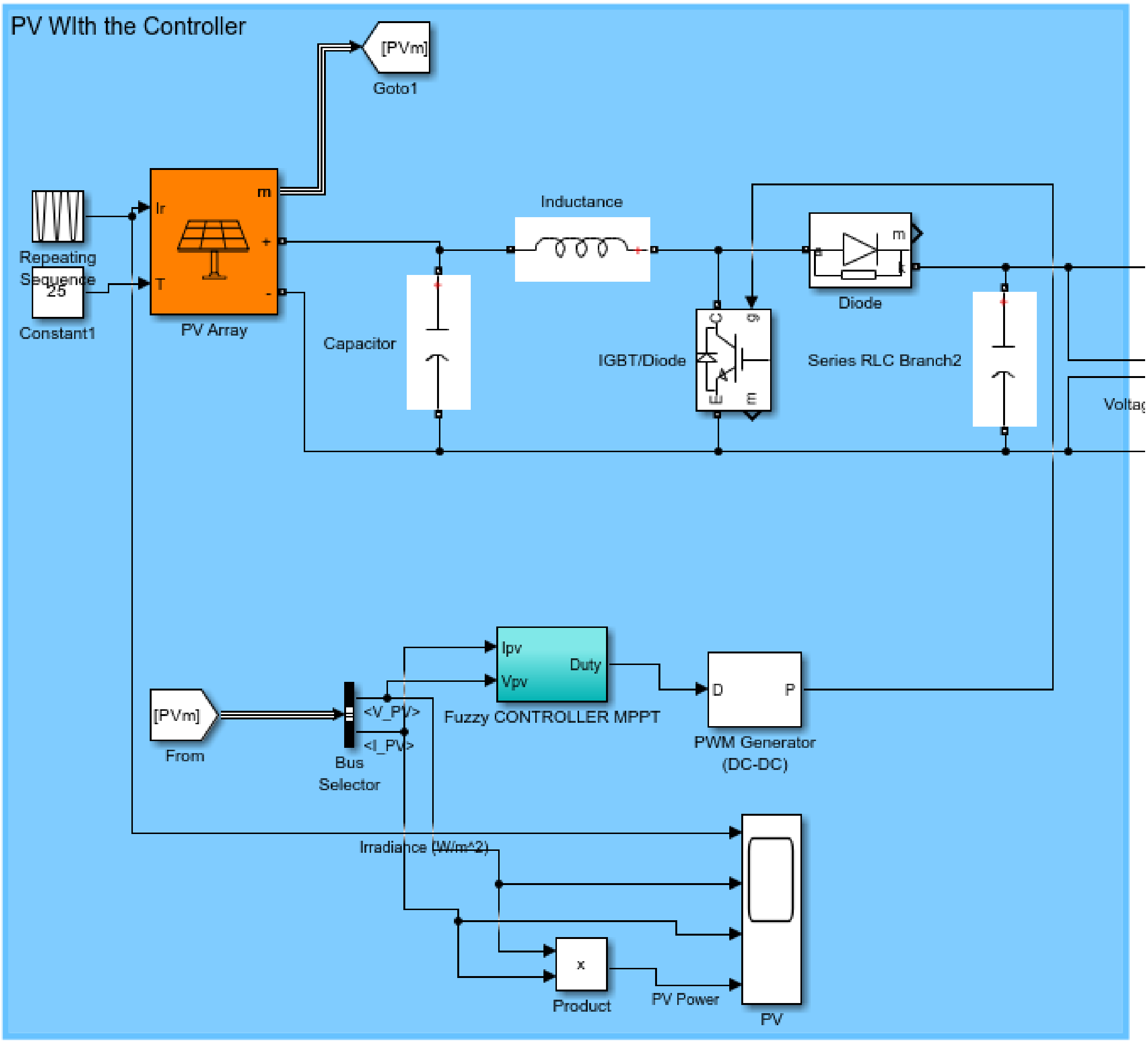

Figure 5.21: **Partial Inside setup of the 30MW PV Grid with the Proposed controller**

Figure 5.21 above shows the inside configuration of the 30MW PV grid that includes the proposed Fuzzy Logic Controller which is connected to the three 150 KV power networks in Angola, but the full description of the PV System has been described in **Figure 5.20**. The proposed controller was operating at the maximum power point.

Results for Scenario 2

The PV grid has been operating at its maximum power point and it has been generating and supplying 30MW. Furthermore, the integration of the PV system with the proposed controller has been controlling the power network so that the power supplied from Bus generation (Bus 3) is 20 MW. The sum of the PV grid power with the power from Bus generation (Bus 3) gives a total generation capacity of 50MW as shown in **Figure 5.22.** Therefore, the load supply is now generating the necessary power to satisfy the load demand and the PV grid is generating its maximum power. The “P all” block represents the results of the true power, the “Q all” block represents the results of the reactive power, and the other “From” and “Goto” blocks have been used to determine and analyse other parameters of the network such as the voltage and the current in the generation and the load buses.

