

Design, Modelling, and Optimization of Grid-Connected Solar Photovoltaic and Wind  
Hybrid System: A Case Study of Dire Dawa City



Rediet Besufikad

A Thesis Submitted to

Department of Electrical Power and Control Engineering

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Hybrid System: A Case Study of Dire Dawa City

Rediet Besufikad

Advisor: Dr. Milkias Berehanu

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Office of Graduate Studies  
Adama Science and Technology University

Jun, 2024  
Adama, Ethiopia

## **Declaration**

I hereby declare that this Master Thesis entitled “Design, Modelling and Optimization of Grid Connected Solar Photovoltaic and Wind Hybrid System (Case Study: Dire Dawa City)” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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## Recommendation of Advisor

I the advisor of this thesis, hereby certify that I/we have read the revised version of the thesis entitled “Design, Modelling and Optimization of Grid Connected Solar Photovoltaic and Wind Hybrid System (Case study: Dire Dawa City)” prepared under my guidance by Rediet Besufikad submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Electrical Power and Control Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Milkias Berhanu



10/10/2024

Advisor

Signature

Date

## Approval Sheet

I the advisors of the thesis entitled “Design, Modelling and Optimization of Grid Connected Solar Photovoltaic and Wind Hybrid System (Case study: Dire Dawa City)” and developed by Rediet Besufikad. hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Milkias Berhanu



10/10/2024

Advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by Rediet Besufikad have read and evaluated the thesis entitled “Design, Modelling and Optimization of Grid Connected Solar Photovoltaic and Wind Hybrid System (Case study: Dire Dawa City)” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering (Power Engineering).

\_\_\_\_\_  
Chairperson

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
Internal Examiner

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

Dr. Yeshitela Shiferaw



10/08/2024

\_\_\_\_\_  
External Examiner

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

\_\_\_\_\_  
Department Head

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
School Dean

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
Office of Postgraduate Studies, Dean

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

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## List of Abbreviations and Acronyms

### List of Acronyms

| Symbols      | Description                                                |
|--------------|------------------------------------------------------------|
| $A_{array}$  | Total area of the PV array                                 |
| $C_{dc}$     | Boost capacitor                                            |
| $C_{pv}$     | Power decoupling capacitor                                 |
| $D$          | Duty ratio                                                 |
| $E_{go}$     | Band gap energy of semiconductor                           |
| $f_g$        | Grid frequency                                             |
| $f_{res}$    | Resonance frequency                                        |
| $f_s$        | Switching frequency                                        |
| $I$          | Module current                                             |
| $I_d$        | Diode saturation current                                   |
| $I_m$        | Inverter average dc current                                |
| $I_o$        | Saturation current                                         |
| $I_{ph}$     | Photo-current                                              |
| $I_r$        | Solar irradiance                                           |
| $I_{rs}$     | Module reverse saturation current                          |
| $I_{sc}$     | Short-circuit current                                      |
| $I_{sh}$     | Shunt current                                              |
| $K$          | Boltzmann's constant                                       |
| $K_i$        | Short circuit current of the cell at 25 °C and $1000W/m^2$ |
| $L$          | Boost inductor                                             |
| $n$          | The ideality factor of the diode                           |
| $N_p$        | Number of PV modules connected in parallel                 |
| $N_s$        | Number of PV modules connected in series                   |
| $P_{inv}$    | Inverter power                                             |
| $P_{mp}$     | Maximum power point                                        |
| $P_{plant}$  | Plant power                                                |
| $P_{string}$ | String power                                               |
| $P_t$        | Turbine power                                              |
| $q$          | Electron charge                                            |

|                 |                         |
|-----------------|-------------------------|
| $R$             | Radius of the turbine   |
| $R_{load}$      | Load resistance         |
| $R_s$           | Series resistance       |
| $R_{sh}$        | Sunt resistance         |
| $T$             | Operating temperature   |
| $T_r$           | Nominal temperature (K) |
| $V$             | Module voltage          |
| $V_{DClmk}$     | DC link voltage         |
| $V_{load}$      | Load voltage            |
| $V_{mp}$        | Maximum output voltage  |
| $V_{oc}$        | Open circuit voltage    |
| $V_{phase,RMS}$ | RMS phase voltage       |
| $V_t$           | Diode thermal voltage   |
| $V_v$           | Wind speed              |
| $Z_b$           | Base impedance          |

### List of Abbreviations

|      |                                           |
|------|-------------------------------------------|
| AC   | Alternating current                       |
| ACWA | Association of Clean Water Administrators |
| CCL  | Current control loop                      |
| CCM  | Continuous Conduction Mode                |
| CdTe | cadmium telluride                         |
| CIGS | copper indium gallium selenide            |
| CRGE | Climate Resilient Green Economy           |
| CSI  | Current Source Inverter                   |
| DC   | Direct Current                            |
| DFIG | Doubly Fed Induction Generator            |
| EEP  | Ethiopian Electric Power                  |
| FFT  | Fast Fourier Transform                    |
| FLC  | Fuzzy Logic Control                       |
| GOE  | Government of Ethiopia                    |
| GSC  | Grid Side Converter                       |
| GTIs | Grid tied inverters                       |
| HAWT | Horizontal Axis Wind Turbine              |

|          |                                                   |
|----------|---------------------------------------------------|
| HOMER    | Hybrid Optimization of multiple Energy Resources  |
| HRES     | Hybrid Renewable Energy Systems                   |
| HybSim   | Hybrid Gener                                      |
| IEA      | International Energy Agency                       |
| IEEE     | Institute of Electrical and Electronics Engineer  |
| IGBT     | Insulated Gate Bipolar Transistor                 |
| INC      | Incremental Conductance                           |
| IRENA    | International Renewable Energy Agency             |
| LCI      | Line Commutation Inverter                         |
| LF       | Loop Filter                                       |
| MOTECH   | Mobile Technology for community health            |
| MOSFET   | Metal oxide semiconductor field effect transistor |
| MPC      | Model Predictive Control                          |
| MPP      | Maximum Power Point                               |
| MPPT     | Maximum Power Point Tracking                      |
| NASA     | National Aeronautics and Space Administrator      |
| NPC      | Net present cost                                  |
| OSeMOSYS | Open-Source Energy Modeling System                |
| OTC      | Optimal Torque Control                            |
| PCM      | Power Control Mode                                |
| PD       | Phase Detector                                    |
| PI       | Proportional Integral                             |
| PLL      | Phase Locked Loop                                 |
| PM       | Permanent Magnet                                  |
| PMSG     | Permanent Magnet Synchronous Generator            |
| PO       | Perturb and observe                               |
| PR       | Proportional-Resonant                             |
| PSF      | Power Signal Feedback                             |
| PV       | Photovoltaic                                      |
| PWM      | Pulse Width Modulation                            |
| RES      | Renewable Energy Source                           |
| RSC      | Rotor Side Converter                              |
| SCADA    | Supervisor control and Data Acquisition           |

|       |                                     |
|-------|-------------------------------------|
| SCI   | Self-Commutation Inverter           |
| SCIG  | Squirrel Cage Induction Generator   |
| SG    | Synchronous Generator               |
| SPWM  | Sinusoidal Pulse Width Modulation   |
| SRF   | Synchronous Reference Frame         |
| SVD   | Space Vector Diagram                |
| SVM   | Space Vector Modulation             |
| SVPWM | Space Vector Pulse Width Modulation |
| THD   | Total harmonic distortion           |
| THI   | Third harmonic injection            |
| TSR   | Tip Speed Ratio                     |
| UPF   | Unity Power Factor                  |
| VAWT  | Vertical Axis Wind Turbine          |
| VCL   | Voltage Control Loop                |
| VCM   | Voltage Control Mode                |
| VCO   | Voltage Controlled Oscillator       |
| VOC   | Voltage-Oriented Control            |
| VSC   | Voltage source converter            |
| VSI   | Voltage Source Inverter             |
| VSWT  | Vertical speed wind turbine         |
| WEC   | Wind Energy Conversion              |
| WECS  | Wind Energy Conversion System       |
| WRSG  | Wound Rotor Synchronous Generator   |
| ZCD   | Zero Crossing Detector              |

## Abstract

*Ethiopia predominantly generates its electricity via hydropower, a resource that is dependent on fluctuations in water levels. To address this issue, this thesis investigates the design, modeling, and optimization of a grid-connected solar photovoltaic (PV) and wind hybrid system for Dire Dawa City, Ethiopia. The Felema district was selected for this research due to its potential for solar and wind resources, proximity to the existing grid, and availability of suitable land. The optimal configuration of 20 MW of solar PV, 22.5 MW of wind power, and 10 MW from the grid was determined using the HOMER Pro software. This hybrid system has a net present cost of \$42.3 million and a levelized cost of energy of \$0.037/kWh. To model and simulate the performance of this hybrid system, MATLAB/Simulink was utilized. For the solar PV system, a fuzzy logic control-based maximum power point tracking (MPPT) algorithm was implemented and shown to have superior tracking efficiency compared to other MPPT methods. The wind energy conversion system employed a doubly-fed induction generator (DFIG) with an indirect optimal torque control (OTC) strategy. The complete PV-wind hybrid system was then connected to the utility grid according to IEEE standards. The results of this study demonstrate the technical and economic viability of a grid-connected solar-wind hybrid system to supplement Ethiopia's hydropower-dominated electricity generation, improving the country's energy security and resilience.*

**Keywords:** Doubly-fed induction generator, Dire Dawa City, Ethiopia, Fuzzy Logic Controller, Grid-connected, Indirect optimal torque control, Optimization, Renewable energy, Solar Photovoltaic.

# CHAPTER ONE

## 1. INTRODUCTION

### 1.1. Background of the study

Energy is essential not only for all communities, nations, or organizations, but also for human life itself. Additionally, it is necessary for all modern economic sectors and facilitates all economic activity (Atems & Hotaling, 2018). Thus, energy is an important factor of growth for all countries (Ahmed & Azam, 2016). Due to this, the global energy demand has increased significantly. The global energy demand grew by 2.9% in 2018. By 2040, the consumption of energy will have reached 740 million terajoules, which is an additional 30% growth (theworldcounts, Global energy consumption only going up, 2024).

The two types of energy that human society uses on a daily basis are renewable and non-renewable. non-renewable energy sources are finite and cannot replenish themselves in our lifetimes. Fossil fuels, which include coal, oil, and natural gas, make up the majority of nonrenewable energy sources. Globally, fossil fuels continue to be the leading contributors for electric power production. In 2022, coal made up approximately 35.8% of the world's power mix, with natural gas coming in second with a share of 22%. In 2021, the United States, China, and India supplied the majority of the coal required to generate power (Statista, 2023).

The consumption of non-renewable energy sources has a major negative influence on the environment and society. These effects include greenhouse gas emissions, habitat destruction, air and water pollution, and geopolitical resource-related conflicts. As a result, a large number of nations have shifted to new and promising energy sources that are sustainable, renewable, and socially acceptable. Examples of these include geothermal, biomass, wind, solar, small hydro, geothermal, ocean thermal, and tidal energy (Abidi, Sidhom, & Chihi, 2023).

Recently, as environmental awareness has grown among the public and governments, sustainable and renewable energy sources have been seeing an significant increase in many parts of the world. According to (iea, 2023), 107 gigawatts (GW) of renewable capacity are added globally, the largest absolute increase ever, to more than 440 GW in 2023. This is equivalent of more than the entire installed power capacity of Germany and Spain combined (iea, 2023).

Africa, one of the continents with the greatest rate of growth in the world, will confront a significant energy-related challenge in the years to come. By 2030, more than 600 million

people in sub-Saharan Africa will not have reliable access to electricity, with a majority of the region's population depending on conventional energy sources (Tiruye, et al., 2021). Even though Ethiopia's economy is among the fastest-growing in Africa, it has some of the least access to modern energy sources worldwide. The installed generation capacity of the country is currently 5200 MW, which is less than 60% of the total population. Hydropower accounts for over 90% of installed capacity, wind for 8%, and thermal sources for 2% (trade, 2024). However, droughts have had a significant impact on the hydro-dominated systems; thus, the Ethiopian government (GOE) is currently working to expand the generating mix with additional sources, including solar, wind, and geothermal, to create a more climate-resilient power system (trade, 2024).

Due to their development in technology, accessibility, cost-effectiveness, and adaptability (Maaruf & Khalid, 2021). solar and wind energy sources are among the most well-known renewable energy sources (Manwell, McGowan, & Breger, 2018). Furthermore, the latest advancements in power electronics technology allow for more flexible and cheaper operational control over the integration of renewable energy sources into the power grid (Wang, et al., 2016). However, the energy from these sources is intermittent and depends on meteorological factors like wind speed, temperature, and irradiance extent. Therefore, one way to partially mitigate the unpredictability is to incorporate the complementarity of these two resources and appropriately combine them to produce a hybrid system (Carvalho, Guardia, Marangon, & Lima, 2019).

Maximum power point tracking (MPPT) techniques are used to extract optimal load power when wind speed changes or solar irradiation falls (Rekioua, Rekioua, Elsanabary, & Mekhilef, 2023). To track the maximum power output of solar panels (Katche, Makokha, Zachary, & Adaramola, 2023) and wind turbines (Pande, Nasikkar, Kotecha, & Varadarajan, 2021), several types of MPPTs are used. While they all aim to increase power, all of them are alike in their performances.

The major problem with most classical MPPT techniques for PV systems is their poor performance during varying weather conditions, and they do not track well under partial shading conditions. Similarly, the main problems with MPPT controllers in wind energy conversion systems are their cost-effectiveness and the energy conversion efficiency of wind turbines operating at variable wind speed conditions.

This thesis designs and models a hybrid PV energy conversion system that combines solar and wind power and is connected to an infinite grid in order to address the aforementioned issues. Fuzzy Logic (FLC)-based MPPT has been employed in PV systems due to its

robustness, low oscillations, and high convergence rate. Due to their lower cost, lower capacity of power converters, and good damping for weak grids, doubly fed induction generators, or DFIGs, are used in wind energy conversion systems, or WECS. Voltage-oriented control (VOC) is employed to control the rotor-side converter (RSC) and grid-side converter (GSC). On the rotor side, MPPT algorithms are implemented by using indirect optimal torque control, or OTC.

## **1.2. Motivation**

Ethiopia's energy crisis, especially considering its significant reliance on hydropower, is becoming more vulnerable to environmental shifts and climate change. The decline in water levels in crucial water sources poses significant challenges for electricity generation, leading to frequent power disruptions and blackouts. This situation is particularly concerning for Dire Dawa, a desert city with substantial industrial activities, where reliable energy access is essential for economic growth and development.

This research focused on its potential to contribute to Ethiopia's energy mix diversification. With a growing population and rising energy demands, the country must explore and integrate renewable, sustainable, and environmentally friendly alternative energy sources, such as solar and wind. However, the intermittent nature of these resources presents challenges in achieving maximum power output. Thus, this research aims to tackle these challenges by developing innovative Maximum Power Point Tracking (MPPT) algorithms specifically designed for solar PV and wind systems. By enhancing energy extraction efficiency, the proposed algorithms do not only optimize the use of available renewable resources but also ensure a more stable and reliable energy supply for Dire Dawa and potentially for other regions in Ethiopia facing similar issues.

## **1.3. Statement of problem**

Ethiopia mostly relied on hydropower to generate electricity. hydropower depends on water level, as the water level decreases, the power generated from it also decreases. Currently, some water sources (rivers, and lakes) in Ethiopia have diminished and are lost. Haromaya Lake is an example (Teshome, 2018), if this phenomenon occurred in other water sources that are used as sources of electric power generation, the country is therefore, facing frequent power disruptions and blackouts. This issue has a significant impact on Dire Dawa, a desert city in Ethiopia, which hosts numerous industrial activities; therefore, the government should have paid great attention. Several studies and papers have proposed various remedies for the aforementioned issue; diversifying the energy mix is one of those alternatives that is

considered in this research work, as population growth inevitably led to a rise in the nation's power requirements. Ethiopia should so diversify its energy sources, including geothermal, solar, and wind. Solar and wind energy sources are Renewable, sustainable, eco-friendly, and economical. Nevertheless, they are intermittent and dependent on the weather. So, it's difficult to get maximum power from these energy sources.

Currently, Different maximum power point tracking (MPPT) algorithms are already available; however, most of them exhibit oscillations in variable sun irradiance and wind speed conditions, Therefore, there is a need to develop efficient MPPT algorithms specifically designed for wind and solar PV systems in order to optimize power extraction. This thesis aims to investigate and propose novel MPPT algorithms for solar PV systems that installed in Dire Dawa City. The research will focus on developing algorithms that are robust, accurate, and capable of adapting to changing sun irradiance and wind speed conditions.

The proposed algorithms should address the unpredictable nature of solar and wind energy and enable the extraction of maximum power to satisfy the city energy demand and mitigate the effects of power shortages. By developing efficient MPPT algorithms, this research contributes to the sustainable and reliable usage of renewable energy in Dire Dawa as well as other cities of the country

## **1.4. Objectives**

The following describes the general and specific objectives of this thesis work:

### **1.4.1. General Objective**

The general objective of this thesis is to design and model grid connected photovoltaic and Wind hybrid system.

### **1.4.2. Specific Objectives**

The following are the specific objectives of this thesis work:

- To analyze the energy demand and load characteristics of residential households in Dire Dawa city.
- To study solar and wind energy potential in eastern Ethiopia, Dire Dawa city
- To design and model a hybrid system that combines solar PV and wind energy technologies for grid-connected electricity generation in Dire Dawa city.
- To assess the technical and economic feasibility of the hybrid system in terms of its installation, operation, and maintenance cost.

### **1.5. Scope of Thesis**

Geographically, the study assessed solar irradiance and wind speed data specific to the region, considering site selection criteria such as proximity to the power grid and available land. The research encompassed resource analysis, hybrid system configuration, and economic viability, Homer Pro software used as a tool for optimization, and MATLAB/Simulink for modeling and simulation. The temporal scope includes the collection of historical meteorological data over a 5-10-year period and an overall project timeline of 6-12 months, allowing for future energy demand projections and technological advancements to be considered in evaluating the system's feasibility.

The thesis focuses on the design, mathematical modeling and optimization of PV and wind hybrid system. the optimal sizing and simulation of the hybrid system is done by using Homer pro and MATLAB software. A two stage PV system is simulated and the PV array is controlled by FLC based MPPT controller and VSI is controlled and synchronized with the grid by using synchronously rotating reference frame decoupled controller. The DFIG based WECS is selected. The rotor side converter and the grid side converter are controlled by VOC. The indirect optimal torque controller (OTC) is used in order to control the wind turbine. Finally, the PV and wind energy systems are hybridized and connected to the grid. The result of PV system, DFIG based WECS and hybrid system are discussed and FFT analysis performed to find total harmonic distortion index to ensure the system satisfied the IEEE standard.

### **1.6. Significance of the study**

The significance of the study for this thesis has been summarized as follows:

- The scarcity of electricity in Ethiopia is a severe issue, as just 20% of the population is linked to the national grid. The remaining 80 percent of people living in rural areas only have limited access to power. In order to assist electrify the rural sections of Dire Dawa City, this thesis investigates the possibilities of a grid-connected solar PV and wind hybrid system that can be duplicated in other parts of the nation.
- Ethiopia has a wealth of unused renewable energy resources, including wind and solar energy. This thesis assesses the Dire Dawa region's potential for solar and wind energy and proposes an appropriate hybrid system to utilize these resources.
- The thesis helps to improve Ethiopia's energy security and diversify the country's energy mix by including a grid-connected solar PV and wind hybrid system, which reduces Ethiopia's heavy reliance on fossil fuels.

- This thesis offers a detailed techno-economic and environmental evaluation of the suggested hybrid system, including net present cost, energy cost, and greenhouse gas emission reduction, in order to determine its financial feasibility and sustainability.
- The optimal configuration and sizing of the hybrid system components are determined by the thesis using capable optimization and modeling approaches, such as HOMER software, to ensure maximum energy generation and cost-effectiveness.
- The results and approaches discussed in this thesis can be implemented in other Ethiopian regions as well as possibly in other developing nations dealing with corresponding problems with rural electrification and the integration of renewable energy sources.
- In addition to offering insightful analysis and a case study for scholars and decision-makers in the field of renewable energy, the thesis contributes to the body of knowledge already available on the design, modeling, and optimization of grid-connected solar PV and wind hybrid systems.

### **1.7. Limitation of the Study**

This study had the following limitation

- Due to the study's exclusive focus on Dire Dawa City and the Felema district, variations in resource availability, grid infrastructure, and local conditions across Ethiopia may have an impact on the optimal system configuration and performance.
- While the hybrid system could be fully modeled and optimized through the use of HOMER Pro and MATLAB/Simulink, the results are still based on simulations, which may not accurately reflect the complexities and implementation issues seen in the real world.
- The thesis focused on developing an indirect optimal torque control method for the wind energy conversion system and an MPPT algorithm for the solar PV system based on fuzzy logic. There was not an extensive study of advanced control methods or energy management approaches.
- The study assumed that Dire Dawa City's load demand was constant and did not take future developments like population expansion, industrialization, or energy-saving initiatives into account.

## **1.8. Thesis Organization**

The structure of the thesis is organized as in to six chapters:

Chapter One: This chapter contains an introduction, background of the study, problem statement and study objectives as well as the scope and limitations of this study.

Chapter 2 describes the details of literature review of the grid connected solar PV and wind hybrid systems.

Chapter 3 describes the methodology that has been applied which includes a feasibility study, design, and modeling of grid-connected solar PV and wind hybrid systems with the appropriate controller.

Chapter 4 presents the simulation results and discussion of the proposed grid connected PV and DFIG based wind hybrid system and describes the results of the PV array, wind turbine and the overall system.

Finally, in Chapter 5 an overall system conclusion, recommendations and future works related to this study were stated.

## **CHAPTER TWO**

### **2. LITERATURE REVIEW AND RELATED WORKS**

#### **2.1. Chapter Overview**

This chapter explains about renewable energy, its consumption in the world and also in Ethiopia. Then a detailed explanation and types of hybrid energy systems were also presented. Among the different hybrid configurations, a detailed discussion of hybrid solar PV and wind energy systems is presented, and related articles have also been reviewed.

#### **2.2. Overview of Hybrid renewable energy system**

Renewable energy sources are ones that originate naturally and don't deplete the resources of our planet. Solar, wind, hydro, geothermal, biomass, and biofuels are examples of renewable energy sources. Renewable energy sources are more sustainable and cleaner. Furthermore, these energies are now more economically and practically feasible to employ, thanks to advancements in technologies to capture and utilize them. Renewable energies are essential to mitigate climate change and reduce our dependence on fossil fuels (Kharrich, et al., 2021). Thus, investing money in these energy sources may be useful to create jobs and encourage sustainable economic development.

Renewable energy systems that combine two or more renewable energy sources to produce electricity are known as hybrid systems. When compared to single-source systems, hybrid renewable energy systems have the potential to be more reliable and efficient (Singh & Bansal, 2018). They also lower the cost of energy produced and enable a more efficient use of the resources that are already accessible. Due to these reasons, there has been a global increase in the use of hybrid systems, particularly in isolated or rural areas (Ganjei, et al., 2022). Renewable energy sources, such as wind turbines or solar generators, or even a combination of them, are vital components of a hybrid renewable energy system's structure. (Kartite & Cherkaoui, 2019). According to (Kartite & Cherkaoui, 2019), HES has classified based on structure in to three categories:

1. Presence/absence of conventional source
2. Presence/absence of storage
3. Renewable energy used.

In this thesis, Solar and wind hybrid power plants are designed hence the detail explanation of the two renewable energy resources are presented below.

### 2.2.1. Hybrid of solar PV and wind energy systems

Although solar-wind hybrid power plants are about twice as efficient as previously thought, solar and wind power generations operate properly better together. In a recent study, Solarpraxis and the Reiner Lemoine Institute assessed the surface area where solar photovoltaic systems and wind turbines were constructed together. The same surface area was producing twice as much power, and the shadowing the wind turbines produced only contributed 1 to 2% of the photovoltaic system's loss—far less than originally expected. One of the main advantages is that since these power plants create solar and wind energy at different times and throughout complimentary seasons, there is no need to expand the grid in order to build them. As a result, the amount of electrical energy sent into the grid is more consistent than it would be if wind or solar power plants were used alone.

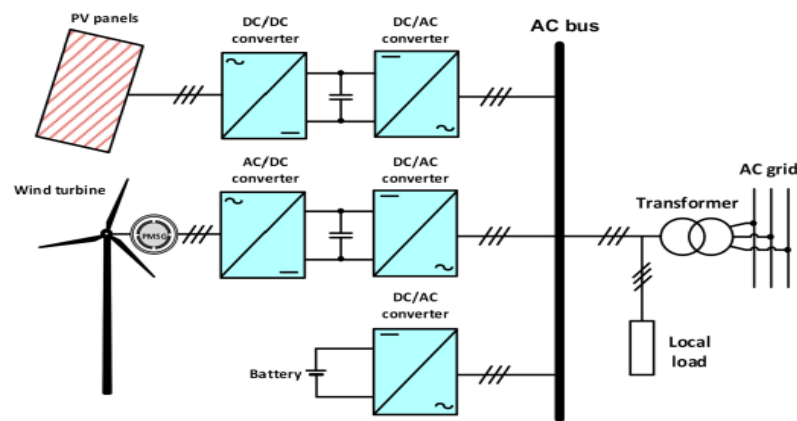


FIGURE 2. 1. Scheme of grid-connected HRES with common DC bus

### 2.2.2. Renewable Energy in the World

Due to their multi-advantages, the percentage consumption of renewable energy in the world is increasing significantly. According to (IEA, 2023), clean technologies, such as heat pumps, solar, wind, and electric vehicles, will supply a considerably greater share of the global energy system by 2030. According to the report, the share of renewable energy in the world's electrical mix will increase from approximately 30% to over 50% in 2030. It is expected that solar PV alone will produce more electricity than the current US power system. The International Energy Agency (IEA) estimates that in 2050, renewable energy sources like hydro, geothermal, solar, wind, and bioenergy will account for two-thirds of the world's energy supply. From now until 2050, solar PV capacity is predicted to increase 20 times, while wind power will increase 11 times, making solar the leading source of energy, contributing one-fifth of electricity supplies. By 2050, fossil fuels are expected to account for just more than one-fifth of the world's energy supply, down from over four-fifths now.

In 2050, electricity is predicted to make up over 50% of all energy used. Figure 2.3 shows the global energy consumption by sources from 2010–2050.

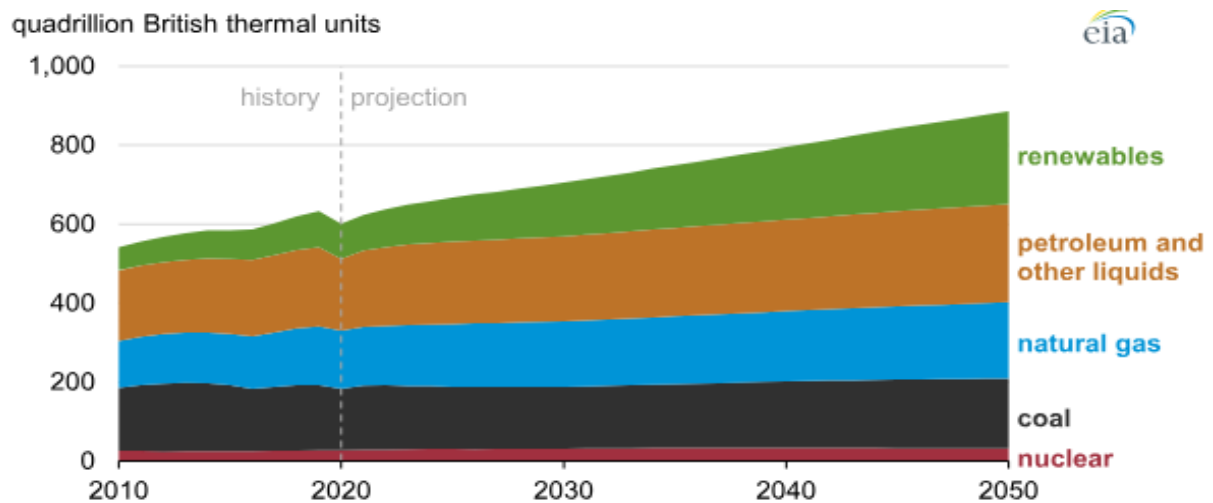


FIGURE 2. 2. Global primary energy consumption by sources (2010-2050) (eia, 2021)

### 2.2.3. Renewable Energy in Ethiopia

Ethiopia is a country located in the East of Africa lies between  $3^{\circ}$  to  $15^{\circ}$  N latitude and  $33^{\circ}$  to  $48^{\circ}$  E longitudes, as shown in Figure 2.2, with land area of about 1.097 million  $km^2$  (Terefe, Peter, & Nonhebel, 2014). The country is the second-largest economy in Eastern Africa and has abundant renewable energy potential to generate over 60,000 megawatts (MW) of electric power from hydroelectric, wind, solar, and geothermal sources (TRADE, 2022). Despite Ethiopia's energy potential, the country is currently facing energy shortages and load shedding. This is due to the challenge of serving a population of over 110 million people and meeting the increasing electricity demand, which is projected to grow by approximately 30% per year (market-intelligence, 2022). Currently, Ethiopia has an installed generation capacity of approximately 4,500 MW. However, there are plans in place to significantly expand the power generation capacity to 17,000 MW within the next 10 years (market-intelligence, 2022). Table 2.1 shows Ethiopian Energy potential.



FIGURE 2. 3. Political map of Ethiopia (Khan & Pawan, 2017)

TABLE 2. 1. Energy Source Potential of Ethiopia (market-intelligence, 2022)

| No | Resource                    | Unit          | Exploite Reserve | %Exploited   |
|----|-----------------------------|---------------|------------------|--------------|
| 1  | Hydropower                  | MW            | 45,000           | <5%          |
| 2  | Solar/day                   | $kwh/m^2$     | 4-6              | <1%          |
| 3  | Wind:<br>Power<br><br>Speed | GW<br><br>m/s | 100<br><br>>7    | 1%<br><br>1% |
| 4  | Geothermal                  | MW            | <10,000          | <1%          |
| 5  | Wood                        | Million tons  | 1120             | 50%          |
| 6  | Agricultural waste          | Million tons  | 15-20            | 30%          |
| 7  | Natural gas                 | Billion $m^3$ | 113              | 0%           |
| 8  | Coal                        | Million tons  | 300              | 0%           |
| 9  | Oil shale                   | Million tons  | 253              | 0%           |

### 1. Wind Energy in Ethiopia

Ethiopia has good wind resources, especially in regions such as the Rift Valley, Somali Plateau, and highland areas, where wind speeds are consistently high with velocities ranging from 7 to 9 m/s. Its wind energy potential is estimated to be 10,000MW (energypedia, 2023). Moreover, the country's geographical location and diverse topography: which includes highlands, rift valleys, and lowlands is favorable for wind energy generation. Thus, Ethiopia's government actively supports wind energy development as part of its Climate Resilient Green Economy (CRGE) strategy. The strategy aims to transform the country into a middle-income nation with a low carbon footprint by 2025. Wind energy is a key pillar of this strategy, leading to significant government investments in wind energy projects (evwind, 2023).

In 2018, the Ethiopian government, together with the Danish Energy Agency, announced a roadmap for the country's development of wind power. This was one of the biggest developments in the sector. The plan addresses a number of issues that have an impact on the nation's wind sector, including grid integration, site selection, bankable data for power sales, financing, procurement guidelines, and operation and maintenance. The roadmap intends to raise the capacity of wind power by 1000 MW by 2025 and seeks to include the private sector more for a more realistic development of the industry.

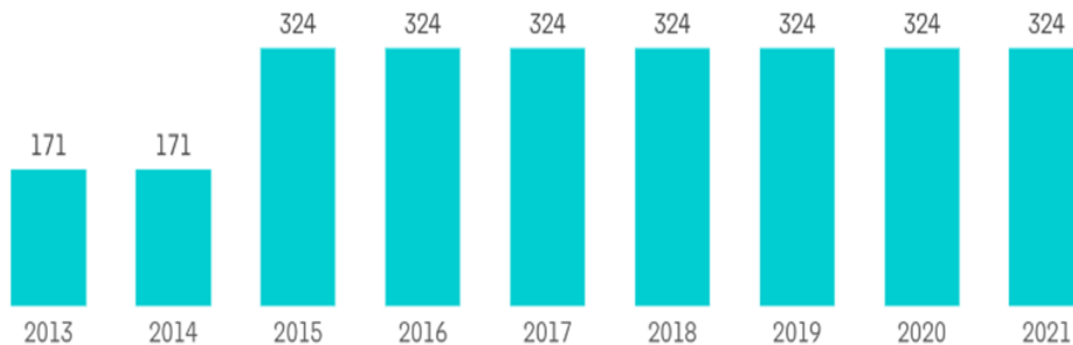


FIGURE 2. 4. Total Wind Energy Installed Capacity in MW, Ethiopia, 2012-2021 (Source, IRENA)

## 2. Solar Energy in Ethiopia

Ethiopia has an immense potential for solar energy, similar to other tropical nations. The country's average solar radiation is about  $5.2 \text{ kwh/m}^2$  per day. However, this potential varies by season. The lowest potential is around  $4.55 \text{ kwh/m}^2$  per day, while the highest reaches approximately  $6.25 \text{ kwh/m}^2$  per day (Bekele, Ayall, & Teshome, 2023).

The Ministry of Finance has proposed six solar projects for interested bidders. ACWA Power, a Saudi company, has signed two power purchase agreements with EEP to create 125 MW of solar power each. The implementation agreement for this project is still being worked out. The government aims to tackle the power issues faced by rural communities by offering off-grid solar solutions. The initial tender for this initiative is anticipated to be announced in the first half of 2022 (market-intelligence, 2022).

### 2.3. Solar Photovoltaic system (PV)

Photovoltaic (PV) power generation has gained immense popularity globally due to its many benefits, including low maintenance requirements, the elimination of noise pollution caused by moving parts, affordability, and improved equipment efficiency in PV systems.

(Fatih, Gani, & Sekkeli, 2020). A photovoltaic system's main elements include solar panels, an inverter, AC and DC cables, an electrical grid, a backup power source, and a monitoring system (Aslam, Ahmed, Ahmed, Assadi, & Ahmed, 2022).

PV systems can generally be divided into two categories (Díaz, Muñoz, Rivera, & Rohten, 2023):

1. the grid-connected configuration and
2. the stand-alone architecture

### **The Grid-connected Configuration**

Grid-connected PV systems are expanding at the quickest rate in the global energy market, and they are a dominant force there. On-grid or grid-connected PV systems only produce electricity while the utility power grid is operational. When the building or facility's energy usage is low, they can transmit any excess power they generate back to the grid, which they need to connect to in order to operate. Additionally, these systems exhibit minimal prices, excellent efficiency, robust scalability, and high reliability (Zsiborács, Hegedu, Csányi, Vincze, & Pintér, 2019).

The power electronics topology will determine whether the grid-connected PV system is a single stage or multiple power processing solution. In Figure 2.5, a grid-connected, two-stage PV system with a PV array coupled to an MPP-tracking DC-DC converter is depicted. An inverter is then connected to the DC-DC converter's output to produce AC output with the required voltage and frequency (Sher, Addoweesh, & Al-Haddad, 2017). For developing a grid-connected inverter, several photovoltaic topologies exist. Among them are power processing systems with one, two, and several stages (Adouairi, Bossoufi, Motahhir, & Saady, 2023).

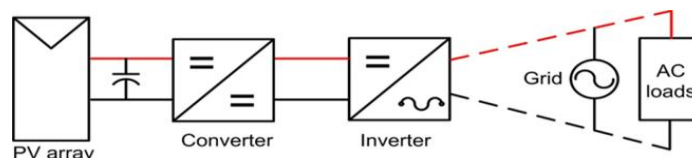


FIGURE 2. 5. A typical PV system for grid connection or AC load (Abdullah, Shakeel, Murtaza, Sulaiman, & Ali, 2023)

### **Stand-alone PV system**

On the other hand, a standalone photovoltaic (PV) system, also known as an off-grid PV system, is an independent PV system that operated without being connected to the electrical grid. This system is commonly used in remote areas where grid access is not possible or expensive. Figure 2.6 showed that a typical standalone PV system, in this system a battery is common in order to utilize when the power from the PV array is less.

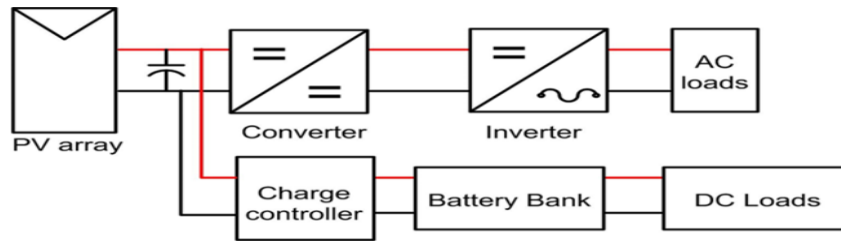


FIGURE 2. 6. A generic standalone PV system (Abdullah, Shakeel, Murtaza, Sulaiman, & Ali, 2023)

### 2.3.1. Photovoltaic Cell

A solar cell, also known as a PV cell is the fundamental component of photovoltaic system which converts sunlight directly into electrical energy through the photovoltaic effect. According to some estimations, silicon makes up 90% of all solar cells that are sold today. This comprises the majority of solar cells on the market. Silicon can exist in a variety of forms, though. The purity of silicon, or the alignment of the silicon modules, is the most defining characteristic of variations (homeowner, 2023).

Solar cells can be arranged into a large grouping called solar modules, and a number of modules are form into a PV array. The photovoltaic cell, module, and array structure is illustrated in Figure 2.7 (Sezen, Aktas, Ucar, & Ozdemir, 2014).

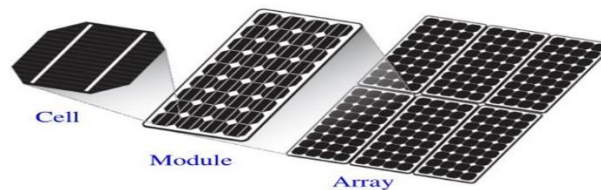


FIGURE 2. 7. PV cell, module, and array structure (Sezen, Aktas, Ucar, & Ozdemir, 2014)

### Types of PV Cells

There are three types of PV cell technologies that dominate the world market: monocrystalline silicon, polycrystalline silicon, and thin film

#### 1. monocrystalline silicon (c-Si)

Pure monocrystalline silicon is used to make these cells. The silicon in these cells is virtually entirely free of imperfections and impurities, having a single continuous crystal lattice structure. Monocrystalline cells have a high efficiency, usually 15%, which is their main advantage. The drawback of these cells is their slightly greater cost compared to other technologies due to the complex manufacturing process needed to generate monocrystalline silicon. (Puthenpurakel & Subadhra, 2016).



FIGURE 2. 8. A monocrystalline silicon cell's front and back (Puthenpurakel & Subadhra, 2016)

## 2. polycrystalline cells

Polycrystalline silicon cell is also called polysilicon or Mult crystalline cells. Many grains of monocrystalline silicon are used to create multi crystalline cells. Molten polycrystalline silicon is poured into ingots during the production process, and these are then sliced into extremely thin wafers and integrated into whole cells. Due to their simplified production method, multi crystal cells are less expensive to make than monocrystalline ones. However, their average efficiencies are only about 12%, which is a minor decrease in efficiency. (Puthenpurakel & Subadhra, 2016).

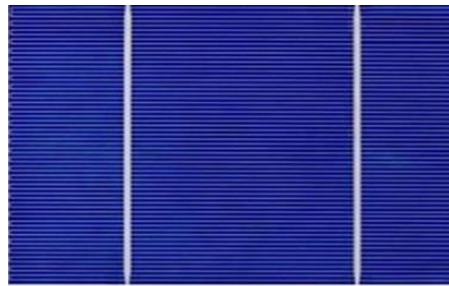


FIGURE 2. 9. Polycrystalline silicon cell (Puthenpurakel & Subadhra, 2016)

## 3. Thin films

Thin-film solar cells are regarded as the second generation of solar energy devices. These cell types include the deposition of a thin layer of semiconductor PV material onto plastic foil, glass, or metal. Since thin films don't have a single crystal structure, they are less efficient, require a larger range of fields, and come with higher associated costs for mounting. Amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), polymer, and organic solar cells are a few types of thin-film solar cells that are suitable for outdoor use (Puthenpurakel & Subadhra, 2016).

### 2.3.2. Maximum Power Point Tracking

Maximum power point tracking (MPPT) algorithms are a practical solution to ensure the continuous operation of the photovoltaic systems, maximize the output of the PV system and overcome nonlinear characteristics under all circumstances (Alrubaie, et al., 2022). The maximum power of the PV system is affected by solar irradiation, atmospheric temperature

and solar cell temperature (Sumathi, Ashok, & Surekha, 2015). By controlling the load (I-V) curve of the PV cell, the MPP can be achieved at maximum point on the load curve. the maximum power current and the maximum power voltage of the PV array must be intersected. In the literature (Katche, Makokha, Zachary, & Adaramola, A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems, 2023), several types of MPPT methods are found. A classification of the most common MPPT methods is given in figure 2.10. hill-climbing and fractional methods are widely adopted in commercial PV systems. (Rub, Malinowski, & Haddad, 2014).

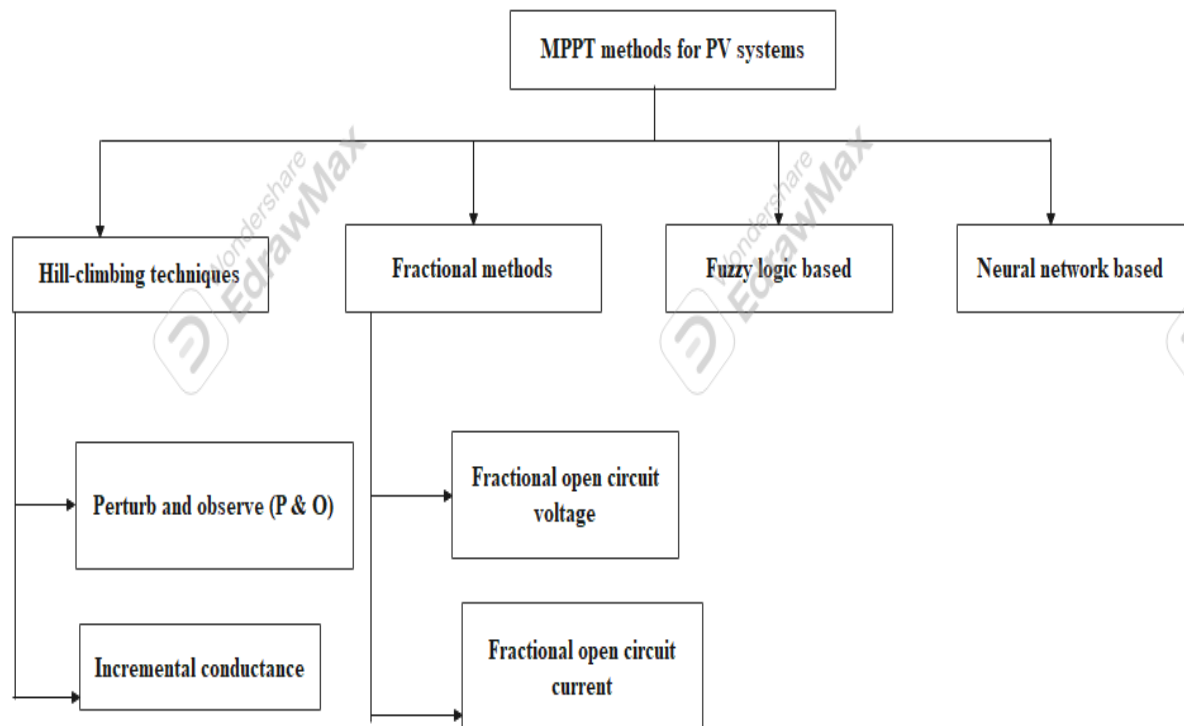


FIGURE 2. 10. MPPT algorithm classification (Abu-Rub, Malinowski, & EAl-Haddad, 2014)

### 1. Perturb and Observe Algorithm

Perturb and Observe (P&O) is the most widely used MPPT algorithm for PV system due to its simple structure, simple implementation and lower cost. It works by perturbing continuously the operating point and observing the impact on the output power of the PV system. Increasing the voltage result in increasing the power when the operating point is on left side of MPP; on the other hand, the power will decrease when the operating point is on the right side of MPP. The flow chart of PO algorithm is shown in figure 2.11. The drawbacks of using this algorithm are its failure to track MPP when there is a big change in the insolation level as well as the continues oscillation around MPP (Mahdi, et al., 2020)

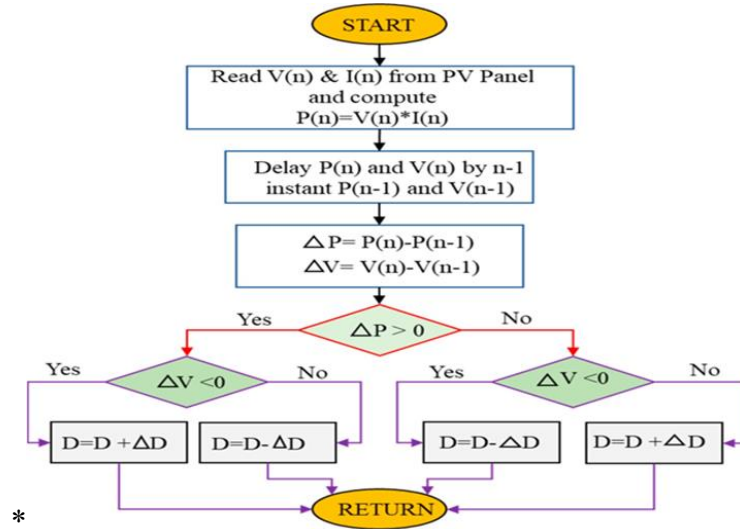


FIGURE 2. 11. PO algorithm flow chart (Ali, et al., 2023)

## 2. Incremental Conductance Algorithm (INC)

Incremental conductance is a type of hill-climbing mppt algorithm which is developed due to the drawback of P&O algorithm. This method is mostly proposed for rapidly changing atmospheric conditions (Rub, Malinowski, & Haddad, 2014). It works by comparing the instantaneous inductance  $\left(\frac{I}{V}\right)$  and the incremental conductance  $\left(\frac{dI}{dV}\right)$  of the PV array. When these two are the same, the output voltage will be the MPP voltage. During this time the control maintains voltage till the irradiation changes and the process is repeated. The flow chart of incremental conductance mppt strategy is depicted in figure 2.9.