It is also important to note that the time between 0s to 0.03s is the transient time and the system is at its steady state only after 0.03s. At the steady state, the true power supplied by the PV grid is 30MW and the generation Bus 3 is supplying 20 MW as shown below in **Figure 5.22.** It can also be observed that the true power is stable in the power network after the transient period. The reactive power supplied from the PV grid is 3.7 VRA and the generation Bus 3 is supplying 11.8MW as shown in **Figure 5.23.** Furthermore, it can be observed in **Figure 5.24** that the solar irradiance in the system is 1000 W/m^2. There is an increase in PV voltage to 6KV and a decrease in PV current from 6000 A to 44.9A, then another increase to 6000 A after 0.01s. There is also a decrease in power from 30MW to 0.15MW, then another increase to 30MW only after 0.01s. It can be observed that there is a decrease in PV voltage, PV Current, and PV power but because the system is operating at the maximum power and the controller is now included, the PV voltage, Current, and power are increasing again and they are stable after 0.01s.

Figure 5.25 shows that during the transient state from 0 to 0.03s the power in the grid and inverter have been increasing up until it reaches the steady state after 0.03s at 30MW. After 0.03 s the power in the grid is stable. The PV system's integration in the Angolan power network has increased the voltage per unit in Bus 2 (PQ load) and BUS 3 (Generation Bus) to 1 p.u on all lines as shown below in **Figure 5.26 and Figure 5.27.**

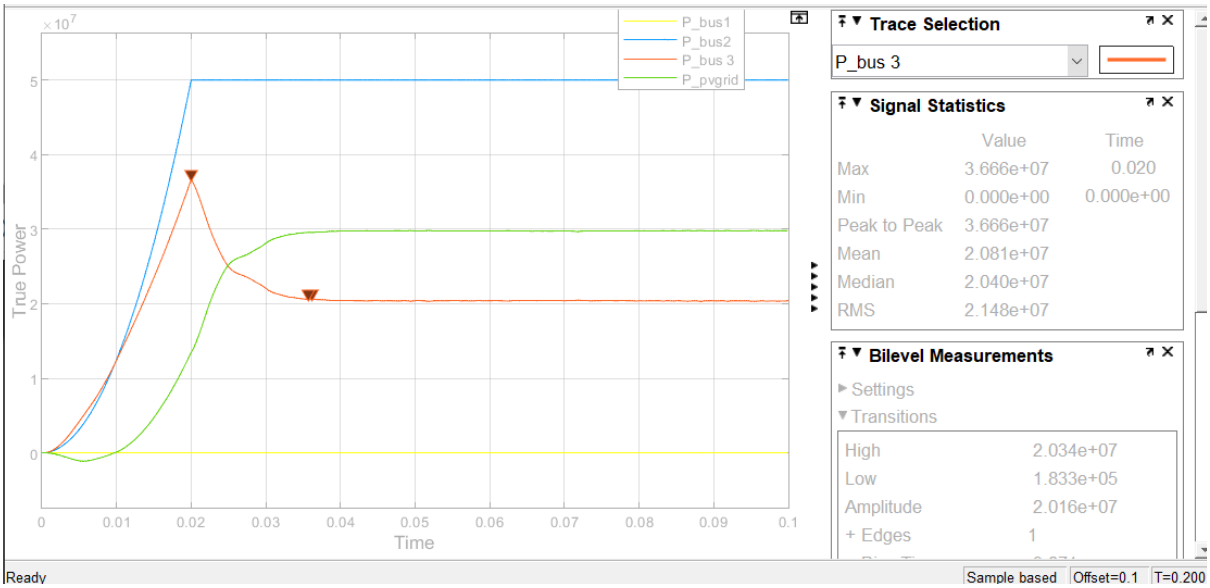

Figure 5.22: True Power of the power network with integration of the PV system and the controller

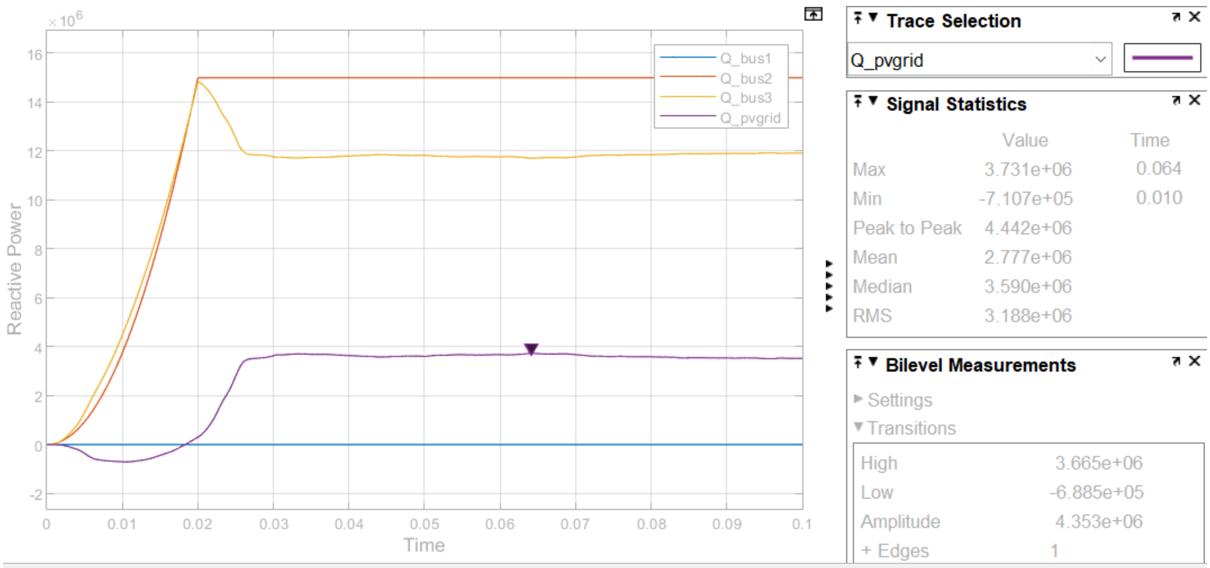

Figure 5.23: Reactive Power of the power network with integration of the PV system and the controller

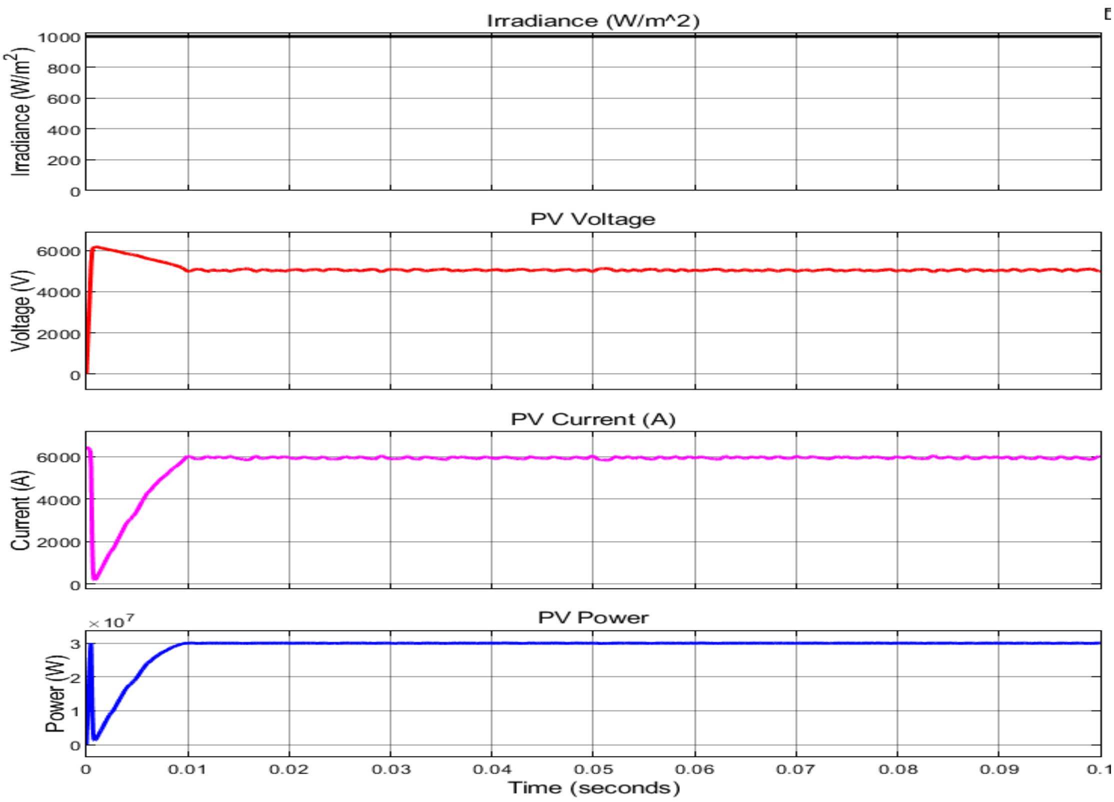

Figure 5.24: **Solar Irradiance, PV voltage, PV current, and PV power of the PV grid system**