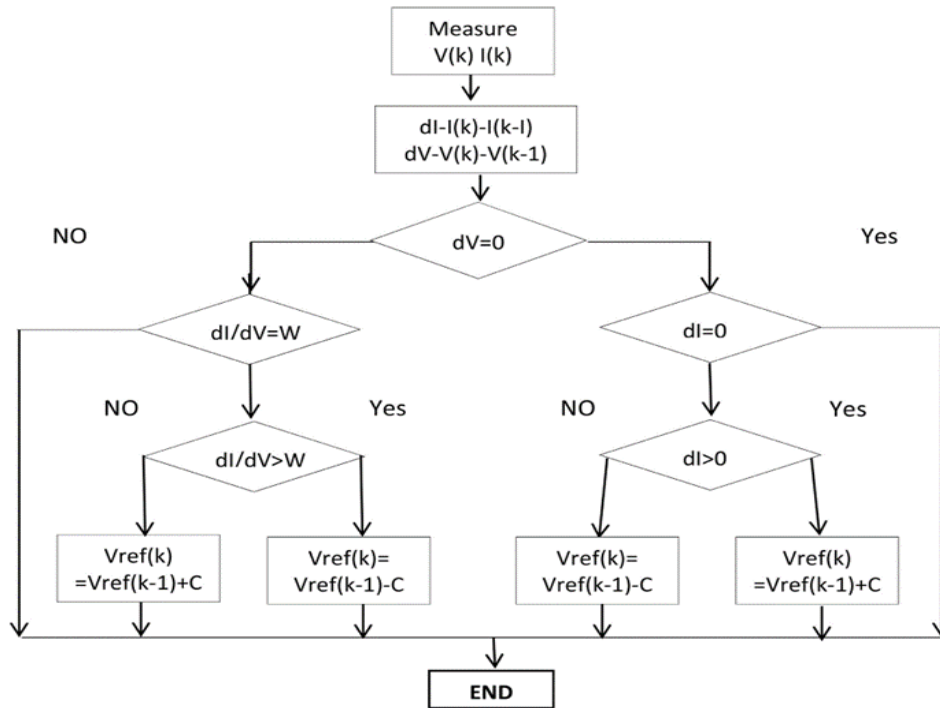


FIGURE 2. 12. Flowchart of incremental conductance (Asoh, Noumsi, & Mbinkar, 2022)

as shown in the flow chart if the change in power with respect to change in voltage  $\frac{dP}{dV} = 0$ , then maximum power point is achieved, The INC algorithm has better ability to find the MPP during sudden changes in irradiance conditions, but it needs a complex controller (Pandiyar, et al., 2021).

### 3. Fuzzy logic control

The experience and understanding of a human operator is represented in terms of linguistic variables known as fuzzy rules by fuzzy logic controllers (FLCs), which are based on fuzzy set theory. The implementation of linguistic fuzzy rules based on the procedures carried out by human operators does not also require a mathematical model of the system, since an experienced human operator can adjust the system inputs to get a desired output by simply looking at the system output, without any knowledge of the dynamics and interior parameter variations of the system. Thus, an FLC becomes adaptive and nonlinear, exhibiting strong performance under parameter fluctuations and the capacity to get the necessary control actions for complex, uncertain, and nonlinear systems without the need for parameter estimates and mathematical models for those systems.

Since the PV system is a highly nonlinear system and the performance of the PV cells is difficult to describe with an accurate mathematical model, the fuzzy control method for MPPT control is very appropriate. By introducing fuzzy control into the MPPT control of the PV system, it will be possible to weaken the power oscillation near the MPP and produce a rapid response to the external environment.

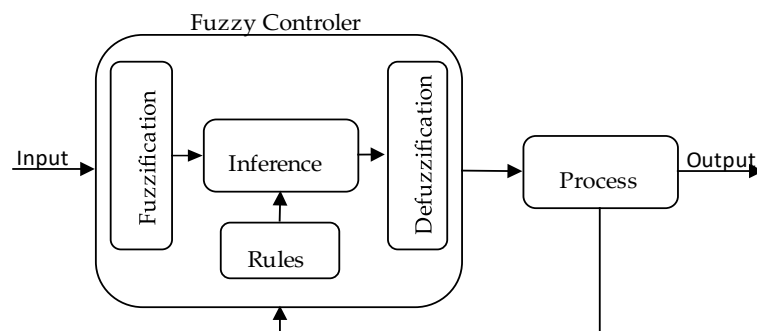


FIGURE 2. 13. A fuzzy controller's block diagram (Robels, Taborda, & Rodriguez, 2017)

The fuzzy control system employs data samples to identify the positional relationship between the operation point and MPP and automatically corrects the voltage value at the operation point to acquire the MPP in order to implement the MPPT control technique. Figure 8 displays a fuzzy controller's block diagram. Fuzzy control generally consists of fuzzification, rule base, and defuzzification (Ko, Huh, & Kim, 2020). The input signals are processed by the fuzzification block, which also gives them a fuzzy value. The collection of

rules is predicated on process knowledge and enables a language description of the variables to be managed. The inference mechanism is in charge of interpreting the data while accounting for the membership functions of the rules. The fuzzy information obtained from the inference mechanism is transformed into non-fuzzy information that is helpful for controlling the process by the defuzzification block.

Define the fuzzy logic controller's output variables for the voltage adjustment of  $dU$  operating point. The continuous sample points of attachment  $e$  slope value and the PV cells  $P - U$  curve change in unit time slope  $\Delta e$  are the input variables.

$$e(k) = \frac{dP(k)}{dU(k)} = \frac{P(k) - P(k-1)}{U(k) - U(k-1)} \quad (2.1)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (2.2)$$

where  $P(k)$  and  $U(k)$  represent the PV cells' output power and output voltage at sampling value of  $k$ -times. It implies that PV cells have been operating at their maximum power output state if  $e(k) = 0$ . By analyzing P-U characteristic curve of PV cells as shown in Figure 2.12, we can conclude following the logic of the MPPT control rules (Rabiul, Rahman, & Xu, 2016).

1. When  $e(k) < 0$  and  $\Delta e(k) < 0$ , P from the left side close to the  $P_{MPP}$ .  $dU$  should be positive, to continue to close to the MPP;
2. When  $e(k) > 0$  and  $\Delta e(k) > 0$ , P from the left side far away from the  $P_{MPP}$ .  $dU$  should be positive, to close to the MPP;
3. When  $e(k) < 0$  and  $\Delta e(k) > 0$ , P from the right side close to the  $P_{MPP}$ .  $dU$  should be negative, to continue to close to the MPP;
4. When  $e(k) > 0$  and  $\Delta e(k) < 0$ , P from the right side far away from the  $P_{MPP}$ .  $dU$  should be negative, to close to the MPP.

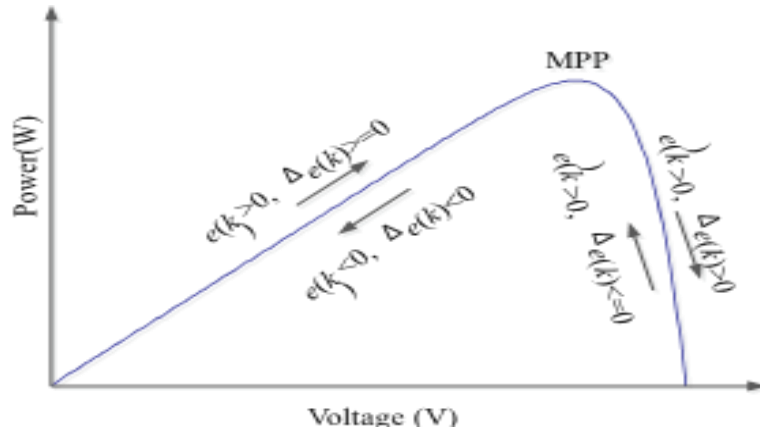


FIGURE 2. 14. The PV P-V characteristic curve (Rabiul, Rahman, & Xu, 2016)

### 2.3.3. DC to DC converters

In the developing field of renewable energy technologies, DC to DC converters are essential components of energy conversion. In order to convert power from a variable direct input voltage to a constant direct output voltage that is either less than or larger than the variable input voltage, these converters are utilized. To transform one voltage level to another, a dc-to-dc converter of a different kind can be employed. A few of them were covered below

#### 1. The buck converter

The DC–DC buck converter, shown in Figure 2.15, steps down the output voltage level to be less when compared with the input voltage level (Venkat, et al., 2020). As a result, this converter can be used to integrate higher module voltages with lower battery voltages or loads. There are various solar PV applications used along with the DC–DC buck converters, are employed in the standalone solar PV pumping systems that are enabled to use the water supply in rural areas, solar battery charger, grid-connected MPPT tracking, and the off-grid PV systems (Venkat, et al., 2020).

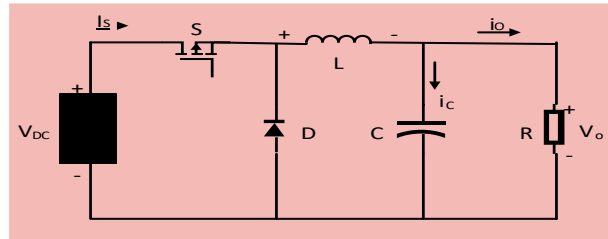


FIGURE 2. 15. DC buck converter circuit diagram (Venkat, et al., 2020)

#### 2. The boost Converter

In some photovoltaic applications, the load side voltage magnitude must be higher than the input voltage. In those applications, the boost converter is applied in the MPPT converter. When the switch is closed, the boost converter operation begins gradually increasing inductor current results in energy storage in the inductor. When the switch is open, the inductor current slowly decreases as the energy stored in the inductor is transmitted to the load via the diode.

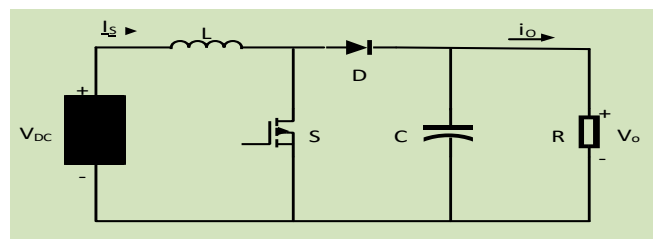


FIGURE 2. 16. Boost converter for the PV application (Venkat, et al., 2020)

### 3. Buck-boost converter

The buck–boost converter in Figure 2.17 is formed by integrating basic buck and boost converter topology and that can be used in various applications as standalone/grid-connected PV systems and motor drives (Venkat, et al., 2020). It shows that there are reduced current ripples when the buck–boost converters operate in the continuous conduction mode (CCM). Buck-boost converter generate an output voltage higher than or lower than the input voltage.

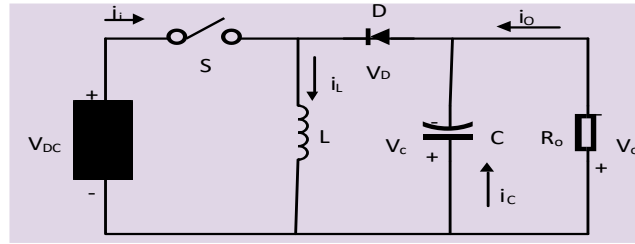


FIGURE 2. 17. Buck-boost converter for the PV application (Venkat, et al., 2020)

#### 2.3.4. Inverters in PV system

The inverter is an essential component in the grid connected PV system. In grid connected PV system the inverter is used to convert the variable dc voltage from the boost converter to a fixed ac voltage and also in responsible for synchronizing the output signal with the grid in terms of frequency and phase shift.

Inverters are generally categorized into line commutation inverters (LCI) and self-commutation inverters (SCI) based on the commutation process (turned ON and turned OFF behavior) (Salem, et al., 2022). A detailed classification of inverters is explained in (Salem, et al., 2022), however in this thesis self-commutation inverters are used. In SCI, a MOSFET or IGBT are used. MOSFETs are used for high frequency (20-800kHz) applications having power ratings less than 20kW, while IGBTs are used for low frequency (20kHz) applications having power ratings greater than 100kw. Due to the development of sophisticated switching devices and improvement in the control strategies, SCIs are preferably used as compared to LCI. The SCIs are further classified into current source inverter (CSI) and voltage source inverter (VSI) (Salem, et al., 2022). They are explained blow:

##### 1. Current Source Inverter

In CSI, the inverter's input is fed with a dc current with same polarity, therefore the polarity of the dc side voltage is used to determine the direction of the average power flow through the inverter. The output current obtained in CSI is constant in amplitude but variable in width. In these types of inverters, an inductor with a considerable size is used to solve the issue of current stability which result in the circuitry will be less effective, bigger, and more expensive (Ishikawa, 2002).

## **2. Voltage Source Inverter**

In VSI, the inverter's input is fed with a dc voltage with same polarity, therefore the polarity of the dc side current is used to determine the direction of the average power flow through the inverter. The output voltage obtained in these types of inverters are constant ac voltage with variable width. VSI needs an enormous capacitor to be connected in parallel with the source of input (Hariri, Desa, Masri, & Zainuri, 2020). For grid-tied PV applications, VSIs are preferred over CSIs due to their low cost, high efficiency, lightweight design, and comparatively low power losses (Salem, et al., 2022).

### **2.3.5. Harmonic Filtering**

A harmonic filter is placed in between the grid and the voltage source inverter (VSI) when it is integrated into the system. Numerous switching harmonics are generated in the grid current as a result of the VSI's pulse width modulation (PWM). Therefore, in accordance with IEEE Std 929-2000 and other standards, a L or LCL filter is required to reduce these current harmonics (Xu & Xie, 2018). The LCL-type filter is receiving increasing attention since it can attenuate harmonics more effectively than the L-type filter with the same inductance, and it is also less expensive and smaller (Chunya, Wei, & Mingjin, 2022). Despite the benefits, using an LCL filter creates a problem when trying to suppress LCL resonance, which causes instability in the system (Thamizh, Geetha, & Subramani, 2018). considering grid impedance values, which vary depending on grid conditions and configuration (weak or stiff grid), can impair their safe functioning. Therefore, maintaining steady performance despite significant grid impedance fluctuations is the primary issue of LCL filter design for grid-connected power converters (Ben, Wissem, Slama, & and Monmasson, 2017). In the Literature (Ruan, et al., 2018), different Design approaches are presented. The detailed design procedure for the LCL type filter is presented in Chapter 3.

### **2.3.6. Control Structure of Grid Connected Inverter**

To control the power flow between the inverter and the grid, three phase grid-connected VSI's active and reactive power control are crucial. Voltage control mode (VCM) or power control mode (PCM) can be used to control VSI (Saeed & Memon, 2023). By modifying the voltage magnitude and phase angle, the VSI controls the grid voltage in VCM, but in PCM, it modifies the output current magnitude and phase angle to control the amount of active and reactive power injected into the grid. Precise control of active and reactive power is accomplished through the use of fuzzy logic control, model predictive control (MPC) control techniques, and PI controller-based control.

More obviously, the control approach used for the three-phase PV inverters consists of two cascaded loops. There are several possible configurations for cascaded loops, such as an outer voltage and inner power loop or an outer power and inner current loop. However, the most popular approach makes use of a quicker inner current control loop and a slower outside dc-link voltage control loop (Mustafa & Noman, 2017).

In most cases, the outside voltage control loop is necessary to keep the PV system and the grid's power balance. This controller modifies the reference current to add more electricity to the grid if the PV system has excess power available.

. In order to send electrical power into the grid, the inner current control loop maintains power quality and lowers harmonics in the current. One of the three reference frames, such as the synchronous reference frame (d-q), stationary reference frame ( $\alpha\beta$ ), or natural reference frame (a-b-c), can be used to apply the control strategy. For every grid current phase in the natural reference frame, a separate controller is needed. Hysteresis and dead beat are employed in the natural reference frame since the currents are sinusoidal nonlinear. (Yang, Chen, & Blaabjerg, 2014). The control structure in natural reference frame is shown in Figure 2.18.

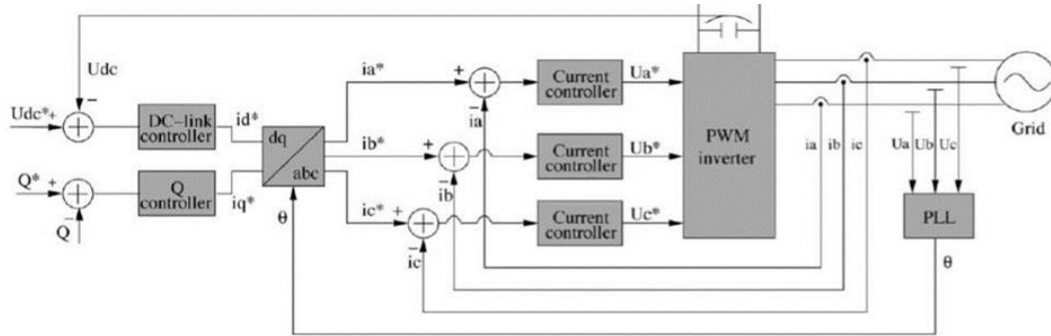


FIGURE 2. 18. In Natural reference Frame Control Structure (Yang, Chen, & Blaabjerg, 2014)

Control variables like grid currents are converted into stationary reference frame ( $\alpha\beta$ ) in stationary reference frame. In the ( $\alpha\beta$ ) reference frame, the resulting components are sinusoidal. Because the time-varying signal makes it difficult for the PI controller to eliminate the steady-state error, The usage of proportional-resonant controllers

In stationary reference frame, the control variables such as grid currents are transformed in to stationary reference frame ( $\alpha\beta$ ). The resultant components in the  $\alpha\beta$  reference frame are sinusoidal. Since the PI controller is not good at removing the steady-state error when the signal is time varying Proportional-Resonant controllers are used (Yang, Chen, &

Blaabjerg, 2014). Figure 2.19 shows one potential way to construct control structure in stationary reference frame.

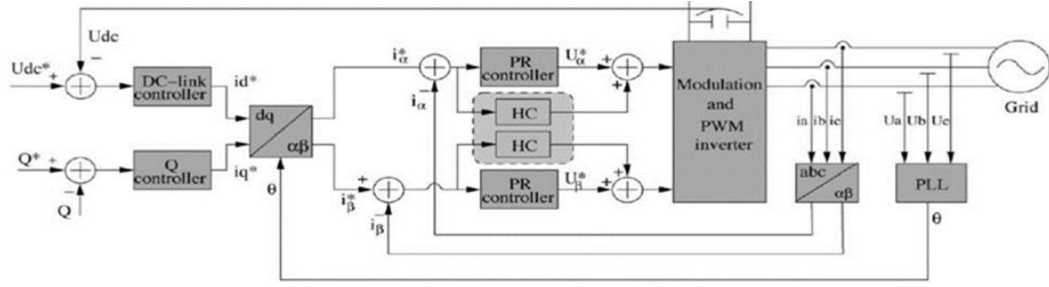


FIGURE 2. 19. General Structure for Implementation of Control in Stationary RF (Yang, Chen, & Blaabjerg, 2014)

The control variables are DC values in a synchronous reference frame because the sinusoidal grid voltage and current are converted into a frame that spins synchronously with the grid voltage. As a result, the variables under control are turning into DC quantities. Every deviation in the grid's voltage or current will be reflected to the relevant components on the d and q axes, making filtering and controlling the system with proportional-integral (PI) based controllers simple (Yang, Chen, & Blaabjerg, 2014). Figure.2.20 shows general control structure in synchronous reference frame (SRF)

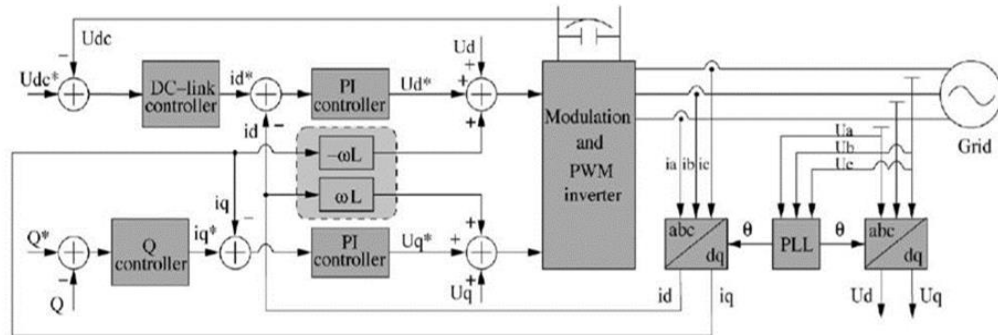


FIGURE 2. 20. . General Control Structure in Synchronous Reference Frame (Yang, Chen, & Blaabjerg, 2014)

A synchronous reference frame is proposed in this thesis. Active and reactive power injection into the grid can be independently managed thanks to this control strategy's decoupling terms and voltage feedforward in the control loop (Huang, Shi, Sun, & Wang, 2013).

### 2.3.7. Grid Synchronization

Grid synchronization is a crucial aspect of three phase solar inverters connected the grid. Through careful monitoring of the electrical grid's voltage and frequency, solar inverters maintain synchronization with it. Solar inverters use sophisticated synchronization mechanisms to modify their output voltage and frequency to match the grid. Consequently,

it ensures a seamless insertion (dronequote, 2023). There are many different kinds of grid synchronization methods; several are described in the literature and are covered in the section below (Sumathi, Ashok, & Surekha, 2015)

### 1. Zero Crossing Detectors

The Zero Crossing Detector (ZCD) is used to detect the change in polarity of AC power. A pulse is produced that displays  $180^\circ$  in the opposite scenario and  $0^\circ$  in the case of a positive to negative transition. This algorithm's disadvantage is that it degrades ZCD performance when harmonics and notches are present.

### 2. Phase Locked Loop

A PLL is a type of closed loop feedback control system that is nonlinear and synchronizes both the phase and frequency of its output signal with an input signal or reference. An ideal PLL would be immune to disturbances, harmonics, sags/swells, notches, and other distortions, and would deliver fast and accurate synchronization information. (Ranjan, 2016). The phase detector (PD), which compares the input/reference signal with the output signal to generate an error signal, the loop filter (LF), which eliminates unwanted harmonic terms from the error signal, and the voltage-controlled oscillator (VCO), which produces the output signal whose frequency varies around a central frequency based on the output of the loop filter, are the three basic parts of the phase-locked loop (PLL). Figure 2.21 displays a PLL's block diagram (Sumathi, Ashok, & Surekha, 2015).