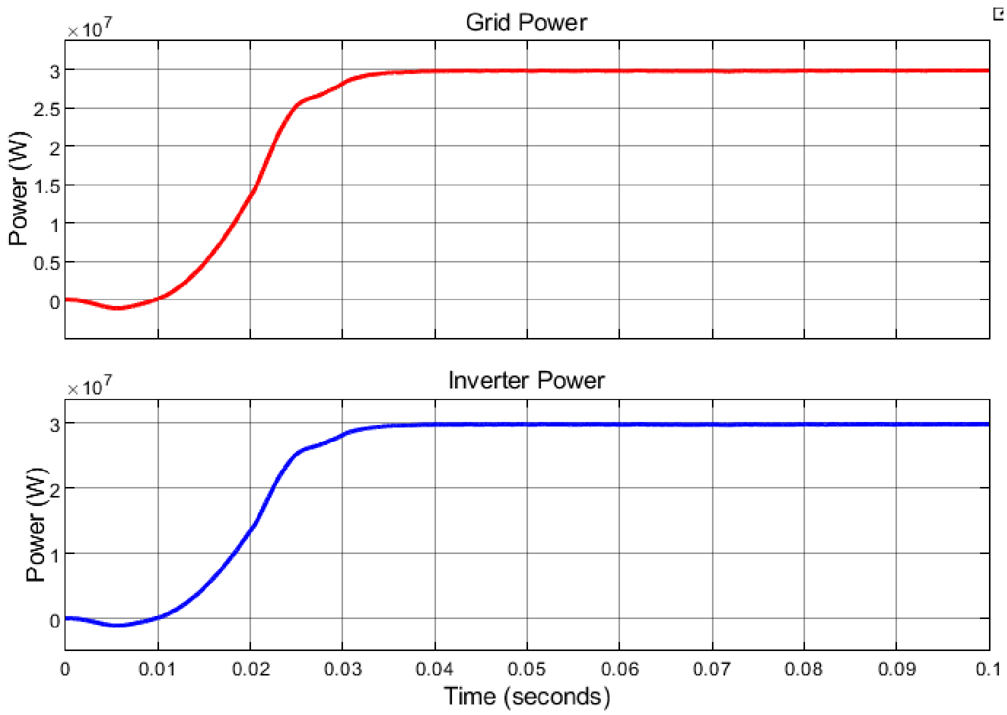

Figure 5.25: **Power for the Grid & Inverter**

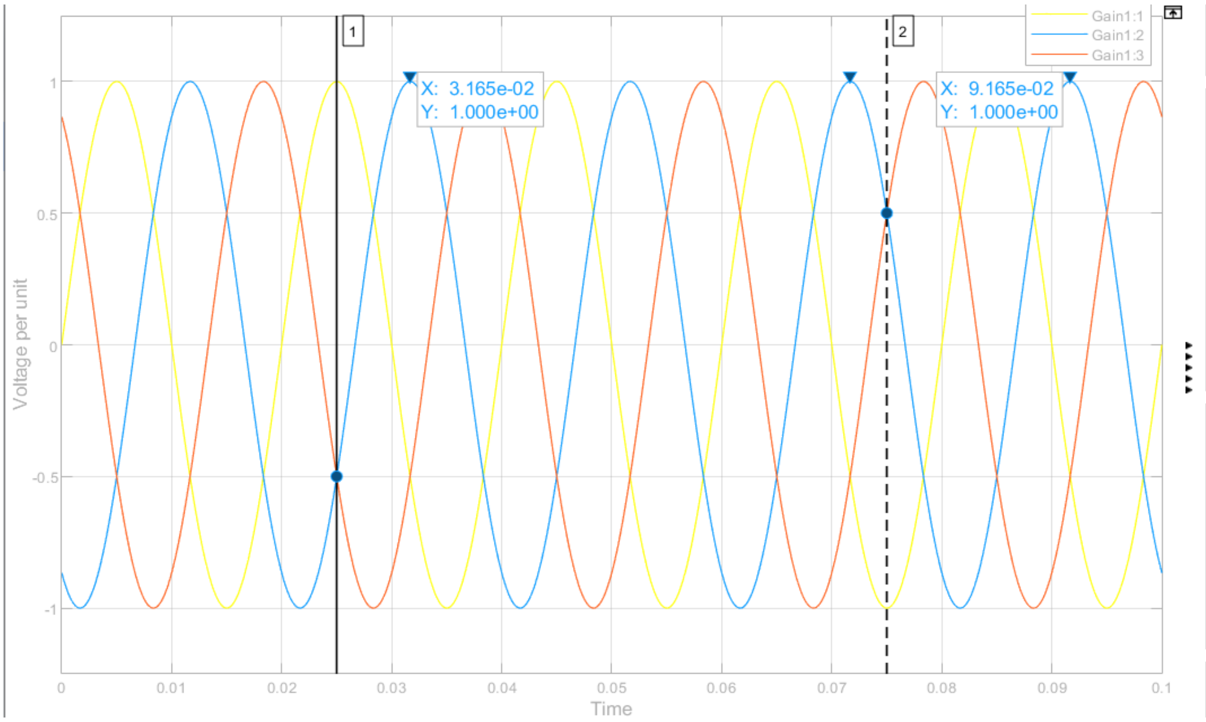

Figure 5.26: ***Per Unit Load Voltage Profile at Bus 3 (PQ-Load) when the load demand is higher than the load supply with the PV system and the controller***

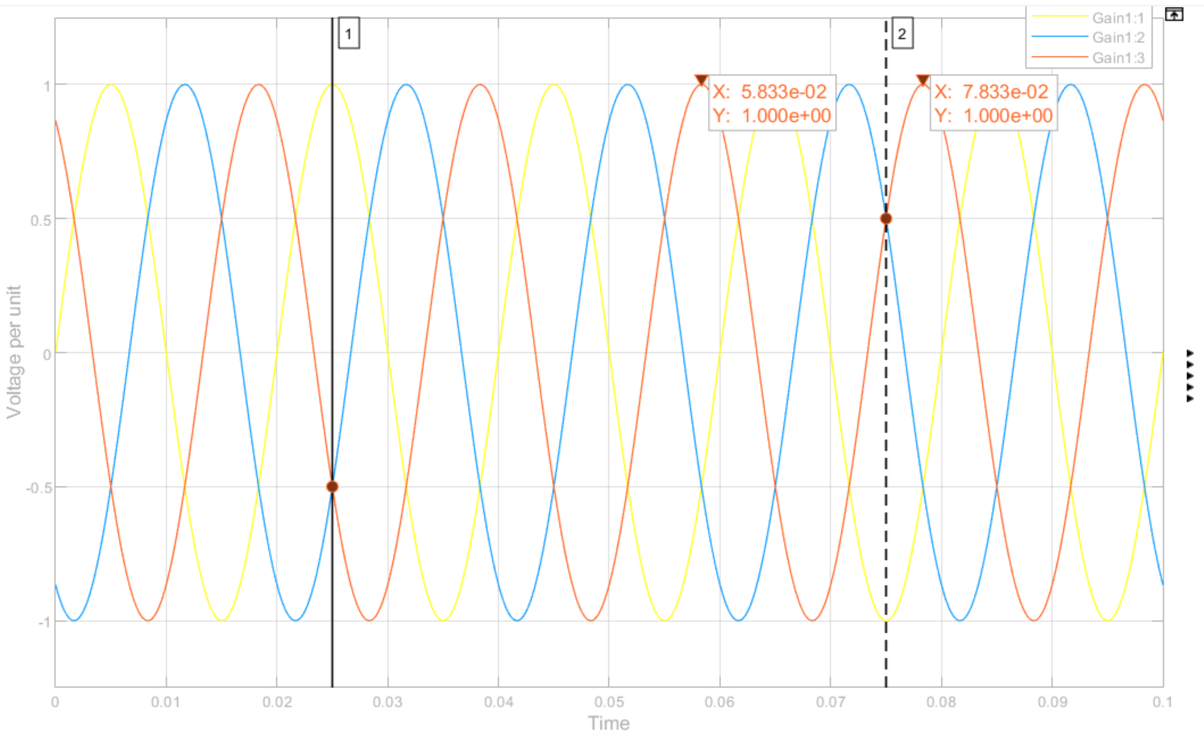

Figure 5.27: **Per Unit Load Voltage Profile at Bus 2 (PV-Generation) when the load demand is higher than the load supply with the PV system and the controller**

5.5 Discussion and Analysis

The proposed controller has been tested in a three-bus power network with the integration of a PV system. Firstly, it was observed that the selected Angolan power network was facing instability due to the load demand which was higher than the load supply causing a decrease in voltage, then the PV system's integration into the power network was able to supply additional power to satisfy the load demand, but the PV system was poorly performing because it was not operating at its maximum power point and it was not generating its maximum power, it was only generating 0.00293 MW. Afterwards, the proposed controller was introduced into the PV system which significantly increased the performance of the PV system by enabling the PV grid to generate 30MW and also to maintain the power network stability. Furthermore, The voltage per unit in all three phases was increased from 0.92 p.u to 1 p.u due to the integration of the PV system and the controller.

The integration of the PV system alone was able to increase the per unit voltage profile during high load demand, but for better stability, the controller was introduced in the last scenario to ensure that the additional voltage supplied by the PV system to the network is within the standard voltage allowable limits to keep a safe and stable operating of the system. However, more studies need to be conducted to test the performance of the Fuzzy Controller for more complex power networks with PV and other renewable energy systems. Furthermore, the results in the last scenario represented graphically in **Figure 5.22** show that the proposed controller can positively contribute to the stability of the Angolan power network.

Various research has been conducted in the past regarding the controller and different controllers have been developed for power transmission networks, PV systems, and other renewable energy systems but the problem of power stability was ignored and not addressed properly. Therefore, the implication and simulation applications of the findings for the proposed controller in this research project prove that the proposed controller can improve the performance of the PV system when it is integrated into the power transmission network. The use of this proposed controller will not only have a positive impact on the energy sector, but it will also have a direct impact on the environment by increasing the use of green energy and by decreasing toxic gas emissions in the atmosphere. It will also have a direct impact on the economy of the country by allowing many industries to operate without interruption and by providing job opportunities.

5.6 Limitations and Challenges

There were some limitations faced to achieve the activities required for this research project. Furthermore, there were some challenges faced during the development of the proposed controller, the data for the membership functions and fuzzy rules were not imported into MATLAB'S workplace which caused an obstacle for the simulations to run because MATLAB could not find the necessary data for the Fuzzy Logic Controller. The Simulation can only be successful after importing the membership functions and the fuzzy rules in MATLAB's workplace.

During the modelling of the PV system, the main challenge faced was selecting the correct type of PV module. The other challenges faced during these simulations were finding the specific blocks in MATLAB to construct the PV systems, the controller and the power network for the load flow analysis. The incorrect connection of the block to the branch of the system was also another challenge because a wrong connection would automatically stop running the simulations.

Some potential improvements will need to be taken into consideration for future simulation activities of this type:

- Saving MATLAB files while creating the circuit and performing the simulations to avoid the possibility of repeating everything from zero if something occurs such as a sudden shutdown of the laptop due to the battery charge or due to some technical problems.

- Always save the membership functions and the fuzzy rules in the workplace folder of MATLAB to avoid wasting time with the import process.

- Make use of the Excel sheet with formulas to easily calculate the parameters of PV modules.

- Start firstly by exporting the necessary blocks needed for the modelling of the controller, and PV energy to be done.

The practical activities throughout this chapter were able to provide a realistic understanding of the integration of the controller into the PV energy system. Every component plays an important role in the results. Therefore, it is extremely important to understand and measure all the necessary factors needed to be included in the system because you cannot manage what you cannot measure. For the successful development and modelling of a controller, all the variables and data need to be determined and measured in the initial phase. The proposed

Fuzzy Logic Controller developed in this research project proves to provide some power stability when it is integrated with a PV system.

Power stability of renewable energy systems such as PV Systems has been the main challenge over the past years. It is also directly connected to the economy of any country because various sectors need stable electricity to operate daily. Power and voltage instability is the cause of many problems such as loss of properties, electrocution, fire outbreaks, blackouts, poverty, and much more. The fuzzy controller developed in this project is based on the maximum power point technique and can provide power stability by extracting and controlling the maximum solar power available in nature.

The next chapter covered the deliverables of this project, the conclusion regarding the modelling and simulation of the Angolan power network and load flow analysis, the conclusion regarding the simulation of the Angolan power network integrated with PV without and with the controller, and the conclusion regarding the design and development of the proposed controller. The next chapter also covered future work that needs to be conducted on controllers for renewable energy.