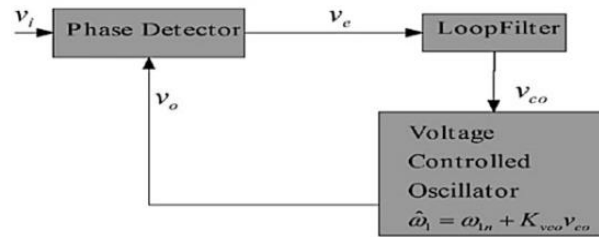


FIGURE 2. 21. block diagram of PLL (Sumathi, Ashok, & Surekha, 2015)

#### 2.3.8. Modulation Techniques for Inverter

The pulse width modulation (PWM) is the most efficient method used to vary both the voltage and frequency within a three-phase inverter (Mahbub & Mohiuddin, 2021). In grid tied inverter, the output voltage from the inverter's output voltage is 380/400V, in order to get this voltage, the inverter has to be controlled by adjusting the on and off of its component for providing pulses at their gate terminals. This is achieved by PWM techniques, moreover these techniques are used to reduce the low order harmonics produced by the inverter during dc to ac conversion process, the higher order harmonics are minimized by filters. There are

various PWM techniques (Rashid, 2014). In this thesis, the detailed discussion of sinusoidal PWM and space vector PWM Techniques are presented.

### 1. Sinusoidal PWM technique (SPWM)

In industrial applications, SPWM is widely employed (Sumathi, Ashok, & Surekha, 2015). A sinusoidal signal (reference signal magnitude:  $V_{ref}$  and frequency:  $f_{ref}$ ) and a triangle signal (carrier signal magnitude is  $V_c$  and frequency  $f_c$ ) are compared to generate Pulse Width Modulation (PWM) signals in the SPWM (Kocalmis & Sunter, 2016). This modulation process's primary output voltage is low, which is a disadvantage. Carrier and reference signals are shown in Figure 2.22.

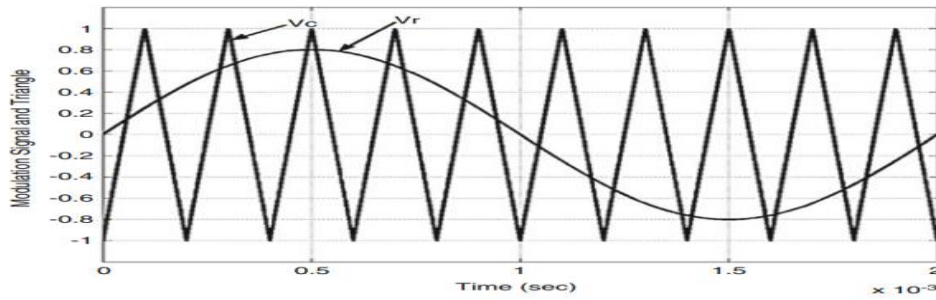


FIGURE 2. 22. Reference and carrier signals of the SPWM technique (Sumathi, Ashok, & Surekha, 2015)

### 2. Space Vector PWM (SVPWM) Technique

Space vector modulation (SVM) is one of the real-time modulation techniques and is widely used for digital control of voltage source inverters (Wu, Lang, Zargari, & Kouro, 2011). Figure 2.23a shows the SVPWM of a two-level inverter (Madasamy, et al., 2019)

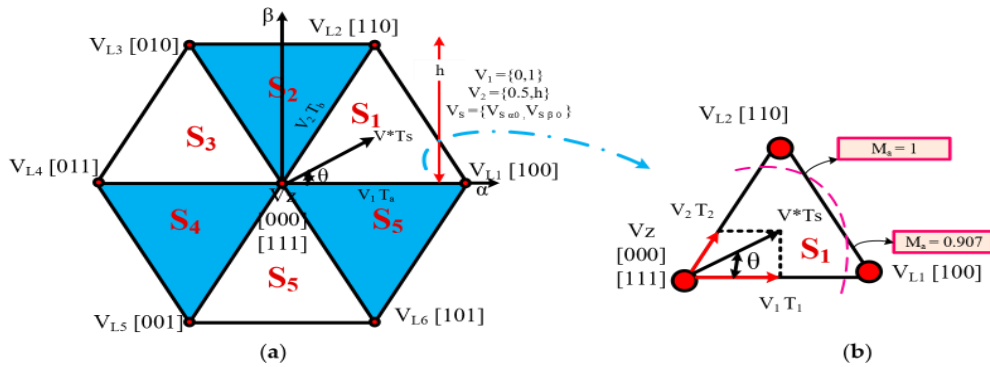


FIGURE 2. 23. (a) Space vector diagram (SVD) for two-level inverter, (b) sector-1 for two-level inverter SVD (Madasamy, et al., 2019)

In this case, every sector is an equilateral symmetrical triangle with height ( $h = \sqrt{3}/2$ ), represented as  $S_i$ , where  $i = 1$  to 6. Here, the edge vectors ( $V_1$  to  $V_6$ ) are referred to as non-zero (active vectors), while  $V_0$  and  $V_7$  are considered zero vectors. Three closest switching vectors two active and one zero are used to compute the SVM switching in any sector in on-

time. The switching timings are synthesized by the movement of the reference or target vector  $V^*$  positioning inside the sector. Here, the sector-1 is taken into consideration in order to comprehend the two-level switching of SVPWM, as seen in Figure 2.21b. After multiplying  $V^*$  by the sample time ( $T_s$ ), one can find the volts-second of  $V^*$ . Next, by referring to sector-1, the time integral of  $V^*$  is approximated by adding the products of the two non-zero vectors ( $V_1$  and  $V_2$ ) and their time widths ( $T_1$  and  $T_2$ ).

For sector-1, the reference voltage  $V^*$  volts-sec equation is computed as follows:

$$V^*T_s = T_1V_1 + T_2V_2 + T_0V_0 \quad (2.5)$$

$T_1$  and  $T_2$  represent the time (sec) widths of the adjacent switching vectors,  $V_1$  and  $V_2$ , respectively. The zero-vector state can be either the switching state [000] or [111], or both. The  $V^*$  angle ( $\theta$ ) movement within the sector is calculated by:

$$\theta = \tan^{-1} \left( \frac{V_\alpha}{V_\beta} \right) \quad (2.6)$$

The values of  $\theta$  sample the  $V^*$  in different sectors. For instance, when  $\theta$  equals  $115^\circ$ , the  $V^*$  approaches sector-2, as sector-2 is situated at an angle ranging from  $61^\circ$  to  $120^\circ$ .

Depending on the  $V^*$  position, SVPWM can be classified as linear modulation (where  $M_a \leq 0.907$ ) or over modulation (where  $M_a > 0.907$ ), depending on whether it is inside or outside the hexagonal SVPWM (refer to Figure 2.21)

$T_s = T_1 + T_2 + T_0$  represents the total period.  $T_1$  and  $T_2$  are computed by projecting the  $V^*$  location with respect to the SVD origin (zero point) along the  $\alpha$  and  $\beta$  axes. From now on, the volts-sec formulas for the  $\alpha$ - and  $\beta$ -axes are as follows:  $V_{\alpha 0}^S T_s = T_1 + 0.5T_2$  and  $V_{\beta 0}^S T_s = hT_2$ . The formulas for the active vector time are therefore  $T_2 = T_s V_{\beta 0}^S / h$  and  $T_1 = T_s (V_{\alpha 0}^S - V_{\beta 0}^S) / 2h$ . The zero-voltage time  $T_0$  is found with the assistance of  $T_1$  and  $T_2$ , given the switching frequency.

#### 2.4. Wind Energy Conversion system (WECS)

The kinetic energy contained in the wind is transformed into mechanical energy by a wind energy conversion (WEC) system. This mechanical energy is then used as a prime mover to propel a rotating electrical generator. A wind turbine, gearbox, generator, interfacing converter, appropriate control systems, and, of course, a tower are the typical components of a WECS. WEC systems have the option of being integrated into the electrical grid system or built as stand-alone schemes to offer power to isolated local consumers in distant places. WECS are classified in to two types, fixed speed WECS, and variable speed WECS (Chhipa, et al., 2021).

## 1. Fixed speed WECS

In fixed-speed WECSs as shown figure 2.24, the wind turbine generator is connected to the grid through a soft-starter and a transformer. A squirrel cage induction generator (SCIG) is solely used in a fixed-speed WECS where the rotational speed of the generator is constant regardless of wind speed (engineering, 2023). Fixed speed WECS have advantages such as simplicity, reliability, and compatibility with existing power grids. However, they have disadvantages such as lower energy capture compared to variable speed systems and limited control over turbine performance based on varying wind speeds.

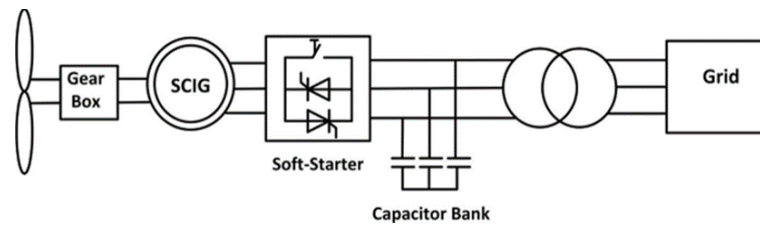


FIGURE 2. 24. Grid-tied fixed-speed squirrel cage induction generator WECS  
(engineering, 2023)

## 2. Variable speed WECS

In variable-speed WECSs, the generator rotates at different rotational speed with respect to the wind to track maximum power. Due to changing rotational speed of the generator, the frequency also varies. Thus, a frequency converter is used to match the generator frequency with grid frequency. Variable-speed WECSs offer several benefits over fixed-speed WECSs. For example, it improves energy efficiency by capturing more electricity at varying wind speeds. The generator's ability to adjust speed in response to wind speed reduces the mechanical stress generated by gusts of wind. Moreover, larger wind turbines may be built because to variable-speed WECS. The main disadvantage of the variable-speed WECS is that it is more expensive and complex than the fixed-speed WECS since it needs a power converter to regulate the generator's rotational speed. However, since the power converter separates the grid from the generator, control over the grid's active and reactive power is still available (engineering, 2023).

### 2.4.1. Wind turbines

A wind turbine is a device which converts the kinetic energy of the wind into mechanical energy and in turn in to electrical energy. Over the years, there have been significant advancements in wind turbine technology which leads to increasing efficiency, reliability and cost effectiveness. Here are some of the latest developments in wind turbine technology (Laurie & Carol, 2023):

- **Longer Blades:** When a turbine's blades grow noticeably longer, it may absorb more energy. Segmenting blades, for example, can lower the cost of installing a turbine by simplifying shipping.
- **Taller towers:** Higher hub heights have stronger winds than what today's conventional turbines can handle. Height increases of an average of 17 meters give longer blades the extra clearance they need to reach those high-altitude winds.
- **Low-specific-power wind turbines.** The rotor size of these turbines is bigger than the generator size. Larger rotors capture more wind, which increases the generator's energy transfer and wind power availability.

Based on their axis of rotation, wind turbines can be categorized as either vertical (VAWT) or horizontal (HAWT).

### 1. Horizontal-Axis Wind Turbines (HAWTs)

The most often utilized wind turbines are horizontal axis wind turbines (HAWTs) due to their robustness and efficiency. Located at the summit of the tower and facing the direction of the wind are the wind turbine's main rotor shaft and electrical generators. This kind of turbine has to be built with a large crane to raise the components to the top of the tower and a substantial support for the tower to hold the weight of the generator, gearbox, and blades. (EnergyEducation, 2023). High power output, high efficiency, high dependability, and high operating wind speed are HAWT's major benefits (luvsid, 2023).

### 2. Vertical-Axis Wind Turbines (VAWTs)

The first kind of wind turbines, known as vertical axis wind turbines (VAWTs), have their main rotor shafts positioned vertically. Small power versions of these wind turbines are offered for sale. The general benefits of VAWTs include simplicity due to the lack of a yaw or pitch mechanism; easy maintenance due to all the parts that would typically be in a nacelle being on the ground; HAWT may "seek the wind" by altering the blades' axis of rotation in response to abrupt changes in the velocity vector, which may result in a large energy loss (Rao, 2019).

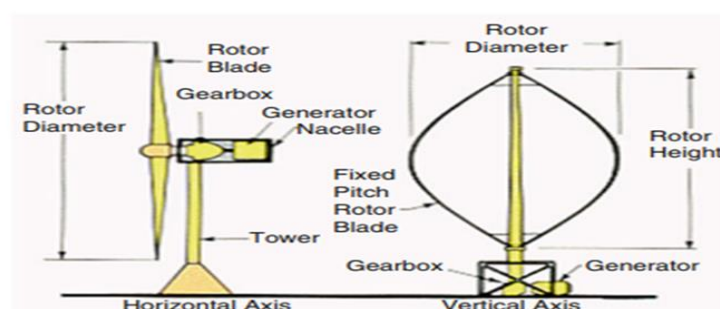


FIGURE 2. 25. Typical wind turbine configuration (Rao, 2019)

The major drawback of VAWTs is their lower theoretical and practical efficiency.

#### 2.4.2. Wind energy Generators

Generators in WECSs are used to convert the rotational mechanical energy in to electrical energy. Several types of generators have been used in wind energy systems over the years. These include: the squirrel cage induction generator (SCIG), doubly fed induction generators (DFIG), and synchronous generator (SG) (wound rotor and permanent magnet) with power ratings from a few kilowatts to several megawatts (Boldea, 2005).

##### 1. Squirrel-cage induction generator (SCIG)

The SCIG is a type of induction generator with simple and rugged construction. This generator is relatively cheap and require less maintenance. SCIG is used in traditional direct grid connected wind energy system. In this system, the SCIG is directly connected to the grid. Due to the generator slip caused by wind speed, the generator speed varies by only a few percent, thus it is used for fixed speed wind turbines. Because SCIGs use reactive power, wind turbines based on them usually have an installation for reactive power adjustment as well as a soft-starter mechanism (Rao, 2019).

Figure 2.26 showed the SCIG based WECS configuration.

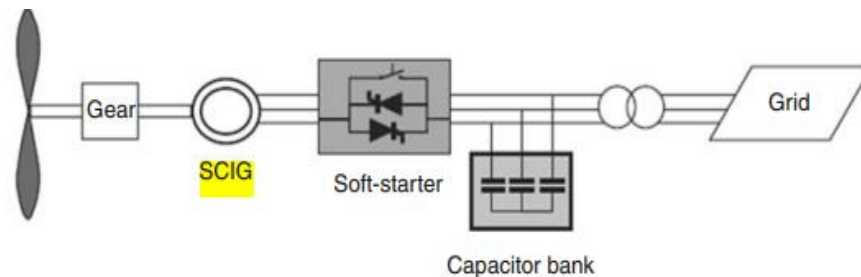


FIGURE 2. 26. SCIG-based WECS configuration (Rao, 2019)

##### 2. Doubly fed induction generator (DFIG)

DFIG-based WECS are preferred and are employed worldwide (Chhipa, et al., 2022). As shown in figure 2.27, the stator is directly connected to the grid, while the rotor is connected to the grid via a back-back converter. In DFIG-based WECS, a back-to-back two-level IGBT voltage source converter (VSC) system is typically employed.

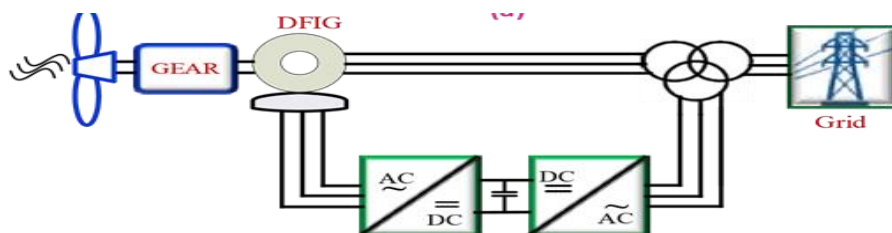


FIGURE 2. 27. DFIG wind energy system configuration (Hannan, et al., 2023)

A generator is said to as doubly fed because it has the ability to supply energy to the grid from both its stator and rotor. The RSC is used to control the torque or active/reactive power by controlling the current component, while the GSC regulates the dc-link voltage and guarantees that the converter operates at unity power factor. Reactive power compensation from external sources is unnecessary since the system has the capacity of controlling reactive power.

The DFIG wind energy system has a speed range of around  $\pm 30\%$ ; which means it may operate 30% faster or slower than synchronous speed. Since the speed range of 60% can often satisfy all wind conditions, it is enough for the wind turbine's variable-speed operation. The maximum slip, or around 30% of the rated power, establishes the maximum power that the rotor circuit can handle. As a result, electric power may flow in both directions in the rotor circuit: from the grid to the rotor and vice versa. Nevertheless, the converter system only needs to process about 30% of the rated power. The DFIG wind turbine's energy conversion efficiency is greatly increased when compared to fixed-speed systems because reduced-capacity converters are used, which also leads to cost, weight, and physical size reductions.

### 3. Wound rotor generator (WRSG)

In practical WECSs with a large number of poles running at low rotor speeds utilize the wound-rotor synchronous generator (WRSG). WRSG, or wound rotor synchronous generator As WRSGs' stator windings are directly linked to the grid, the supply grid's frequency rigidly controls the WRSGs' rotating speed. Slip rings and brushes or a brushless exciter with a revolving rectifier are used to excite the rotor winding with direct current.

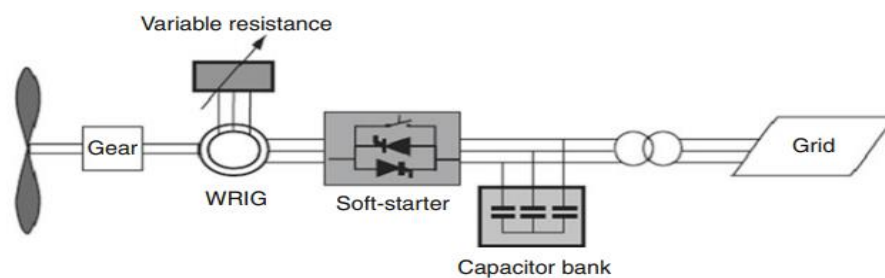


FIGURE 2. 28. WRIG based WECS configuration (Rao, 2019)

Unlike the induction generator, the synchronous generator does not require additional reactive power correcting mechanism. The exciter field is produced by the rotor winding, through which direct current flows, and it rotates at a synchronous speed. The number of pole pairs in the rotor and the frequency of the rotating field determine the synchronous generator's speed. One of the advantages of WRIG is that a gearbox is not required.

However, the cost of such a gearless design is a massive, heavy generator and a full-scale power converter that has to handle the system's whole output.

#### 4. Permanent magnet generator (PMSG)

Permanent magnet synchronous generators (PMSGs) generate rotor magnetic flux by the use of permanent magnets. A high-power density may be achieved without rotor windings, which reduces the generator's size and weight. In addition, the absence of rotor winding losses decreases the rotor's thermal stress. PMSG offers a number of disadvantages despite of their benefits; permanent magnets are costly and prone to demagnetization. In addition, a full-scale power converter must be used when using PM excitation in order to match the voltage and frequency of generation to the voltage and frequency of transmission, respectively. This is an additional cost.

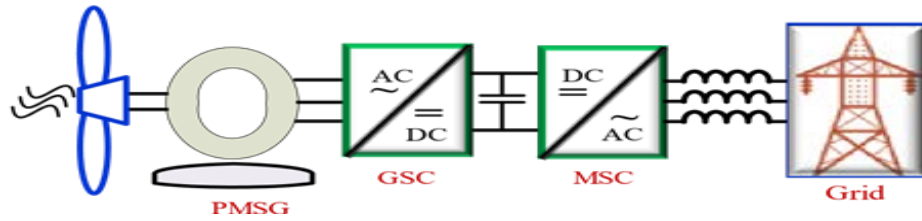


FIGURE 2. 29. PMSG-based WECS configuration (Hannan, et al., 2023)

#### 2.4.3. Maximum Power point tracking for WECS

Variations in wind speed result in different output powers from wind energy systems. Due to non-linear nature of the wind, it is difficult to keep the wind turbine operating at its maximum power output under all wind speed conditions. Therefore, over the years, several maximum power point tracking (MPPT) algorithms have been developed to track the maximum power point of the wind turbine (Rekioua D. , 2014).

##### 1. Tip Speed Ratio Method (TSR)

The TSR algorithm has benefits such as a simple algorithm scheme and fast signal processing due to the low input data, demonstrating that the TSR algorithm plays an optimal rotor speed conversion role under continuous environmental conditions (Le, Duong, & Le, 2023).

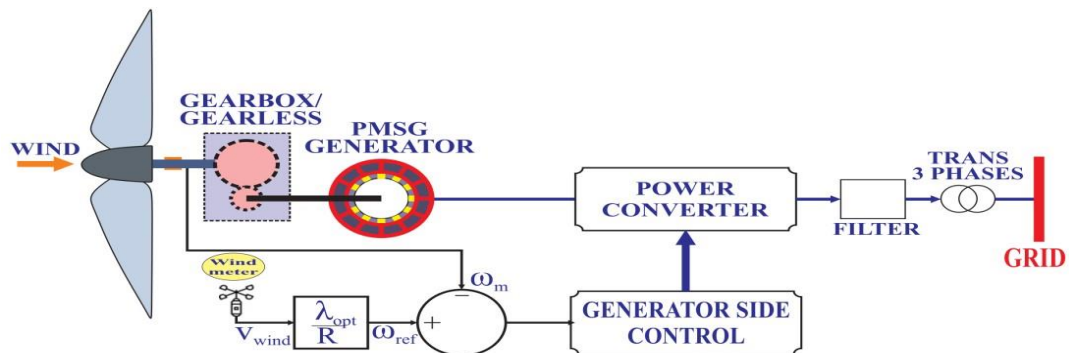


FIGURE 2. 30. Diagram of TSR MPPT algorithm (Le, Duong, & Le, 2023)

In this method, the wind turbine's maximum power output is obtained by maintaining the tip speed ratio at its optimal value,  $\lambda_{T,opt}$ . Figure 2-20 illustrates the basic concept of this control scheme: the generator speed reference  $\omega_m^*$  is produced by using the measured wind speed  $V_w$  in accordance with the optimal tip speed ratio  $\lambda_{T,opt}$ . When the generator reaches a steady state and the MPPT is reached, the power converters regulate the generator speed  $\omega_m$  to meet its reference.

## **2. Power Signal Feedback (PSF) Method**

The power signal feedback (PSF) control method, which is realized based on the knowledge of the characteristics of the turbine, is widely adopted due to its effectiveness and simple implementation (Chen, Cai, & Lin, 2019). This method maximizes the output power by producing a reference power signal. Wind speed and torque are used as input signals, and the controller corrects the difference between the optimal and actual power of the system (Pande, Nasikkar, Kotecha, & Varadarajan, 2021).