CHAPTER SIX

DELIVERABLES, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

In this thesis, a controller was developed and suggested for a renewable system that was integrated into a three-phase power network to support and improve the performance of the power network. An extensive literature review was conducted on the proposed controller for renewable energy systems and the controller-based Maximum power point was modelled to provide a stable output power under different changes in solar irradiances. The proposed controller was found to be efficient in mitigating the intermittence problems of solar energy as well as the impact of solar irradiance variability problems. Even under the increase or decrease of solar irradiance, the proposed controller was able to enable the PV system to operate at the maximum power point in the power network. It was also found that the PV grid without the proposed controller was poorly performing and was not able to generate and supply at least 20% of its total capacity, but after introducing the proposed controller, the PV Grid system was able to operate at its full capacity. Furthermore, it was found that the proposed controller can provide a stable output power when the temperature increases or decreases within a certain period of time. The simulation results showed good performance of the proposed fuzzy controller-based Maximum power point for PV system in terms of power stability.

The modelling and simulations of this thesis were done using MATLAB. In this chapter, the summary of results obtained from the findings due to the deliverables of the thesis is presented. Section 6.2 presents the deliverables of the thesis. Section 6.3 presents the conclusion of the modelling and simulation of the Angolan power network and load flow analysis. Section 6.4 discusses future research work regarding controllers for renewable energy. Section 6.5 is the reference of the journal sent for publication.

6.2 Thesis deliverable

The deliverables that were completed in the study are summarized in this section.

6.2.1 Literature review

The literature review was conducted to analyse in detail the impact of the Fuzzy Logic Controller on renewable energy. After reviewing various articles, papers, and books, it was found that several reviews and studies have been conducted regarding different controllers for renewable energy for power networks, but those reviews focused more on monitoring and protection functions. The implementation of controllers for power stability of power networks has been neglected.

The literature review conducted in this thesis focused on the development of a Fuzzy Logic Controller for renewable energy to achieve power stability in a power network. This was done to contribute with more information regarding the impact of a controller on the power network regarding power stability.

6.2.2 Theoretical framework

The theory discussed in this thesis covers renewable energy, controllers for renewable energy, and power stability for power networks. Various papers, articles, and books assessed during the completion of this thesis also provide some important theories regarding the integration of controllers into renewable energy.

6.2.3 Modelling and simulation of the Angolan power network and load flow analysis

An Angolan power network in the province of Huila was selected, modelled, and some simulation case studies were conducted in this thesis. This same power network was experiencing power instability due to the load demand that was higher than the power supply. Therefore, the load flow analysis was conducted to analyse the system's operating conditions so that the controller can be integrated with a renewable energy system to control and achieve power stability in the power network.

6.2.4 Simulation of the Angolan power network integrated with PV without the controller

The PV system was introduced to the Angolan power network without a controller to support the power network so that power stability could be achieved and also to satisfy the load demand. The simulation was conducted through MATLAB to analyse the behaviour of the Angola power network.

6.2.5 Design and development of the proposed controller

The proposed controller was designed and modelled using MATLAB/SIMULINK. This proposed controller was integrated into the PV system to provide stability.

6.2.6 Simulation of the Angolan power network integrated with PV using the proposed controller

The simulation of the same Angolan power network was conducted through MATLAB with the integration of the PV system and the proposed controller when the load demand was higher than the power supply.

6.3 Conclusion

This section gives a summary of the conclusions of the study.

6.3.1 Conclusion regarding Modelling and simulation of the Angolan power network and load flow analysis

The load flow analysis conducted on the power network located in Angola was able to demonstrate the behaviour of the power network. The voltage per unit at the load bus (Bus 3) and the generation bus (Bus 2) was not within the standard voltage permissible limit of ± 5 %. The standard allowable voltage range is between 0.95 p.u and 1.05 p.u, anything above or below this range is considered a non-permissible voltage for the power network because it will cause disturbances and instability in the power network which will directly have a negative impact on the consumers.

6.3.2 Conclusion regarding Simulation of the Angolan power network integrated with PV without the controller

The integration of the PV system in the Angolan power network has increased the voltage per unit in Bus 2 (PQ load) and BUS 3 (Generation Bus) to the standard allowable voltage range for all three phases, but there is a risk of having an excessive voltage in the system if the load demand decreases exponentially during a certain period of the day because when the load decrease the voltage increases. It is important to understand that the load demand is never the same during the day. There are periods of the day with higher load demand and periods of the day with less load demand. As a result, a controller can be a useful tool for managing this variation in load demand and guaranteeing that the system is running within a safe voltage range and at its maximum power.

6.3.3 Conclusion regarding the design and development of the proposed controller

The Fuzzy Logic Controller that was designed and developed in this project was able to control the system whenever there is a variation of solar irradiance so that a stable current and power are supplied to the consumers.

6.3.4 Conclusion regarding Simulation of the Angolan power network integrated with PV using the proposed controller

The proposed controller was able to enable the PV system to operate at its Maximum Power Point and it was also able to control the PV system to supply a voltage that is within the standard voltage allowable limit as well as to ensure that additional power supply in the system is not excessive. Furthermore, the proposed controller in the Angolan power network was able to inject additional power to satisfy the load demand and to control this additional power so that it does not exceed the load demand to avoid the occurrence of instability due to excessive power supplied.