## **3. Optimal Torque Control Method (OTC)**

OTC method is a fast response and robust as well as a simple method to generate the reference speed of the generator in some operating ranges (Meghni, Chojaa, & Boulmaiz, 2020). This method adjusts the generator torque to get the optimal value at varying wind speeds. But it requires a knowledge of the characteristics of turbines ( $C_{pmax}$  and  $\lambda_{T,opt}$ ).

### **2.4.4. Power electronic converters for WECS**

In wind energy conversion systems (WECS), power converters are commonly used. Since wind direction and speed patterns change daily and seasonally due to the unpredictable nature of air flow, thus it makes the operation more difficult. Power electronics are designed to reduce mechanical stresses that might have a negative impact on the system's performance, increasing efficiency and ensuring system reliability.

In fixed-speed WECS, the converters are used to reduce inrush current and torque oscillations during the system start-up, whereas in variable-speed WECS they are employed to control the speed/torque of the generator and also the active/reactive power to the grid (Wu, Lang, Zargari, & Kouro, 2011). In literature (Rajendran, et al., 2022), (Afonso, et al., 2021) and (Olabi, et al., 2021) various types of Power electronic converter configurations are available. However, in this thesis DFIG based WECS is used hence a back-to-back converter is studied.

### Back-to-back converter

IGBT or SiC switches could be used in the converter, with the latter showing advantages in efficiency, cost, and volume (Loncarski, Hussain, & Bellini, 2023).

The back-to-back converter's configuration is depicted in the figure 2.30. The two converters can be independently controlled thanks to the decoupling or dc link capacitor.

The configuration is further imposed by the dc-link capacitor, which reduces the system's overall lifetime. The switching loss of the back-to-back PWM converter is another drawback. due to the arrangement requires two converters, there are high switching losses (Aashish, 2019).

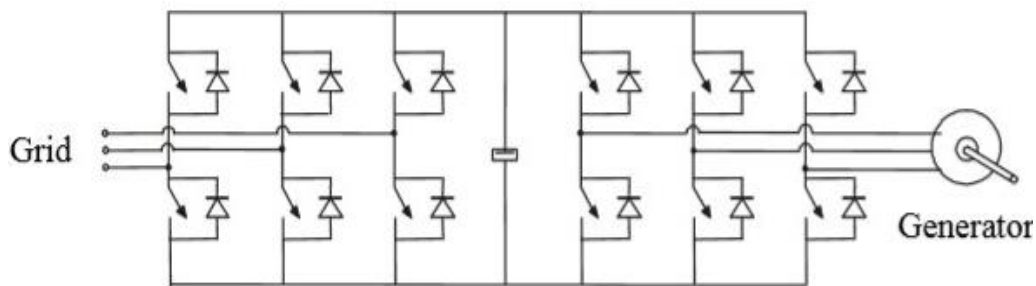


FIGURE 2. 31. Back-to-Back PWM converter of configuration (Aashish Pant, 2019)

### 2.5. Related Works

Numerous scholarly research publications have discussed grid-connected solar PV and wind hybrid systems utilizing various control strategies and methodologies. The pros and demerits of the methodology used in the closely related studies to the proposed research endeavor are reviewed. Research gaps are identified after a literature review.

The authors (Boke, Moges, & Dejen, 2022) discusses the economic reform agenda of Ethiopia, which aims to achieve a lower-middle-income status by 2030 and sustain economic growth to reach medium-middle and higher-middle-income status by 2040 and 2050, respectively. They evaluated the optimal renewable energy mix for power generation and associated investment costs to achieve upper-middle income country by 2050. The authors have used an Open-Source Energy Modeling System (OSeMOSYS) to assess the optimal energy supply options for Ethiopia and their result indicated that the country has to invest nearly 70 billion US dollars in power plant investments between 2021 and 2030 in order to achieve the lower-middle-income goal for energy per capita consumption by 2030 and an estimated 750 billion US dollars needs to be invested cumulatively between 2031 and 2050 in order to reach upper-middle-income energy consumption rates by the year 2050.

The authors of (Bayu, Khan, Hagos, Mahela, & Guerrero, 2022) examine the implementation of a hybrid power generation system designed to provide reliable electricity to rural

communities in Ethiopia. The authors conduct a comprehensive feasibility analysis that combines various renewable energy sources, such as solar and wind, to assess their viability in addressing the energy access challenges faced in these remote areas. The study presents simulation results indicating that the proposed hybrid system can significantly enhance energy reliability and sustainability for rural populations. However, the article has some drawbacks, including a limited economic analysis to evaluate the overall cost-effectiveness and affordability for local communities. Additionally, the study does not fully address potential regulatory and logistical challenges that could impact the deployment of such systems in remote areas. Overall, while the research provides valuable insights into hybrid power solutions for Ethiopian rural areas, it would benefit from a deeper exploration of economic and practical considerations for successful implementation.

The authors (Ghayoor, Swanson, & Sibanda, 2021) investigate the optimal design of a hybrid renewable energy system tailored for residential use. The authors focus on integrating solar and wind resources to enhance energy efficiency and reduce dependence on the grid. They employ simulation models to identify the ideal sizing of components, demonstrating that the proposed system can significantly lower energy costs and improve sustainability for residents. However, the study has some drawbacks, notably the lack of a comprehensive economic analysis to evaluate the financial feasibility and return on investment for homeowners. Additionally, the research does not address potential regulatory challenges or the impact of local policies on the implementation of such systems. Overall, while the article provides valuable insights into optimizing hybrid renewable energy systems for residential applications, it would benefit from a deeper exploration of economic and regulatory factors affecting real-world deployment.

In most literatures related to PV system, classical MPPT has been used. The author (Minda, 2019) explores advanced control strategies for synchronizing solar power systems with the electrical grid. The author focuses on using a synchronously rotating reference frame to enhance the performance and stability of inverter systems, which are crucial for effective grid integration of solar energy. The study presents theoretical models and simulation results that demonstrate improved synchronization and control under varying operational conditions. However, the article has some drawbacks, including a limited discussion on practical implementation challenges and the potential scalability of the proposed control strategy in real-world applications. Additionally, the economic implications of adopting such advanced control methods are not addressed, which could impact their feasibility for widespread deployment. Overall, while the research offers valuable insights into inverter

control for solar power systems, it would benefit from a more thorough examination of practical and economic considerations.

The authors (Tolba, Mohamed, Eisa, & El-Rifaie, 2021) present a detailed study on the modeling and control of hybrid energy systems that integrate multiple renewable sources with a focus on Maximum Power Point Tracking (MPPT) techniques. The authors emphasize the importance of optimizing energy extraction from various sources, such as solar and wind, to enhance the overall efficiency and reliability of grid-connected systems. They provide a comprehensive framework that incorporates advanced control strategies and simulation results, demonstrating the effectiveness of their approach in improving energy management and grid stability. However, the study has some drawbacks, including a lack of economic analysis to assess the cost-effectiveness of the proposed system and limited discussion on practical implementation challenges in real-world scenarios. Overall, while the research contributes valuable insights into hybrid energy systems and MPPT control, it would benefit from addressing economic viability and practical considerations for deployment.

The authors (Kebbaty & Baghli, 2022) examine a hybrid energy system that combines photovoltaic (PV) and wind resources to meet the region's increasing energy demands. The authors emphasize Algeria's renewable energy potential and aim to optimize energy production while ensuring stable grid integration. They address the intermittency challenges of solar and wind energy through a modeling framework featuring advanced control strategies, leading to improved energy reliability and reduced reliance on fossil fuels. However, the study lacks a comprehensive economic analysis to evaluate the feasibility of implementing such a hybrid system in real-world scenarios and does not provide regional comparisons to assess performance across varying climatic conditions. Overall, while the research offers valuable insights into sustainable energy solutions for Algeria, it would be strengthened by a deeper exploration of economic viability and comparative performance.

The authors (Bekiroglu & Yazar, 2022) presents a study on the maximum power point tracking (MPPT) control of a grid-connected doubly fed induction generated (DFIG)-based wind energy conversion system (WECS) under variable wind speed conditions. The authors utilized real wind speed data from the Edremit/Balıkesir region in Turkey to analyze the performance of the proposed control system.

The authors (Chhipa, et al., 2022) presents a study on the modeling and control strategy of a wind energy conversion system (WECS) with a grid-connected doubly-fed induction generator (DFIG). The authors focus on the vector control techniques for the rotor side converter (RSC) and grid-side converter (GSC) to achieve precise control of active and

reactive power. The article also discusses the implementation of a maximum power point tracking (MPPT) controller strategy to optimize power conversion. The proposed control strategy aims to improve the efficiency and performance of the system, ensuring optimal power conversion. The findings of this study can be valuable for the design and implementation of wind energy systems, particularly in remote communities where power supply is a challenge.

The authors (Popa, Nicolae, Nicolae, & Popescu, 2023) focus on developing a comprehensive model for a 10 MW PV power plant, highlighting the significance of solar energy in addressing global energy demands and environmental issues. They address the need for effective modeling tools to optimize energy output and ensure reliable grid integration. The simulations demonstrate that the designed PV plant achieves high efficiency under varying conditions, providing valuable insights into optimal configurations. While the authors advocate for advanced simulation tools to enhance renewable energy integration, the article could improve by including a detailed economic analysis and exploring hybrid systems incorporating wind or energy storage solutions. Overall, the study contributes significantly to solar energy modeling but leaves opportunities for further research in hybrid configurations and practical implementation challenges.

The authors (Macit & Vural, 2022) focuses on the increasing significance of renewable energy, particularly photovoltaic (PV) systems, in meeting global energy demands. It addresses the challenges of efficiently integrating a 1 MW grid-connected PV system, emphasizing the need for effective control strategies to manage fluctuations in solar irradiance and maintain grid stability. The authors present simulation results demonstrating that their proposed control algorithms significantly enhance the system's performance and energy output. In conclusion, they advocate for further research into advanced control techniques and the integration of energy storage solutions. However, the article does not consider hybrid systems incorporating wind energy and fails to provide an economic analysis of the proposed strategies. Additionally, it does not explore advanced Maximum Power Point Tracking (MPPT) methods, which could improve energy capture further.

The author (Moges G. , 2018) present the modelling and analysis of integration of solar, wind and fuel cell to the existing power grid. The thesis investigates the implementation of a power flow controlling system to ensure efficient and reliable power distribution. The author does not explain the best MPPT controller algorithms for PV system.

Despite the increasing reliance on renewable energy sources such as solar and wind in Ethiopia, there remains a significant gap in effective Maximum Power Point Tracking

(MPPT) algorithms tailored for the unique challenges presented by these intermittent resources. Existing MPPT techniques often struggle with oscillations under variable solar irradiance and wind speed conditions, leading to suboptimal energy extraction and inconsistent performance. Furthermore, while numerous studies have explored various renewable energy solutions, there is a lack of focused research on hybrid solar PV and wind systems specifically designed for the climatic and geographical context of Dire Dawa City. This research aims to fill this gap by developing novel MPPT algorithms that are robust, accurate, and adaptive to fluctuating environmental conditions. By addressing the limitations of current methodologies, this study seeks to enhance the efficiency and reliability of renewable energy systems in Ethiopia, ultimately contributing to the country's energy security and sustainability goals.

## CHAPTER THREE

### 3. METHODOLOGY

#### 3.1. Introduction

This Chapter deals with the approach followed for feasibility study, design and modelling grid connected solar PV and wind hybrid system. Dr. Fone Virtual Location Software and Google Earth Website used to select the optimal site for the proposed hybrid system, then Homer Pro software is employed for properly sizing the solar and wind hybrid system, finally the detail design and modelling is discussed.

#### 3.2. Feasibility Study

##### 3.2.1. Site Location

The proposed solar-wind hybrid system falls in the District Felema (Dire Dawa city) of Ethiopia. The geographical location of the identified site is in latitude of 9, 5833 (934'59.988"N) and longitude of 41, 8667 (4152'0.120"E) and with average altitude of 1,221m above sea level. The district of Felema is located in south-east of Dire Dawa city. The project is located 14km away from the Dire Dawa main substation. The key location plan of the project site is depicted in figure 3.1.



FIGURE 3. 1. Selected site (Felema) for the proposed system

Proposed location for solar PV and wind hybrid system in Dire Dawa Felema locality

This area has an enormous quantity of land, a portion of which can be used for the intended solar PV and wind farms. The proposed area has a minimal population size, which is favorable for the project's designs. The land has high wind potential and sun resources and is located 1,100–1,200 meters above sea level. With an average wind speed of 10.26 m/s and horizontal solar radiation of  $6.05 \text{ kWh/m}^2$ , there are plenty of resources available. High

wind energy and solar radiation potential were suggested by the obtained data's resource information.

### 3.2.2. Resource Assessment

A detailed description of wind speed, temperature, and solar irradiation used for optimal sizing and configuration analysis is presented below:

#### Solar Radiation and Clearness Index

Dire Dawa's sun insolation at longitude 41° 51' 1.3349" E and latitude 34' 7.88768" N was taken from the NASA meteorology and solar energy webpage. Considering the latitude, month of the year, and average radiation value, the clearness index, which measures the percentage of solar radiation that reaches the top of the atmosphere and passes through to reach the Earth's surface, is computed by HOMER. As shown in figure 3.2, February, March, and April have the highest levels of sun irradiation, while July and August have the lowest. The clarity index has a large value from October to May, reaching a maximum of 0.694 in February. With a clearness index value of 0.495, July and August have the lowest.

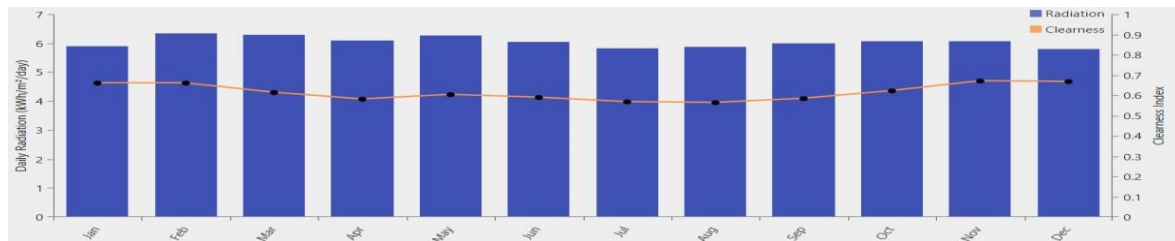


FIGURE 3. 2. Monthly Solar radiation

#### Temperature

The monthly average temperature of Dire Dawa, which is obtained from NASA surface meteorology, is required by the HOMER software simulation. The average annual temperature of the area is 24.04 °C. Figure 3.3 displays the monthly average temperature for Dire Dawa, Ethiopia.



FIGURE 3. 3. Average Monthly Temperature Resource of Dire Dawa

#### Wind speed resource

The proposed site wind speed data over 22 years on the basis of longitude and latitude were taken from the NASA database website. Figure 3.4 showed that the proposed location's

annual average wind speed was measured at an anemometer height of 78 m, which is 10.26m/s.



FIGURE 3. 4. Average monthly average wind speed resource

### 3.2.3. Economic Analysis

The cost of the components is the main factor considered when choosing the power system components in this thesis work, as the main objective of the work is to determine the optimal power system configuration that would meet the demand with the lowest net present cost (NPC) and cost of energy (COE). An estimation of the component costs is produced based on current market pricing. (Sinha & Chandel, 2014).

**Component initial capital cost:** This is the total installed cost incurred at the start of the project to acquire and install the component. This cost includes total PV cost, total wind cost, inverter cost and grid connection cost.

**Replacement cost:** When a component's functional life is approaching its end, this is the cost required to replace it. For the reasons listed below, its cost differs from the component's initial cost. Not every spare part for a component needs to be replaced when it reaches the end of its life cycle. Donor expenses may cover all or part of the initial costs; replacement costs, however, may not take travel expenses into account.

**Operation and maintenance (O&M) cost:** This is the price that is allocated for system upkeep and functioning. The costs of operation and maintenance for each scheme component taken into account in this thesis vary. The fixed operation and maintenance expenses, capacity shortfall penalties, and emission fines are examples of the various O&M costs that HOMER takes into account.

### Solar PV Size and Cost

During designing the hybrid system, the cost, efficiency and lifetime of each component is an important factor. Since, in this research work a large-scale grid connected hybrid system is designed. Therefore, the efficiency of each component is taken in to consideration beside the cost and lifetime. Because designing a large-scale grid connected hybrid system with less

efficient component will have a significant impact on the whole system connected to it. Therefore, by considering the above-mentioned factors the solar panel, wind turbine and converters have been selected by surveying different products. A 4.25kW solar panel is considered, this panel has 10 solar modules each of them having 425W capacities, mono-crystalline silicon and manufactured by Sunpower solar panel which is China company known as Model- SPR-425E-WHT-D with an efficiency of 19.66% [appendix A-1]. The operation and maintenance cost of the selected solar panel is taken 1% per year.

TABLE 3. 1. Input parameters of PV system (IRENA, 2016)

| PV size<br>(Kw) | Capital Cost<br>(\$) | O&M cost<br>(\$) | PV Life<br>(year) | Size Considered                  |
|-----------------|----------------------|------------------|-------------------|----------------------------------|
| 4.25            | 552.5                | 5.525            | 25                | 0,5000,10000,15000, 20000, 25000 |

### Wind Turbine Size and Cost

Both a single large wind turbine or number of smaller wind turbines can be used to generate a large amount of energy based on the wind speed. during selecting the size of a wind turbines, turbines quantity, service time, hub height, cost of the turbine's component, types of generated electricity and cut-in wind speed are the major criteria to be considered (Moges G. , 2018). Since, in this case the consumers have used AC type load, therefore a turbine which generate AC type electricity has to be chosen. Acciona AW-70/1500 Kw [appendix A-2] AC power rating type to produce 23MW power output is selected in this thesis work. This wind turbine is manufactured by Acciona Energy S.A., Spain. The total installed capital cost is averaged from \$1.7-1.8 Million per MW (Vestas, 2023). The mean installed cost of this turbine is taken about \$1.7 Million/MW, the replacement and operation cost and maintenance cost of this wind turbine is considered about 65% and 2% of capital cost respectively.

TABLE 3. 2. Input parameters of Wind Turbine (IRENA, 2016)

| PV size<br>(Kw) | Capital Cost<br>(\$) | Replacement<br>cost (\$) | O&M cost<br>(\$) | PV<br>Life<br>(year) | Size Considered  |
|-----------------|----------------------|--------------------------|------------------|----------------------|------------------|
| 1500            | 2,065,500            | \$1,342,575.00           | \$413,100.00     | 25                   | 0, 5, 10, 15, 20 |

### Power Converter Size and Cost

A converter is a device which is used to maintain power flow in between AC and DC in a power system component. during selecting a converter size, the rated power of the converter needs to match or exceed the peak load. Moreover, there is no any guide for maintenance

and operating costs of the converter. Thus, in this thesis 0,5000,10000,12500, 15000, 17500 and 20000kW of converter size are considered with a capital cost of \$2,000, replacement cost is about \$1400 which is 70% of the capital cost, efficiency of converter is around 90% and the lifetime of the converter will end for 15 years (Mohammed, Amirat, Benbouzid, & Elbast, 2014). Table 3.3 showed the categorized cost of the converter fed in to the homer pro software.

TABLE 3. 3. Power converter parameters in to Homer

| Converter size (Kw) | Capital Cost (\$) | Replacement cost (\$) | O&M cost (\$) | PV Life (year) | Size Considered      |
|---------------------|-------------------|-----------------------|---------------|----------------|----------------------|
| 500                 | 2,065,500         | \$1,342,575.00        | \$413,100.00  | 25             | 0, 5, 10, 15, 20, 25 |

### 3.2.4. Energy Production Forecast

The main factor influencing the size and cost of the components of a hybrid system is often the electric loads. Thus, determining on the loads is one of the most important steps in the design of the hybrid system (Bekelea & Boneya, 2014). The total load demand of the city was acquired from the EEP SCADA system because the proposed system in this thesis needs to satisfy the city's load demand. HOMER software is used to facilitate the analysis. The software estimated the peak load once the loads were entered on an hourly basis (24-hour data). Additionally, it created a monthly load synthetically from the 24-hour input data. Since power systems are necessary to serve loads, modeling a power system starts with modeling the load or loads. Figures 3.5 and 3.6 illustrated the daily and monthly electricity demand required for Dire Dawa City.

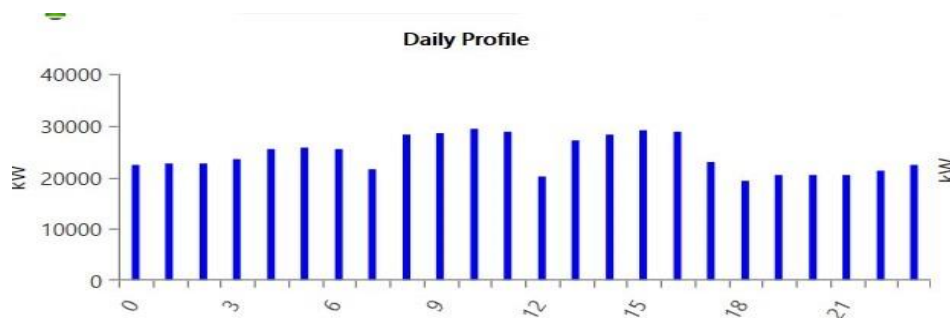


FIGURE 3. 5. Total daily load demand profile of Dire Dawa city

The total daily load demand and daily energy consumption of the city are shown in figure 3.5 that 52.24336 MW and 58.4464 **MWh/day**, respectively.

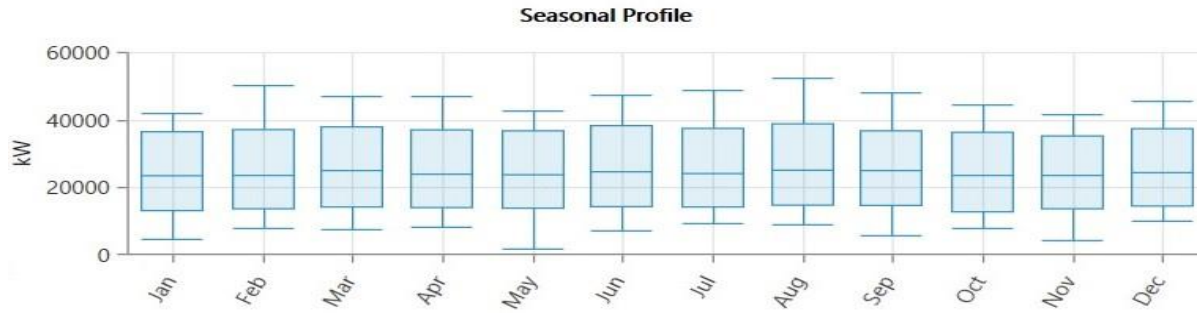


FIGURE 3. 6. Dire Dawa City monthly load profile

Figure 3.6 shows the proposed system's monthly average load profile. Based on the above figure, we saw that August was the month with the highest value, around 52.248 MW. In October, November, and May, the value is approximately 44.5 MW, which is low.