6.4 Achievement of the objectives of the study

This research's main objective was to improve Angola's electrical conditions by developing a controller for renewable energy systems such as the PV system. The other objectives of this study were to minimize the power outages in Angola due to unstable power, to minimize the cost involved in the maintenance of the power transmission network in Angola, to investigate literature reviews done on controllers for PV or wind energy systems, to improve the monitoring of the power transmission network in Angola, to make efficient use of renewable resources in Angola, to perform simulations then analyse the final results, and to perform the load flow analyses to investigate the performance of the power network when disturbances occur.

- **To minimize the power outages in Angola:** The results of the simulation demonstrated that even with varying solar irradiation, the suggested controller produces a stable output. This stable output power will significantly mitigate the power outages in the system.

- **To minimize the costs involved in the maintenance of the power transmission network in Angola:** The use of solar energy will significantly minimize the maintenance costs of power transmission networks because there are no moving parts involved and no fuel involved. The sun is free in nature.

- **To investigate literature reviews done on the development of a controller for renewable energy systems such as PV or Wind energy:** After conducting an extensive literature review, it has been found that the fuzzy controller-based maximum power point minimizes faults in the system, maximizes the efficiency of the renewable energy, and highly maintain the stability of the system.

- **To improve the monitoring of the electrical system in Angola:** PV system can be monitored remotely with the use of intelligent electronic devices.

- **To mitigate the occurrence of faults in the power transmission network in Angola:** The proposed controller improves the efficiency of the PV energy system.

- **To perform some simulations and analyzed the final results**: Simulations of the DC-DC converter, Fuzzy Logic Controller, and PV system were performed through MATLAB/Simulink under different solar irradiances.

- **To perform load flow analyses to investigate the performance of the power network when disturbances occur:** The load flow analysis of three 150 KV transmission lines 200 km, 150km, and 150 km long in the province of Huila was performed through MATLAB software to determine the voltage profile and other important parameters as well as to understand better the power transmission network in Angola.

6.5 Future work

This research discussed the controller for PV energy systems for power transmission networks, but more studies can be conducted on controllers for other renewable energy systems such as biomass, nuclear, etc. To properly comprehend the cost of constructing solar energy systems, a cost and benefits analysis should be carried out in the future. This will make it clearer how Angola may expand its use of renewable energy technologies. Affordably priced renewable energy storage should be the subject of more research.

6.6 Publications

Enhancing PV System Stability in the Angolan Power Network through Modelling and Simulation of Fuzzy Logic Controllers.

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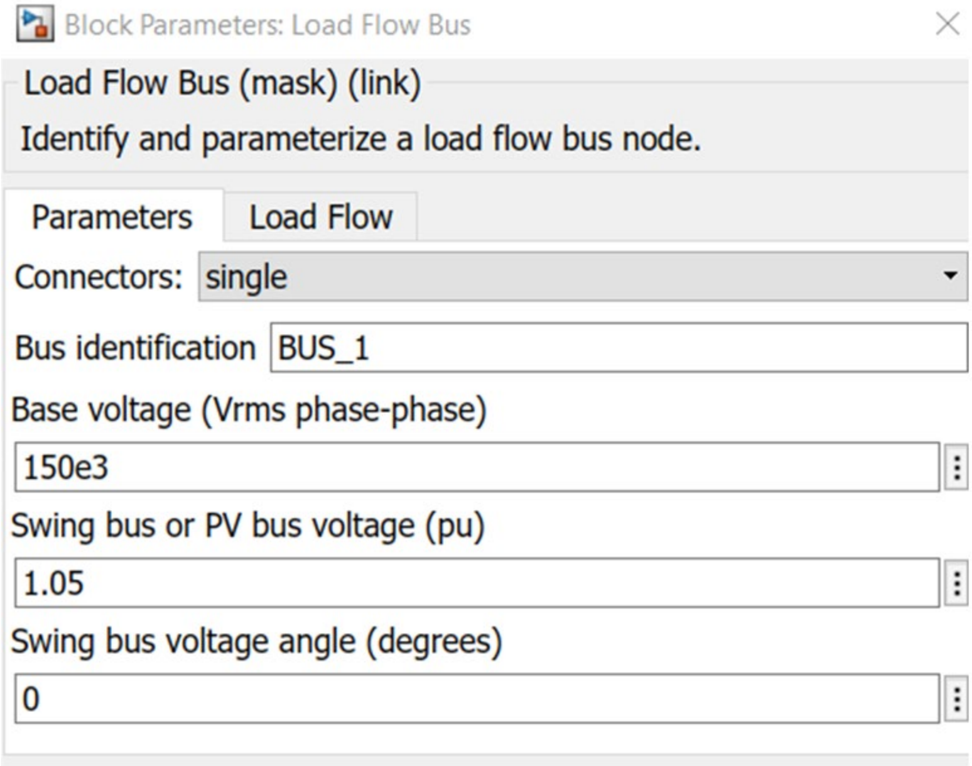
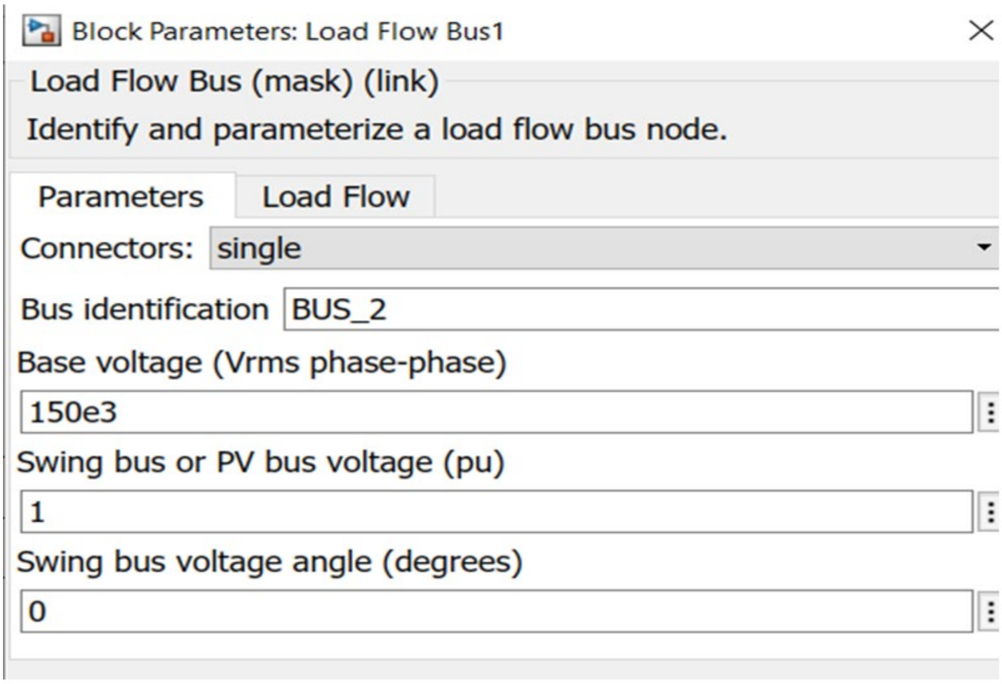
Appendix