### 3.3. Design of Grid-connected PV System

The PV array and grid-connected inverter stages are two phases of a two-stage grid-connected photovoltaic system, as illustrated in Figure 3.7. Using solar panels, the PV array stage produces direct current (dc) electricity from sunlight. A second stage transforms the dc power into alternating current (ac) so that it may be fed into the electrical grid. This system therefore makes it possible to integrate renewable energy sources efficiently with the existing grid infrastructure.

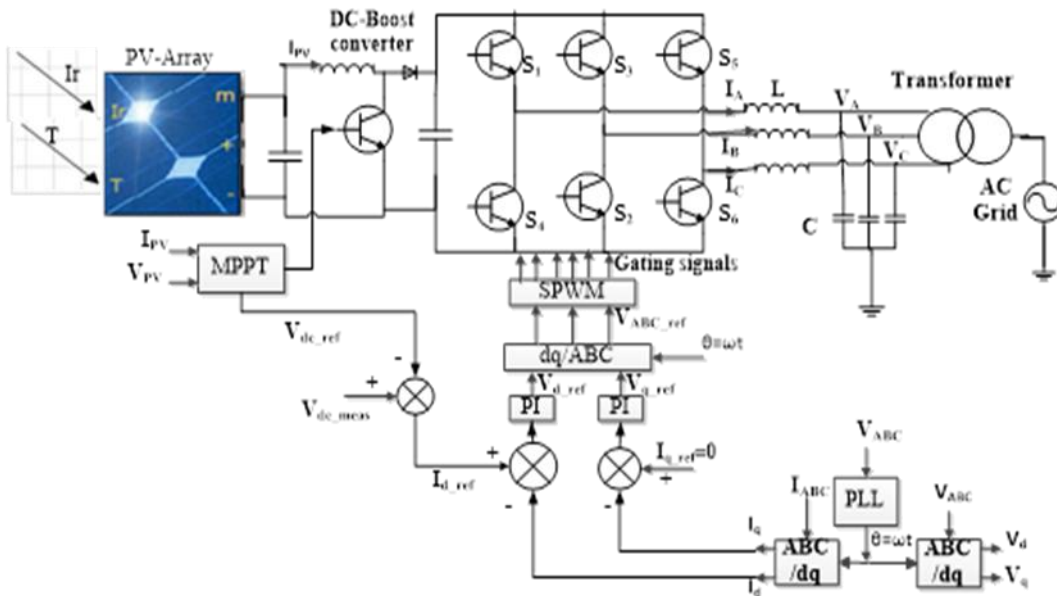


FIGURE 3. 7. Grid-connected conventional PV system (Gebrekidan, 2017)

#### 3.3.1. Sizing of PV Array

The efficiency of the overall renewable energy system and the cost of installation are directly impacted by the choice of PV module. Sunpower SPR-425-WHT-D PV module based on monocrystalline silicon cells is preferred in the design despite having a better efficiency than

polycrystalline silicon cells because of its low cost and availability. This module has an efficiency of 19.66% and consists of 128 cells, with dimension 2067 x 1046 mm (solarreviews, 2020). The number of series-connected PV modules in the PV system must be calculated using the DC link reference voltage. The DC link minimum voltage is determined in a way that (Macit & Vural, 2022)

$$V_{DClink} \geq 2\sqrt{2}V_{phase,RMS} \quad (3.1)$$

For this thesis  $V_{phase,RMS}$  is taken as 220V, therefore

$$V_{DClink} = 2\sqrt{2} \times 220V \cong 622.25V \quad (3.2)$$

In practical terms, the DC link voltage, also known as the DC-DC converter's output reference voltage, is 700V. Considering that each PV module's maximum output voltage  $V_{mp}$  is 72.9 V, as stated by the manufacturer. The PV module number  $N_{ser}$ , which is connected in series, is calculated using the following formula:

$$N_{ser} = \frac{1}{2} \frac{V_{DClink}}{V_{MP}} \cong 5 \text{ modules} \quad (3.3)$$

The maximum power of a series-connected PV string can be computed using the following formula, taking into account the above results:

$$P_{string} = N_{ser} \times P_{mp} = 5 \times 425W = 2125W = 2.125KW \quad (3.4)$$

Where;

$P_{mp}$ : maximum power point

The number of strings connected in parallel is calculated using the rated power of one inverter, as the number of series connected PV modules is known (Dinut, Stefan, Marian, & Popescu, 2016). A 500 Kw 2-level inverter provided by Satcon Technology Corporation was used for this thesis. (sdlsolar, 2010). The required number of strings to operate in parallel is calculated as

$$N_{par} = \frac{P_{inv}}{P_{string}} = 236 \text{ parallels} \quad (3.5)$$

Where;

$P_{inv}$  : the power of one inverter

The solar PV system has a 20MW installed capacity. Thus, the following formula is used to determine the number of PV arrays and inverters:

$$N_{inv} = \frac{P_{plant}}{P_{inv}} = 40 \quad (3.6)$$

Where;

$P_{plant}$ : the installed power capacity of the PV park

Finally, 236 parallel connected PV strings are used in the design of each PV array. Five PV modules are connected in series to make up each string. Consequently, each PV array's necessary area is determined as (Hauke, 2014)

$$A_{array} = \frac{5 * 236 * 0.11675m^2}{0.7} \cong 196.81Hectare \quad (3.7)$$

As seen in Figure 3.8, 40 PV arrays are finally used to reach a 20MW capacity. Since the PV arrays are built as central structure types, each PV array is connected to the grid by means of a single DC-DC converter and an inverter.

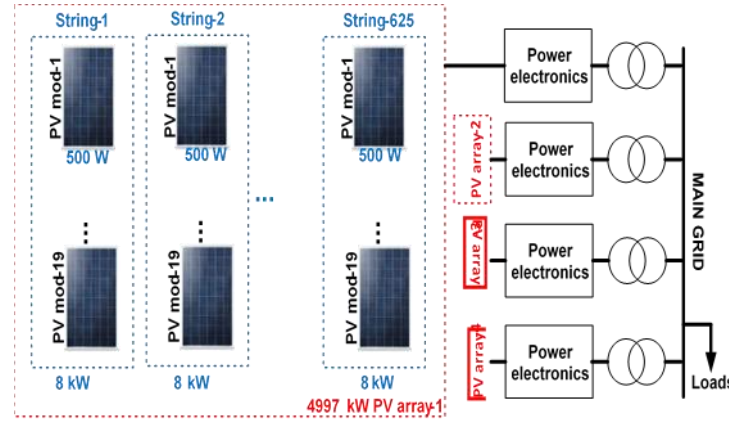


FIGURE 3. 8. 20 MW grid-connected photovoltaic system simplified diagram (Macit & Vural, 2022)

### Modeling of PV Cell

The fundamental component of a photovoltaic generator is a PV cell, which is constructed of the semiconductor material silicon. It uses the photoelectric effect to transform the energy from sunshine into DC power. The PV cell's equivalent circuit is depicted in Figure 3.9.

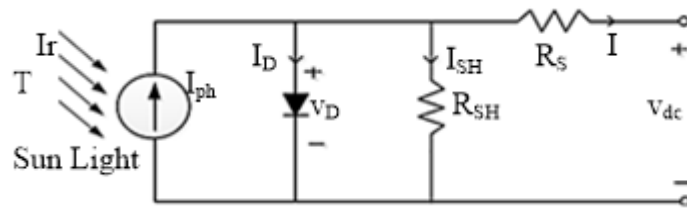


FIGURE 3. 9. PV cell equivalent circuit (Hingorani & Gyugyi, 2010)

Since the source of the PV cell is light energy or photon energy, the module photo-current is given as follows:

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times \frac{I_r}{1000} \quad (3.8)$$

Where;

$I_{ph}$ : photon-current (A)

$I_{sc}$ : short circuit current (A)

$K_i$ : short circuit current of the cell at 25 °C and  $1000W/m^2$

$T$  : operating temperature (K)

$I_r$ : solar irradiance ( $W/m^2$ )

The module reverse saturation current  $I_{rs}$  is given by:

$$I_{rs} = \frac{I_{sc}}{\left[ e^{\left( \frac{qV_{oc}}{N_s K n T} \right) - 1} \right]} \quad (3.9)$$

Where;

$q$ : electron charge, its value is  $1.6 \times 10^{-19} C$

$V_{oc}$ : open circuit voltage (V)

$N_s$  : number of series connected cells

$n$  : the diode ideality factor

$K$  : Boltzmann's constant, its value is  $1.3805 \times 10^{-23} J/K$

The module saturation current which is a function of temperature is expressed as:

$$I_o = I_{rs} \left[ \frac{T}{T_r} \right]^3 e^{\left[ \frac{q \times E_{go}}{nK} \left( \frac{1}{T} - \frac{1}{T_r} \right) \right]} \quad (3.10)$$

Where;

$T_r$  : nominal temperature (K), its value is 298.15 K

$E_{go}$  : band gap energy of semiconductor typically silicon, its value is 1.1eV

The module output current is expressed by:

$$I = N_p \times I_{ph} - N_p \times I_o \times \left[ e^{\left( \frac{V/N_s + I \times R_s/N_p}{n \times V_t} \right) - 1} \right] - I_{sh} \quad (3.11)$$

Where;

$N_p$  : number of parallel connected PV modules

$R_s$  : series resistance ( $\Omega$ )

$R_{sh}$  : shunt resistance ( $\Omega$ )

$I_{sh}$ : shunt current (A)

$V_t$  : diode thermal voltage (V),

$$V_t = \frac{K \times T}{q} \quad (3.12)$$

Shunt current is given by:

$$I_{sh} = \frac{V \times N_p/N_s + I \times R_s}{R_{sh}} \quad (3.13)$$

For this thesis, 500W POWERSYNC module is selected and the datasheet is found in Appendix A-1.

### 3.3.2. DC boost Solar Converter

The PV array voltage level  $V_{pv}$ , has to be raised to make it possible to integrated with the grid. his is accomplished by the DC-DC boost converter, which raises the SPV array's  $V_{pv}$ , and maintains a steady DC link voltage to be fed to the grid side VSI. Figure 3.10 shows the DC boost solar converter's circuit diagram.

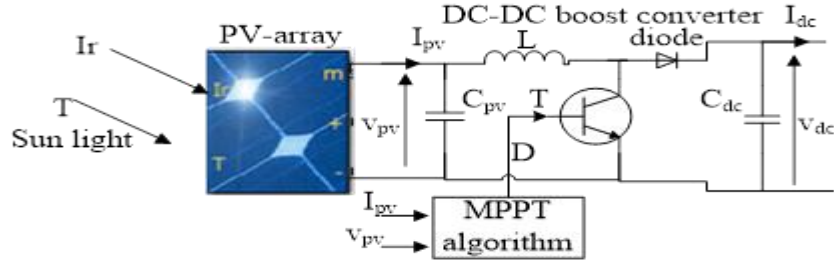


FIGURE 3. 10. DC boost solar converter with MPPT (Gebrekidan, 2017)

The DC boost solar converter's proper design and mathematical modeling reduce the PV system's transient responsiveness and steady-state error. The inductor value of the DC boost solar converter is selected as:

$$L \geq \frac{V_{dc} \times D(1 - D)}{f_s |\Delta L_{ripple}|} \quad (3.14)$$

Where;

$V_{dc}$  : dc-link voltage

The power decoupling capacitor  $C_{pv}$  connected across the PV array is selected as follows:

$$C_{pv} \geq \frac{I_m \times D^2}{0.02(1 - D)f_s V_{pv_{mpp}}} \quad (3.15)$$

The PV system's generated energy is stored by the DC boost converter capacitor, which is placed in parallel with the load.

$$C_{dc} \geq \frac{V_{load} \times D}{f_s \times \Delta V_{load} \times R_{load}} \quad (3.16)$$

### 3.3.3. Maximum Power Point Tracking

In chapter 2, the use and types of MPPT algorithms have been discussed. In this thesis work, the PO with PI controller and FLC MPPT are used.

#### 1. Perturb and Observe with PI controller MPPT

The perturb and observe MPPT is one of the most widely used control methods in PV system. This method mainly monitors the PV module's change in power ( $dP$ ). When this is done,

the PV module voltage sign ( $dV$ ) is also checked in order to modify the duty cycle ( $D$ ) for a future update and correction. A module's power and voltage (P-V) characteristic is typically used to monitor the output power of the module over the duration of its operational point. The algorithm works as follow, the actual point is on the left of the MPP when the gradient  $\left(\frac{dP}{dV}\right)$  is positive, otherwise the point is on the right side of the power curve if there is a negative gradient. This tracking is executed several times until  $\frac{dP}{dV} = 0$ ,

which is the tracked MPP for the PV module. A perturbation's number, also known as the MPPT's frequency, is the total number of perturbations made in one second (Katche, Makokha, Zachary, & Adaramola, 2023).

The general equations for voltage perturbation used by the P&O method are given in equations (3.17) to (3.19) below. The difference is in whether duty cycle control uses variable (adaptive control) or fixed step sizes. Once the PV power  $P(t)$  is measured, it is compared to the maximum power  $P(t - 1)$ ; the difference delta ( $\delta$ ) is then used to create a duty ratio that guide the converter to either raise or lower the voltage by  $\Delta V$ .

$$P(t) == V(t) \times I(t) \quad (3.17)$$

$$\delta = P(t) - P(t - 1) \quad (3.18)$$

$$V(t) = V(t - 1) \pm \Delta V \quad (3.19)$$

Figure 3.11 showed the block diagram of the proposed PO MPPT controllers.

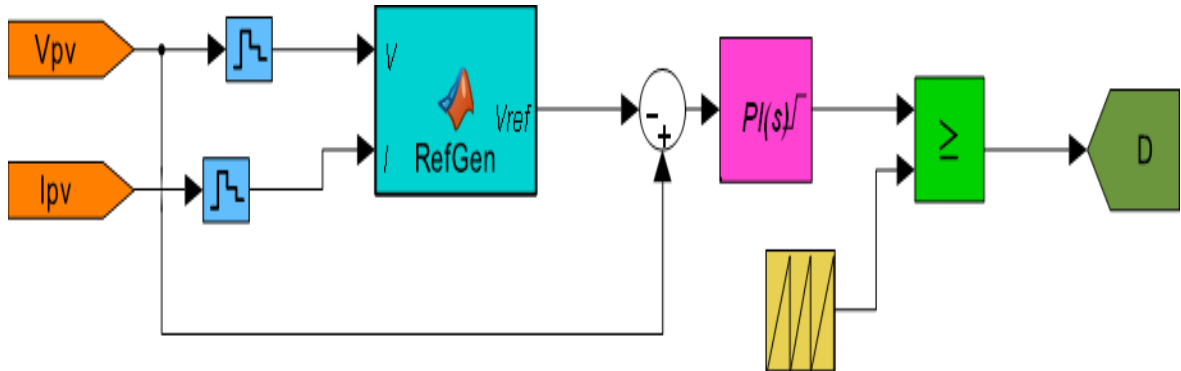


FIGURE 3. 11. Perturb and Observe with the PI controller

## 2. Fuzzy Logic based MPPT

The detailed theory of Fuzzy Logic controller (FLC) was discussed in chapter 2. In this thesis, the Fuzzy Logic Toolbox in Matlab was used to model the controller. The centroid defuzzification method was applied with a Mamdani controller. The fuzzy inference system editor (FIS editor) was used for this process. The Simulink-modeled controller is seen in

Figure 3.12, and in order to obtain the inputs E and CE, a subsystem was created to compute  $\Delta V$  and  $\Delta P$ .

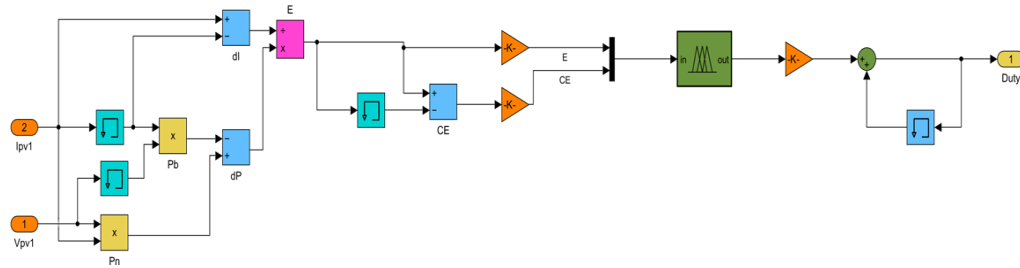


FIGURE 3. 12. Simulink model of FLC

The three stages of the FLC controller are presented in Figure 3.13, a detailed explanation of each stage is found in Chapter 2.

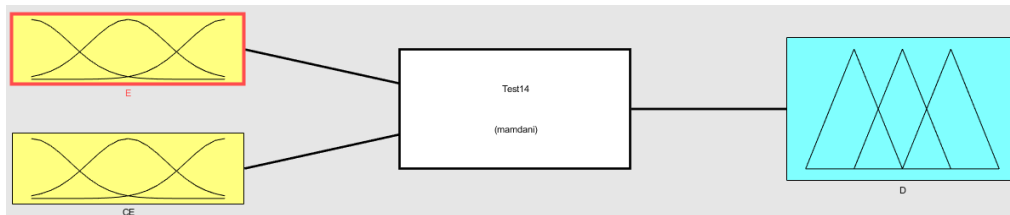


FIGURE 3. 13. Structure of FLC

Fuzzification was performed using triangular membership functions. The linguistic variables listed below were used to define five membership functions for the inputs E, CE, and output D: NB stands for Negative Big, NS for Negative Small, ZE for Zero, PS for Positive Small, and PB Positive Big. The range for error is (-0.07 to 0.07), for the change of error is (-100 to 100) and for the increment in duty cycle is (-0.06 to 0.06). Figure 3.14- Figure 3.16 illustrates the controller membership functions for the inputs (E and CE) and output (D) respectively.

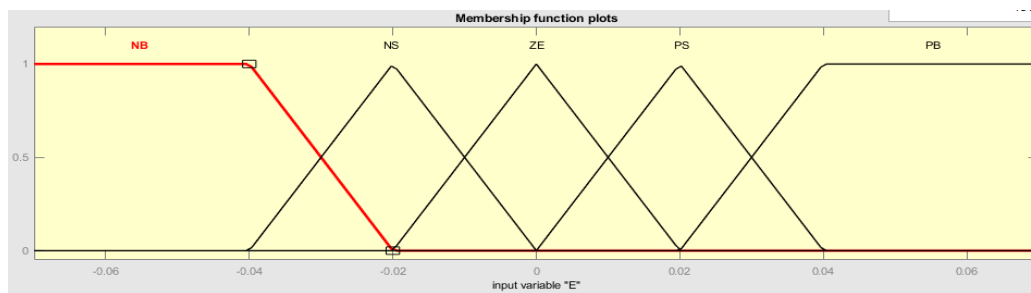


FIGURE 3. 14. The first input variable (E)

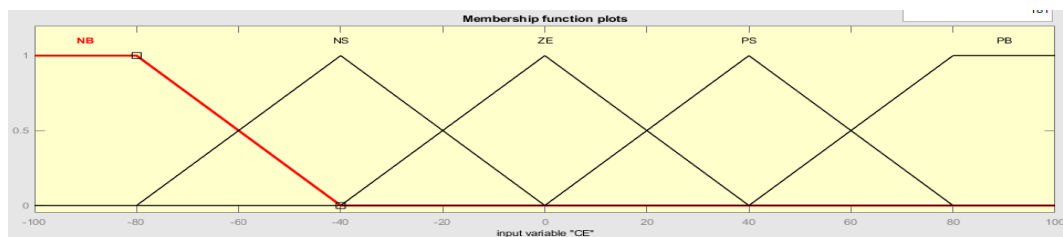


FIGURE 3. 15. The second input variable (CE)

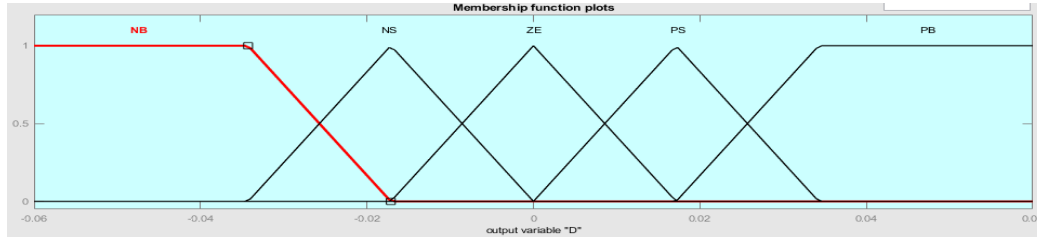


FIGURE 3. 16. The output variable (D)

The 25 fuzzy rules employed by the controller are shown in Table 3.4. The two inputs, E and CE, are denoted by the rows and columns. The controller output placed at the intersection of row with column is a variable.

TABLE 3. 4. Associative fuzzy matrix

| E              | Negative Big | Negative Small | Zero | Positive Small | Positive Big |
|----------------|--------------|----------------|------|----------------|--------------|
| CE             | Big          | Small          |      | Smal           |              |
| Negative Big   | ZE           | ZE             | NB   | NB             | NB           |
| Negative Small | ZE           | ZE             | NS   | NS             | NS           |
| Zero           | NS           | ZE             | ZE   | ZE             | PS           |
| Positive Small | PS           | PS             | PS   | ZE             | ZE           |
| Positive Big   | PB           | PB             | PB   | ZE             | ZE           |

### 3.3.4. Three-Phase Voltage Source Inverter

VSI is an essential element for renewable energy in order to convert dc voltage in to ac and synchronize with the grid. Figure 3.17 depicts the three-phase grid connected VSC power circuit.