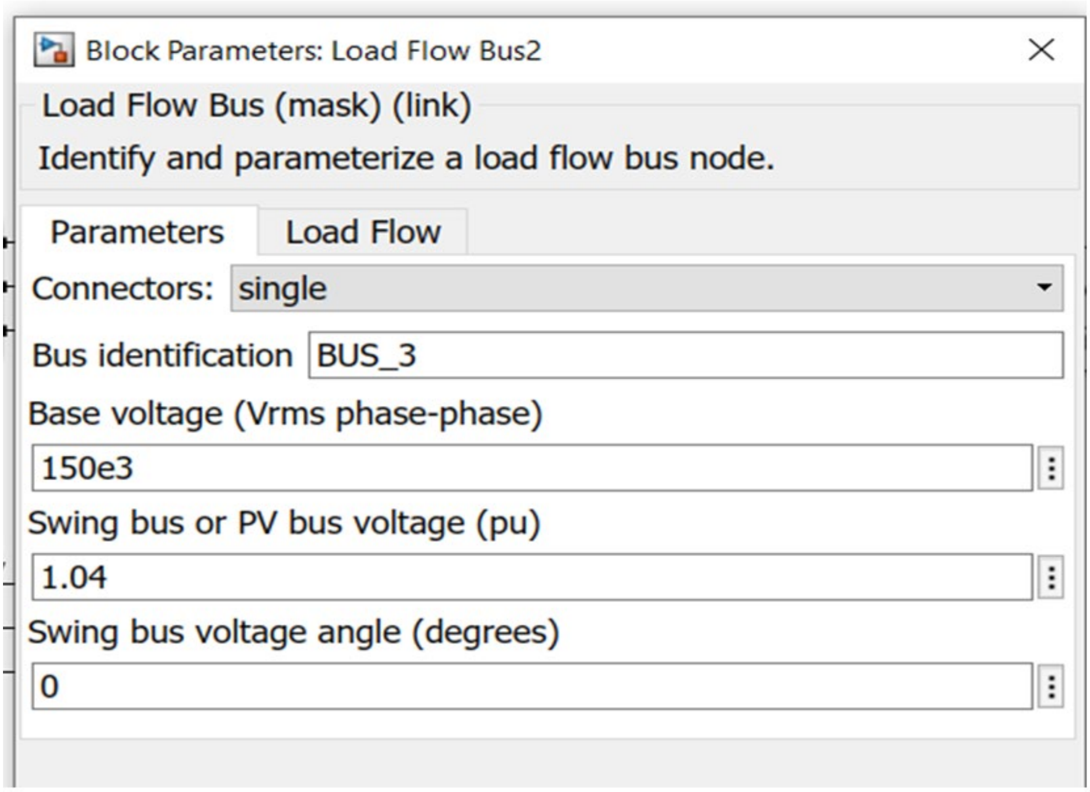
Appendix 4.1: **Parameters of Bus 1 (Slack Bus)**



Appendix 4.2: Parameters for Bus 2 (PV Bus 2)



Appendix 4.3 : Parameters of Bus 3 (PQ bus)



Appendix 4.4: Angola 150kV Transmission Line Parameters

S/N	Transmission line		Length	Impedance	
	From	To	L(km)	Resistance (Rpu)	Inductance (Xpu)
1	Huila	Huambo	200	0.02	0.000127
2	Huila	Namibe	150	0.01	0.000095
3	Cunene	Namibe	150	0.0125	0.00000796

Appendix 4.5: Approximate Transmission Line Parameters with Bundled Conductors at 50Hz

Nominal Voltage	R (Ω/km)	ωL (Ω/km)	ωC (μΩ/km)	MVA
150 KV	0.037	0.376	4.6	100