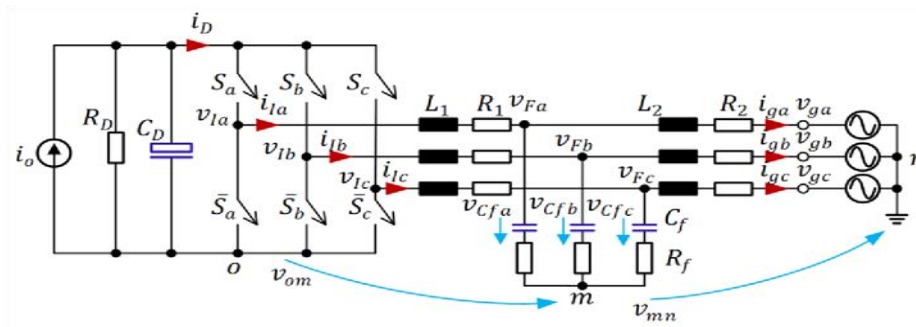


FIGURE 3. 17. Three-phase grid-connected VSC with LCL filter equivalent circuit

The grid currents  $i_{ga}$ ,  $i_{gb}$ , and  $i_{gc}$  can be written as follows

$$\left. \begin{aligned} L_2 \frac{di_{ga}}{dt} &= (v_{Fa,m} + v_{mn}) - v_{ga,n} - R_2 i_{ga} \\ L_2 \frac{di_{gb}}{dt} &= (v_{Fb,m} + v_{mn}) - v_{gb,n} - R_2 i_{gb} \\ L_2 \frac{di_{gc}}{dt} &= (v_{Fc,m} + v_{mn}) - v_{gc,n} - R_2 i_{gc} \end{aligned} \right\} \quad (3.20)$$

where  $v_{Fa,m}$ ,  $v_{Fb,m}$ , and  $v_{Fc,m}$  are the voltages across the filter capacitor  $C_f$  and the series resistor  $R_f$  with respect to point m, which are given by:

$$\left. \begin{aligned} v_{Fa,m} &= v_{cfa} + R_f(i_{ga} - i_{la}) \\ v_{Fb,m} &= v_{cfb} + R_f(i_{gb} - i_{lb}) \\ v_{Fc,m} &= v_{cfc} + R_f(i_{gc} - i_{lc}) \end{aligned} \right\} \quad (3.21)$$

The voltages across the filter capacitor  $C_f$ ,  $v_{cfa}$ ,  $v_{cfb}$ , and  $v_{cfc}$  are determined from

$$\left. \begin{aligned} C_f \frac{dv_{cfa}}{dt} &= i_{ga} - i_{la} \\ C_f \frac{dv_{cfb}}{dt} &= i_{gb} - i_{lb} \\ C_f \frac{dv_{cfc}}{dt} &= i_{gc} - i_{lc} \end{aligned} \right\} \quad (3.22)$$

The VSC currents  $i_{la}$ ,  $i_{lb}$ , and  $i_{lc}$  are given by

$$\left. \begin{aligned} L_1 \frac{di_{la}}{dt} &= (v_{la,o} + v_{om}) - v_{Fa,m} - R_1 i_{la} \\ L_1 \frac{di_{lb}}{dt} &= (v_{lb,o} + v_{om}) - v_{Fb,m} - R_1 i_{lb} \\ L_1 \frac{di_{lc}}{dt} &= (v_{lc,o} + v_{om}) - v_{Fc,m} - R_1 i_{lc} \end{aligned} \right\} \quad (3.23)$$

where the VSC voltages  $v_{la,o}$ ,  $v_{lb,o}$ , and  $v_{lc,o}$  with respect to point o depends on the switching states as following

$$\left. \begin{aligned} v_{la,o} &= S_a V_D \\ v_{lb,o} &= S_b V_D \\ v_{lc,o} &= S_c V_D \end{aligned} \right\} \quad (3.24)$$

For the balanced three-phase three-wire system,  $v_{ga,n} + v_{gb,n} + v_{gc,n} = 0$ ,  $v_{Fa,m} + v_{Fb,m} + v_{Fc,m} = 0$ ,  $i_{ga} + i_{gb} + i_{gc} = 0$  and  $i_{la} + i_{lb} + i_{lc} = 0$ , which results in  $v_{mn} = 0$

Thus, the grid currents can be written as follows

$$\left. \begin{aligned} L_2 \frac{di_{ga}}{dt} &= v_{Fa,m} + v_{ga,n} - R_2 i_{ga} \\ L_2 \frac{di_{gb}}{dt} &= v_{Fb,m} + v_{gb,n} - R_2 i_{gb} \\ L_2 \frac{di_{gc}}{dt} &= v_{Fc,m} + v_{gc,n} - R_2 i_{gc} \end{aligned} \right\} \quad (3.25)$$

Adding the sub-equations of (3.23) together, the common mode voltage  $v_{om}$  is expressed as

$$v_{om} = \frac{-V_D}{3} (S_a + S_b + S_c) \quad (3.26)$$

This common-mode voltage  $v_{om}$  intrinsically exists in the two-level VSC due to limited switching states, which creates a leakage current through the parasitic capacitance between the DC bus and the neutral points of the system. The VSC currents  $i_{la}$ ,  $i_{lb}$ , and  $i_{lc}$  are driven by the differential mode voltages  $v_{la,m}$ ,  $v_{lb,m}$ , and  $v_{lc,m}$  between the VSC legs and the neutral point m of the capacitor bank, which can be written as

$$\left. \begin{aligned} L_1 \frac{di_{la}}{dt} &= V_D (2S_a - S_b - S_c)/3 + v_{Fa,m} - R_1 i_{la} \\ L_1 \frac{di_{lb}}{dt} &= V_D (2S_b - S_a - S_c)/3 + v_{Fb,m} - R_1 i_{lb} \\ L_1 \frac{di_{lc}}{dt} &= V_D (2S_c - S_a - S_b)/3 + v_{Fc,m} - R_1 i_{lc} \end{aligned} \right\} \quad (3.27)$$

The VSC DC current  $i_D$  is written as

$$i_D = i_{la} S_a + i_{lb} S_b + i_{lc} S_c \quad (3.28)$$

If the DC bus is connected to another converter buffered by the DC bus capacitor  $C_D$ , the DC bus voltage  $V_D$  is then modeled as

$$C_D \frac{dV_D}{dt} = i_o - i_D - \frac{V_D}{R_D} \quad (3.29)$$

### 3.3.5. LCL Filter

Due to its higher attenuating capability as compared to other filter types, LCL filter is most commonly used in VSIs (Yu, Li., Zhenwei, & Zhao, 2017). Figure 3.18 illustrated the per phase LCL filter circuit diagram.

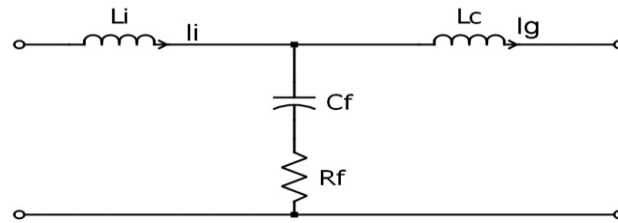


FIGURE 3. 18. The per-phase LCL filter circuit diagram (Meghni, Chojaa, & Boulmaiz, 2020)

The design of LCL filters must take into account a number of crucial factors, including switching ripple attenuation, filter size, and current ripple. The LCL filter's the design procedure is given as follows:

Step 1: - Equations (3.30) and (3.31) describes the value of the base impedance and capacitance. As a result, the percentage of the base values will be used to express the filter values

$$Z_b = \frac{V_{LL}^2}{P_n} \quad (3.30)$$

$$C_b = \frac{1}{\omega_n Z_b} \quad (3.31)$$

When the system's base impedance value is multiplied by the filter capacitance design, the maximum power factor variation observed by the grid is 5%:  $C_f = 0.05C_b$ . It is important to remember that factors more than 5% can be used, as they will compensate for the inductive reactance of the inductors on the filter, reducing the influence at the system power factor. The DC/AC inverter's output has a maximum current ripple which is expressed as:

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_i} (1 - m)mT_s \quad (3.32)$$

When  $m = 0.5$ , the maximum peak to peak current ripple is observed. After that:

$$\Delta I_{Lmax} = \frac{V_{DC}}{6f_{sw}L_i} \quad (3.33)$$

where the inverter side inductor is represented by  $L_i$ . For the specified design characteristics, a 10% ripple in the rated current can be obtained by:

$$I_{Lmax} = 0.1I_{max} \quad (3.34)$$

$$i_{max} = \frac{P_n \sqrt{3}}{3V_{ph}} \quad (3.35)$$

$$L_i = \frac{V_{DC}}{6f_{sw}\Delta I_{Lmax}} \quad (3.36)$$

Thus, the primary goal of the LCL filter design is to minimize the expected 10% current ripple limit to 20% of its own value, which will yield a ripple value of 2% of the output current. Equations (3.37) and (3.38) describe the relationship between the inverter's harmonic current and the once that is injected into the grid:

$$\frac{i_g(h)}{i_i(h)} = \frac{1}{[1 + r[1 - L_i C_b \omega_{sw}^2 X]]} = k_a \quad (3.37)$$

$$L_g = \frac{\sqrt{\frac{1}{k_a}} + 1}{C_f \omega_{sw}^2} \quad (3.38)$$

Where;  $k_a$ : is the desired attenuation factor

The filter capacitor  $C_f$  is given by

$$C_f = \frac{0.01}{0.05C_b} \quad (3.39)$$

The constant  $r$  is the relationship between the inductance at the grid side and the inverter side.

$$L_g = rL_i \quad (3.40)$$

Plotting for various values of  $r$  can assist in assessing the filter's transfer function at a specific resonance frequency that is dependent on the nominal grid impedance. To prevent resonance, some of the switching frequency ripple is attenuated by a resistor that is linked in series  $R_f$  with the capacitor is determined by Equations (3.43). At the resonance frequency, its value should be equal one-third of the filter capacitor's impedance.

$$\omega_{res} = \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \quad (3.41)$$

$$10f_g < f_{res} < 0.5f_{sw} \quad (3.42)$$

Resonant frequency needs to be checked in order to satisfy Equation (3.42). The parameters need to be selected again if it doesn't satisfy.

$$R_f = \frac{1}{3\omega_{res}C_f} \quad (3.43)$$

Figure 3.19 illustrates how the damping resistor affects the LCL-filter's transfer function.

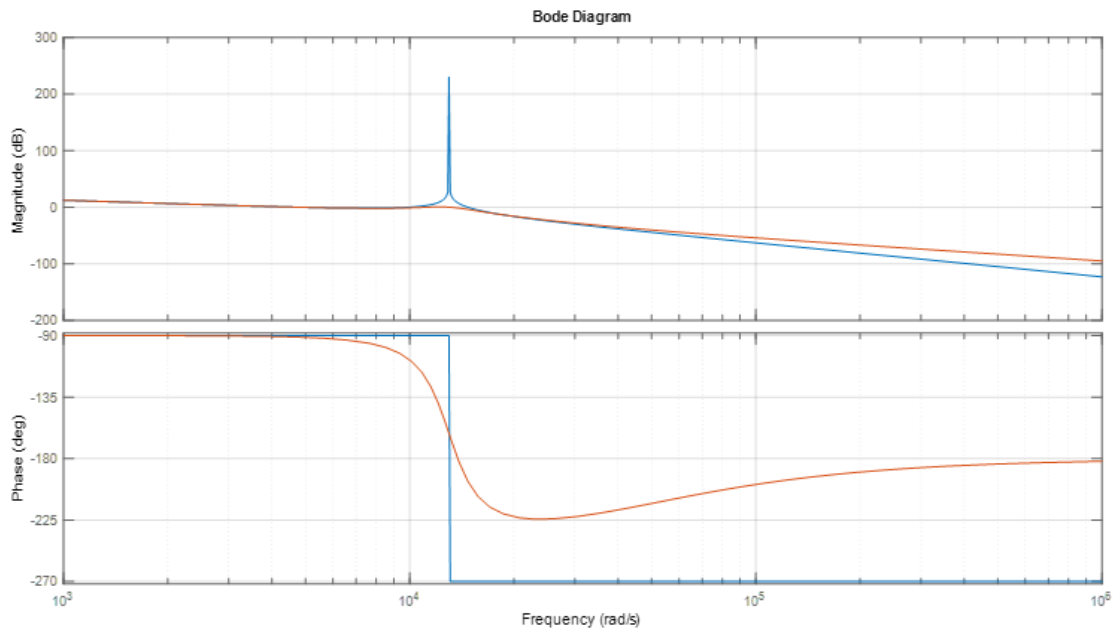


FIGURE 3. 19. LCL filter with and without damping Bode Plot

As shown in figure 3.19, the transfer function of the filter's bode plot without the damping resistor and the damping resistor's effectiveness in keeping the filter's resonance frequency from occurring.

### 3.3.6. Phase Locked Loop

Typically, A PLL that can precisely track the phase of the connected grid is used to operate GTIs. The calculated phase angle is then used by the controller to create synchronous reference signals that can be used for PWM. In this thesis, synchronous reference frame or synchronous phase locked loop has been used. In order to eliminate the steady state inaccuracy and identify the phase angle, the three phase abc voltage values are transformed into the synchronously rotating reference frame. The quadrature component of the transformed synchronously rotating reference frame (dq) voltage is then driven to zero using a typical PI controller. This component of the PLL structure is frequently referred to as the loop filter. Figure 3.20 is an illustration of the suggested PLL technique's construction.

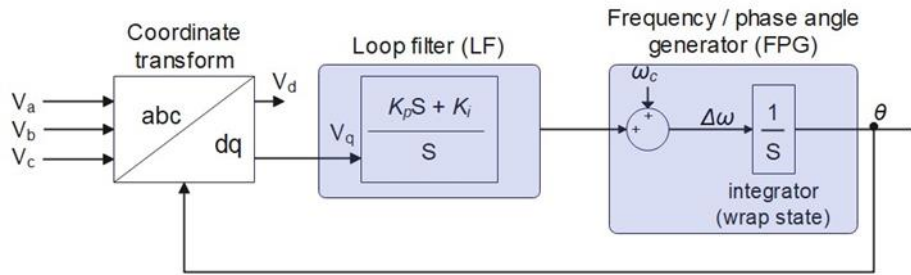


FIGURE 3. 20. Topology of the Phase Locked Loop – PLL (Gao & Barnes, 2016)

PLL topology's TF allows for the tuning of the PI controllers' proportional ( $k_p$ ) and integral ( $k_i$ ) components. By employing a general PI controller's TF, we can derive the closed loop TF as illustrated in

$$G_{OL} = \frac{V_{grid}(k_p s + k_i)}{s^2} \quad (3.44)$$

$$G_{CL}(s) = \frac{G_{OL}}{1 + G_{OL}} = \frac{V_{grid}(k_p s + k_i)}{s^2 + V_{grid}k_p s + V_{grid}k_i} \quad (3.45)$$

Then, compare equation (3.45) with a second order system TF:

$$G_{CL}(s) = \frac{V_{grid}(k_p s + k_i)}{s^2 + V_{grid}k_p s + V_{grid}k_i} = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (3.46)$$

Where;

k: the system gain

$\omega_n$ : natural frequency, and

$\zeta$ : the damping ratio

Equation (3.47) and (3.48) is used to find the natural frequency and damping ratio:

$$\omega_n \sqrt{V_{grid} k_i} \quad (3.47)$$

$$\zeta = \frac{k_p V_{grid}}{2\sqrt{V_{grid} k_i}} \quad (3.48)$$

### 3.3.7. Voltage Oriented Control

In this section, three-phase GTIs with VOC are introduced. The VOC structure is made up of two components: the inner Current Control Loop (CCL) and the outside Voltage Control Loop (VCL). This is a common technique control similar to the cascaded control loops typically seen in motor control structures. An illustration of a three-phase inverter with an LCL filter and a VOC strategy is shown in Figure 3.21 (Habbach, 2022). In this control strategy, a clark and park transformation has been used to transform the grid voltages ( $V_{ga}, V_{gb}, V_{gc}$ ) and grid currents ( $i_a, i_b, i_c$ ) in to dc values. The grid's nominal frequency is 50 Hz, and to determine the precise angular position  $\theta$ , a PLL block has been implemented.

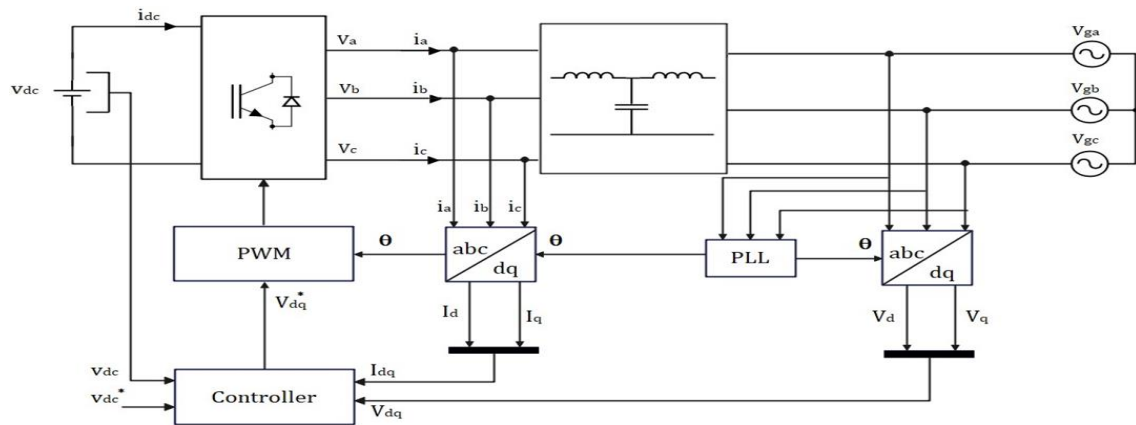


FIGURE 3. 21. VOC structure with LCL filter (Habbach, 2022)

The VCL computes the difference between the measured DC link voltage  $V_{dc}$  and the desired DC-link voltage  $V_{dc}^*$  then generates an error. This error is reduced to zero by using a PI controller, and the output will have the desired d-axis current component. The CCL uses decoupled feedback control to control the currents in the synchronous rotating dq reference frame.

$$L_i \frac{dI_{i,d}}{dt} = V_{id} - V_{cfd} - (R_i + R_d)I_{id} + L_i \omega I_{iq} + R_d I_{gd} \quad (3.49)$$

$$L_g \frac{dI_{g,d}}{dt} = V_{cfd} - V_{gd} - (R_g + R_d)I_{gd} + L_i \omega I_{gq} + R_d I_{id} \quad (3.50)$$

$$C_f \frac{dV_{cfd}}{dt} = I_{id} - I_{gd} + \omega C_f V_{cfq} \quad (3.51)$$

$$L_i \frac{dI_{i,q}}{dt} = V_{iq} - V_{cfq} - (R_i + R_d)I_{iq} - L_i \omega I_{id} + R_d I_{gq} \quad (3.52)$$

$$L_g \frac{dI_{g,d}}{dt} = V_{cfq} - V_{gq} - (R_g + R_d)I_{gq} - L_i \omega I_{gd} + R_d I_{iq} \quad (3.53)$$

$$C_f \frac{dV_{cfq}}{dt} = I_{iq} - I_{gq} - \omega C_f V_{cfd} \quad (3.54)$$

However, by using decoupled components in the current control loop, there is more simplicity in these equations that would enable a feed forward compensation strategy. In addition to balancing the cross-coupling components, the feed forward will allow for independent control of the d- and q-axis components. The synchronous reference frame implementation of a feed forward compensated current controller is shown in Figure 3.22.

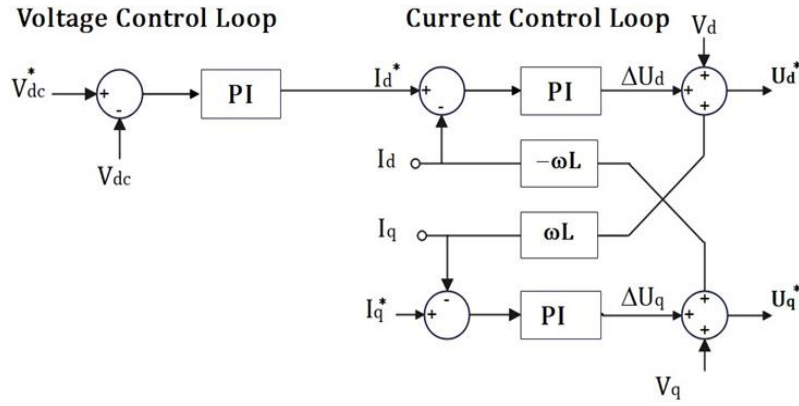


FIGURE 3. 22. Voltage and Current control loop (Habbach, 2022)

By neglecting the LCL-filter capacitor  $C_f$ , the mathematical description of the VOC scheme depicted in figure 3.22 is derived. Moreover, internal resistances of the inductors are neglected since the voltage drop is significantly less than that of the inductors, and the inductor denoted  $L$  is simply the sum of the LCL-filter inductors  $L_i$  and  $L_g$

$$\begin{cases} V_{ga} = L \frac{di_a}{dt} + V_a \\ V_{gb} = L \frac{di_b}{dt} + V_b \\ V_{gc} = L \frac{di_c}{dt} + V_c \end{cases} \quad (3.55)$$

Equation (3.56) and (3.57) expresses the decoupled control equations as shown in figure 3.22.

$$U_d^* = L \frac{di_{Ld}}{dt} - \omega L_{iLq} + v_d \quad (3.56)$$

$$U_q^* = L \frac{di_{Lq}}{dt} + \omega L_{iLd} + v_q \quad (3.57)$$

The active and reactive power is computed by using the dq frame volage and current components.

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \quad (3.58)$$

$$Q = \frac{3}{2}(v_q i_d - v_d i_q) \quad (3.59)$$

In order to achieve UPF, the quadrature reference current components  $I_q$  must be zero. Thus, it is possible to simplify the active and reactive power in to equations (3.60)

$$\begin{cases} P = \frac{3}{2} v_d i_d \\ Q = \frac{3}{2} v_q i_d \end{cases} \quad \text{given that: } i_q = 0 \quad (3.60)$$

### 3.4. Modelling of Grid Connected DFIG based WECS

The mathematical model of 1.5MW grid connected WECS based on DFIG has been discussed in this section. A wind turbine, DFIG, rotor-side and grid-side filters, an MPPT controller, a DC-link capacitor, and two consecutive three-phase pulse width modulated (PWM) voltage source converters (VSCs) with their respective controllers make up the system (Chhipa, et al., 2021). Electrical power is supplied to the DFIG from both the stator and rotor sides. The rotor windings are connected to the electrical grid through a back-to-back voltage source converter using slip rings, while the stator windings are directly connected to the grid. Furthermore, as seen in figure 3.23, the RSC controller is controlled by an MPPT controller.

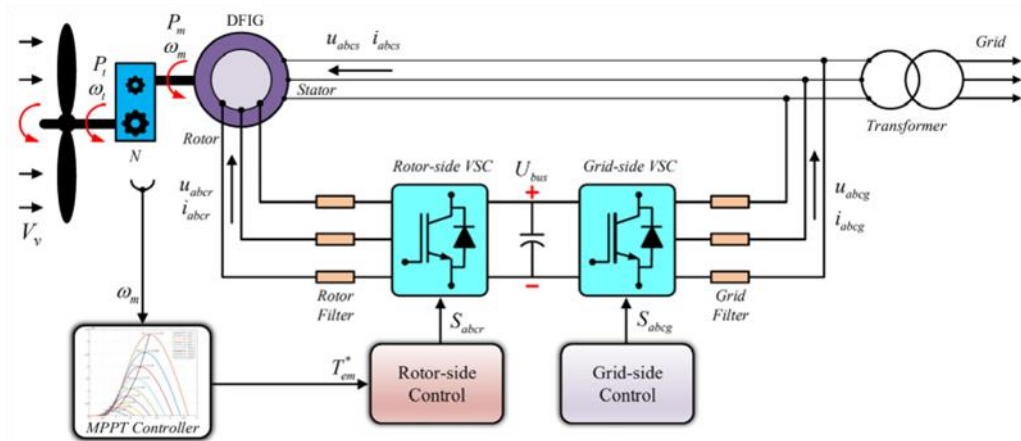


FIGURE 3. 23. Configuration of DFIG-based grid-connected WECS (Chhipa, et al., 2021)

#### 3.4.1. Wind Turbine

The wind's kinetic energy is transformed by the wind turbine into rotational energy in the form of torque. The power available in the wind is given by Equation (3.61);

$$P_v = \frac{1}{2} \rho A_1 V_v^3 \quad (3.61)$$

Where;

$A_1$ : Turbine blade swept area ( $m^2$ )

$\rho$ : Density of air ( $Kg/m^3$ )

$(V_v)$ : Wind speed ( $m/s$ )

The power that the turbine extracts from the wind's available power is given by Equation (3.62):

$$P_t = \frac{1}{2} \rho \pi R^2 V_v^3 C_p(\lambda, \beta) \quad (3.62)$$

Where;

$R$ : Turbine rotor radius ( $m$ )

$C_p(\lambda, \beta)$ : Wind turbine power coefficient

The coefficient  $C_p$  depends on the pitch angle ( $\beta$ ) and tip speed ratio ( $\lambda$ ). A theoretical maximum value of 0.59 is assigned to  $C_p$  by Betz limit. With current technology, a modern wind turbine's power coefficient typically varies between 0.2 and 0.5 depending on its rotational speed and number of blades. At 12  $m/s$  wind speed and 1.225  $Kg/m^3$  air density, the captured power of a three-blade turbine with a rotor diameter of 82 m and a power coefficient of  $C_p = 0.36$  is 1.5 MW (Wu, Lang, Zargari, & Kouro, 2011).

$C_p(\lambda, \beta)$  is expressed by Equation (3.63) and Equation (3.64):

$$C_p(\lambda, \beta) = 0.73 \left( \frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.4} - 13.2 \right) e^{\frac{-18.4}{\lambda_i}} \quad (3.63)$$

$$\lambda_i = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \quad (3.64)$$

With the tip speed ratio

$$\lambda = \frac{R\omega_t}{V_v} \quad (3.65)$$

The torque developed by the turbine can be expressed by Equation (3.66):

$$T_t = \frac{P_t}{\omega_t} \quad (3.66)$$

$\omega_t$ : wind turbine rotor angular rotational speed

### 3.4.2. MPPT

In order to maximize the power extracted from the wind turbine, WECS uses MPPT control. Since the wind speed has a significant impact on the power output of wind turbines, variations in wind speed also affect the turbine's operating points. Under varying wind

conditions, the MPPT algorithm continuously adjusts the wind turbine's rotor speed and the control parameters of the rotor-side converter to ensure that the turbine operates at its maximum power point (MPP). This means that while the turbine is operating on the maximum power point, the VSWT naturally returns to its operating point for any variations in rotational speed around that point in the maximum power curve.

$$\lambda_{opt} = \frac{R\omega_t}{V_v}, \quad C_p = C_{p\_max}, \quad \text{and} \quad C_t = C_{t\_max}$$

The turbine's extracted aerodynamic torque at maximum power is then given by (Chhipa, et al., 2021)

$$T_t = \frac{1}{2} \rho \pi \frac{R^5 \omega_t^2}{\lambda_{opt}^2} C_{t\_max} = K_{opt_t} \omega_t^2 \quad (3.67)$$

$$K_{opt} = \frac{1}{2} \rho \pi \frac{R^5}{\lambda_{opt}^2} C_{t\_max} \quad (3.68)$$

### 3.4.3. DFIG

The most popular kind of generator for wind energy applications is the double-fed induction generator because of its low power loss power converters, greater wind energy capturing capabilities, and excellent four-quadrant active and reactive power regulation (Okedu, 2020). Different reference frames, such as the synchronous frame oriented to either stator voltage or flux, the stationary frame, or the rotor frame, can be used to characterize DFIG (Obaid & Amer, 2016). Figure 3.24 shows, the simplified model of DFIG which is represented by three windings in the rotor and three in the stator.

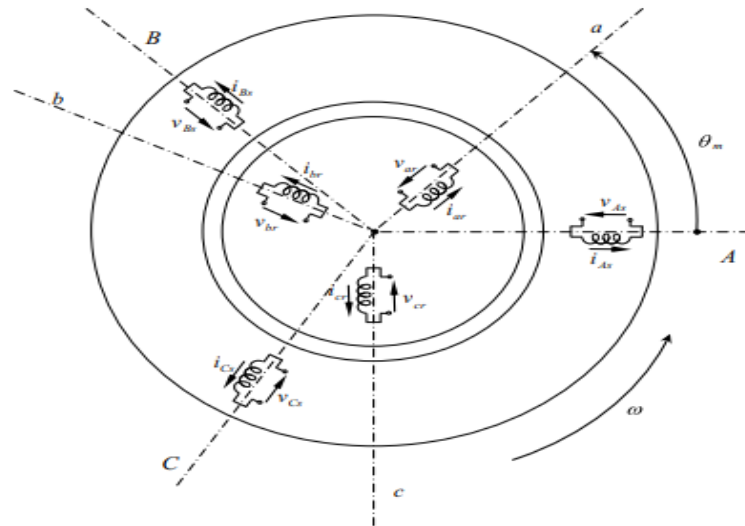


FIGURE 3. 24. DFIM's ideal three-phase windings (rotor and stator) (Abad, Lopez, Rodríguez, Marroyo, & Iwanski, 2011)

The instantaneous stator voltages, currents and fluxes are described as follows:

$$\begin{cases} v_{as}(t) = R_s i_{as}(t) + \frac{d\psi_{as}(t)}{dt} \\ v_{bs}(t) = R_s i_{bs}(t) + \frac{d\psi_{bs}(t)}{dt} \\ v_{cs}(t) = R_s i_{cs}(t) + \frac{d\psi_{cs}(t)}{dt} \end{cases} \quad (3.69)$$

Where;

$R_s$  is the stator resistance

$v_{as}(t)$ ,  $v_{bs}(t)$  and  $v_{cs}(t)$  are the applied stator voltages

$i_{as}(t)$ ,  $i_{bs}(t)$  and  $i_{cs}(t)$  are the stator currents of phase a, b and c

$\psi_{as}(t)$ ,  $\psi_{bs}(t)$  and  $\psi_{cs}(t)$  are the stator fluxes

Similarly, the instantaneous rotor voltages, currents and fluxes are expressed by the following equations:

$$\begin{cases} v_{ar}(t) = R_r i_{ar}(t) + \frac{d\psi_{ar}(t)}{dt} \\ v_{br}(t) = R_r i_{br}(t) + \frac{d\psi_{br}(t)}{dt} \\ v_{cr}(t) = R_r i_{cr}(t) + \frac{d\psi_{cr}(t)}{dt} \end{cases} \quad (3.70)$$

Where;

$R_r$  is the rotor resistance referred to stator

$v_{ar}(t)$ ,  $v_{br}(t)$  and  $v_{cr}(t)$  are the stator referred to rotor voltages

$i_{as}(t)$ ,  $i_{bs}(t)$  and  $i_{cs}(t)$  are the stator referred to rotor currents of phase a, b and c

$\psi_{as}(t)$ ,  $\psi_{bs}(t)$  and  $\psi_{cs}(t)$  are the stator fluxes

In DFIM both the rotor and stator voltages and currents have different frequencies, thus equation 3.71 relates  $\omega_s$  (frequency of stator voltages and currents),  $\omega_r$  (frequency of rotor voltages and currents) and  $\omega_m$  (rotor electrical speed)

$$\omega_s = \omega_r + \omega_m \quad (3.71)$$

The slip  $s$  which is the most commonly used term to relate the stator and the rotor angular frequency is given by equation 3.72

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{\omega_r}{\omega_s} \quad (3.72)$$

In stationary ( $\alpha\beta$ ) reference frame, the stator voltage and magnetic flux equations of the DFIG can be expressed as

$$v_{\alpha s} = R_s i_{\alpha s} + \frac{d\lambda_{\alpha s}}{dt} \quad (3.73)$$

$$v_{\beta s} = R_s i_{\beta s} + \frac{d\lambda_{\beta s}}{dt} \quad (3.74)$$

Where:

$\lambda_{\alpha s}$  and  $\lambda_{\beta s}$  are the stator flux linkages in  $(\alpha\beta)$  reference frame and expressed in equation (4.75) and (4.76) respectively:

$$\lambda_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha r} e^{j\theta_r} \quad (3.75)$$

$$\lambda_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r} e^{j\theta_r} \quad (3.76)$$

Similarly, the rotor voltage and magnetic flux equations of the DFIG in stationary  $(\alpha\beta)$  reference frame can be given as

$$v_{\alpha r} = R_r i_{\alpha r} + \omega_r \psi_{\beta r} + \frac{d\psi_{\alpha r}}{dt} \quad (3.77)$$

$$v_{\beta r} = R_r i_{\beta r} - \omega_r \psi_{\alpha r} + \frac{d\psi_{\beta r}}{dt} \quad (3.78)$$

Similarly, the rotor flux linkages in  $(\alpha\beta)$  reference frame is expressed by

$$\lambda_{\alpha r} = L_m i_{\alpha s} + L_r i_{\alpha r} e^{j\theta_r} \quad (3.79)$$

$$\lambda_{\beta r} = L_m i_{\beta s} + L_r i_{\beta r} e^{j\theta_r} \quad (4.80)$$

The stator and rotor active and reactive power are expressed by equation (3.81) to (3.84)

$$P_s = \frac{3}{2} \text{Re}(\bar{v}_s \bar{i}_s^*) = \frac{3}{2} (v_{\alpha s} i_{\alpha s} + v_{\beta s} i_{\beta s}) \quad (3.81)$$

$$P_r = \frac{3}{2} \text{Re}(\bar{v}_r \bar{i}_r^*) = \frac{3}{2} (v_{\alpha r} i_{\alpha r} + v_{\beta r} i_{\beta r}) \quad (3.82)$$

$$Q_s = \frac{3}{2} \text{Im}(\bar{v}_s \bar{i}_s^*) = \frac{3}{2} (v_{\beta s} i_{\alpha s} - v_{\alpha s} i_{\beta s}) \quad (3.83)$$

$$Q_r = \frac{3}{2} \text{Im}(\bar{v}_r \bar{i}_r^*) = \frac{3}{2} (v_{\beta r} i_{\alpha r} - v_{\alpha r} i_{\beta r}) \quad (3.84)$$

The electromagnetic torque in  $(\alpha\beta)$  reference frame is given by

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_r L_s} \text{Im}(\bar{\psi}_r^* \bar{\psi}_s) = \frac{3}{2} L_m p \text{Im}(\bar{i}_s \bar{i}_r^*) \quad (3.85)$$

In synchronously (dq) rotating reference frame, the voltage vectors of the stator and rotor are expressed as follows:

$$\vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_s \vec{\psi}_s \Rightarrow \begin{cases} v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \end{cases} \quad (3.86)$$

$$\vec{v}_r = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} + j\omega_r \vec{\psi}_r \Rightarrow \begin{cases} v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} \end{cases} \quad (3.87)$$

The direct axis and quadrature axis stator and rotor voltage are expressed by

Where:

$\omega_e$ : the synchronous angular speed

$\omega_r$  : the rotor angular speed

The flux vectors for the stator and rotor in (dq) reference frame is given by equation (3.88) – (3.89)

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \Rightarrow \begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases} \quad (3.88)$$

$$\vec{\psi}_r = L_m \vec{i}_s + L_r \vec{i}_r \Rightarrow \begin{cases} \psi_{dr} = L_m i_{ds} + L_r i_{dr} \\ \psi_{qr} = L_m i_{qs} + L_r i_{qr} \end{cases} \quad (3.89)$$

The stator and rotor active and reactive power are expressed by equation (3.90) to (3.93)

$$P_s = \frac{3}{2} \text{Re}(\bar{v}_s \vec{i}_s^*) = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (3.90)$$

$$P_r = \frac{3}{2} \text{Re}(\bar{v}_r \vec{i}_r^*) = \frac{3}{2} (v_{dr} i_{dr} + v_{qr} i_{qr}) \quad (3.91)$$

$$Q_s = \frac{3}{2} \text{Im}(\bar{v}_s \vec{i}_s^*) = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (3.92)$$

$$Q_r = \frac{3}{2} \text{Im}(\bar{v}_r \vec{i}_r^*) = \frac{3}{2} (v_{qr} i_{dr} - v_{dr} i_{qr}) \quad (3.93)$$

The electromagnetic torque in (dq) reference frame is given by

$$T_e = \frac{3}{2} p \frac{L_m}{L_s} \text{Im}(\bar{\psi}_s \vec{i}_r^*) = \frac{3}{2} p \frac{L_m}{L_s} (\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \quad (3.94)$$

#### 3.4.4. Vector Control for WECS

In this thesis, vector control strategy in synchronously rotating reference frame is employed in order to control both the Rotor side converter (RSC) and grid side converter (GSC). vector control strategy is probably the most extended and established one in an equivalent way to the classic vector control techniques of other different machines (Rub, Malinowski, & Haddad, 2014). This control strategy has the several merits of a good dynamic response in regular and fault operating conditions, it is robust to parameter variation and measurement noise, and has fixed switching frequency (Obaid & Amer, 2016). The detailed model vector-oriented control of RSC and GSC is presented below.

##### Rotor Side Converter (RSC) controller

The voltage provided to the DFIG's rotor winding is controlled by the RSC. From the DFIG model in the preceding section, we can obtain the voltage equation in the dq reference frame by substituting Equations (3.86) in equation (3.88) and taking  $\psi_{qs} = 0$  These yields the following equation as a function of the rotor currents and stator flux.

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d|\vec{\psi}_s|}{dt} \quad (3.95)$$

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_r \sigma L_r i_{dr} + \omega_r \frac{L_m}{L_s} \frac{d|\vec{\psi}_s|}{dt} \quad (3.96)$$

Where;

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (3.97)$$

Assuming a little voltage drop in the stator resistance, the stator flux remains constant due to the stator's direct connection to the grid at a consistent AC voltage; As a result, the term  $\frac{d|\vec{\psi}_s|}{dt}$  is zero (Rub, Malinowski, & Haddad, 2014). It is necessary to estimate the angle  $\theta_r$  for the reference frame transformation. The rotor voltage and currents must first be converted into DQ coordinates before the control can be carried out in dq coordinates. The stator voltage space vector angle may be found first, and then subtracted.  $90^\circ$  from this calculated angle, and as a result, get  $\theta_s$ . For stator voltage grid synchronization, a basic phase-locked loop (PLL) can be employed, which offers resilience to the estimation and rejection of minor disturbances or harmonics.

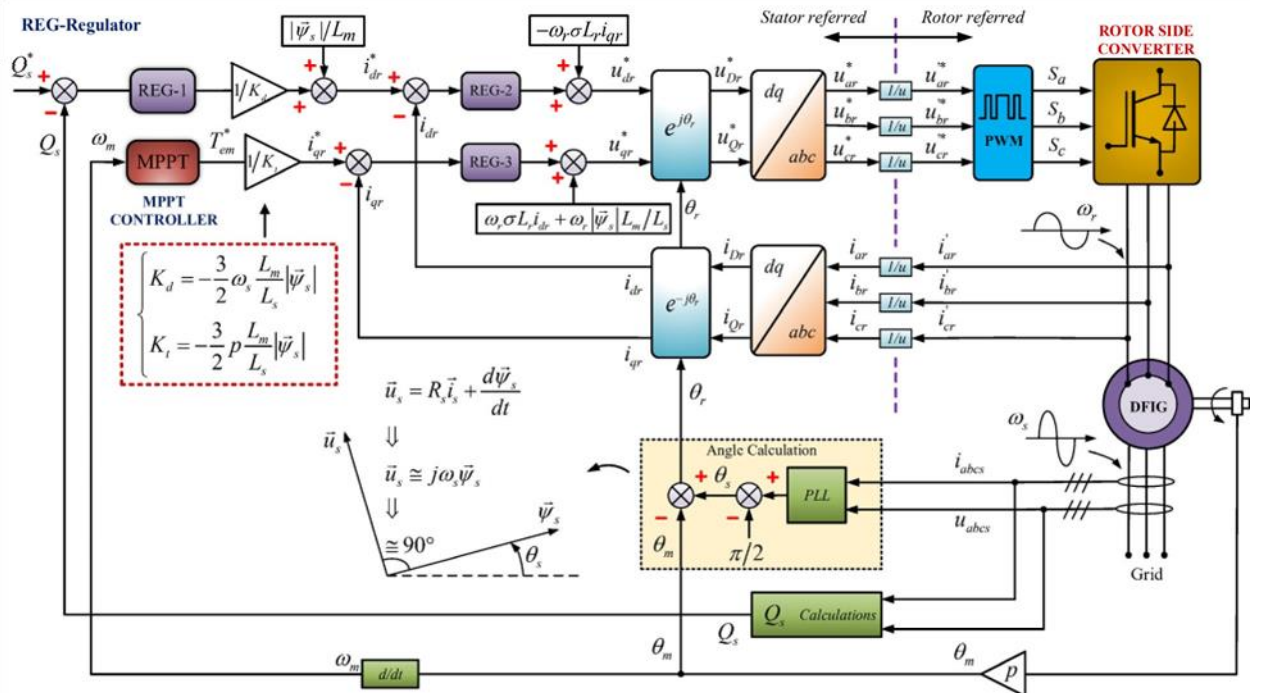


FIGURE 3. 25. RSC control strategy of the DFIG (Chhipa, et al., 2022)

### Grid Side Converter (GSC) Controller

The grid side converter is responsible for controlling the power flow the DFIG based WECS. In the DFIG model, the GSC is used to maintain a constant voltage in the DC link. The GSC

regulates the flow of reactive power between the induction machine's rotor and the grid. The implemented vector controls the d axis of the dq rotating reference frame is aligned with the grid voltage  $v_{dg}$ .

$$\begin{cases} v_{dg} = |\vec{v}_g| \\ v_{qg} = 0 \end{cases} \quad (3.98)$$

The basic equations for the voltages dq components of the grid side controller can be obtained as:

$$v_{df} = R_f i_{df} + L_f \frac{di_{df}}{dt} - \omega_s L_f i_{qf} + v_{dg} \quad (3.99)$$

$$v_{qf} = R_f i_{qf} + L_f \frac{di_{qf}}{dt} + \omega_s L_f i_{df} + v_{qg} \quad (3.100)$$

The block diagram of the implemented vector-oriented control is depicted in figure 3.26

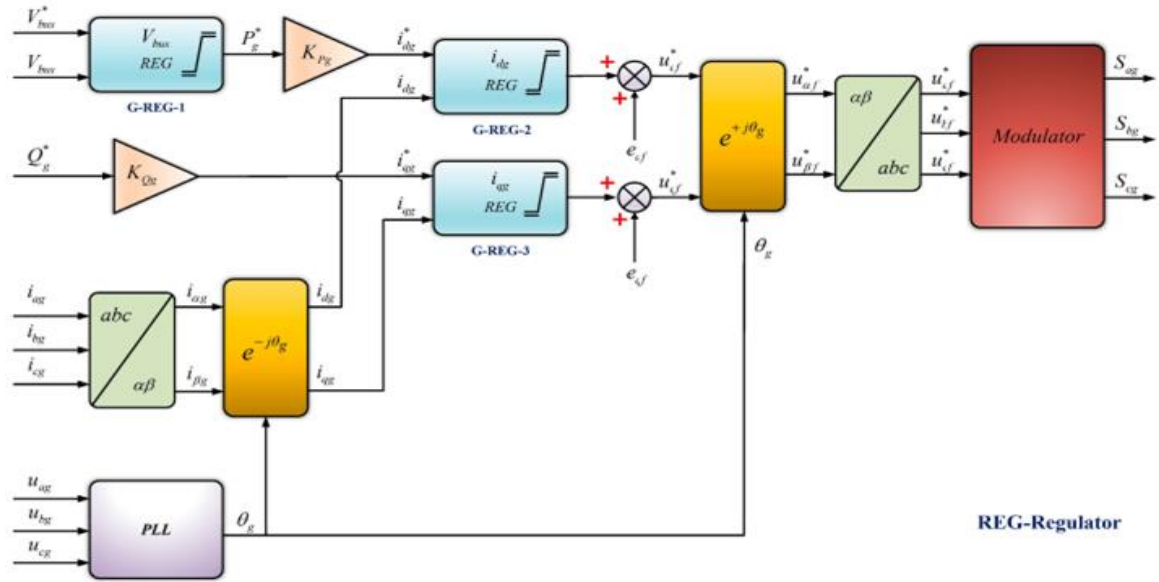


FIGURE 3. 26. Block diagram of GSC vector control strategy (Chhipa, et al., 2022)

In the block diagram, PLL is used to estimate the grid angle while in this thesis the grid angle is calculated using angle calculation block which will explained in the later section. The constant gains in the above block diagram are defined as below:

$$k_{pg} = \frac{1}{\frac{3}{2} v_{dq}} \quad (3.101)$$

$$k_{qg} = \frac{1}{-\frac{3}{2} v_{dq}} \quad (3.102)$$

### 3.4.5. Sinusoidal PWM with Third Harmonics Injection

Sinusoidal Pulse Width Modulation (PWM) with Third harmonic injection (THI) is a PWM techniques which is used in three phase power electronics converters to control the output

voltage waveform of an inverter. This is achieved by adding a third harmonic signal to each of the reference signal, the output voltage of the inverter is increased by 1.15 times of the SPWM (Awahab, 2023) without loss of quality, as represented in Figure 3.27 (Gonzalo, 2017).

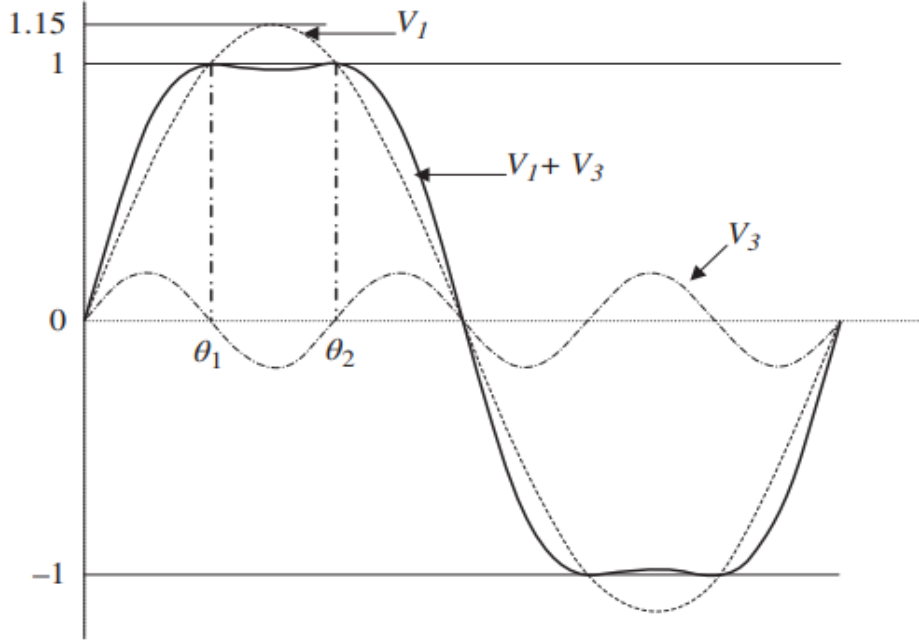


FIGURE 3. 27. Fundamental, third harmonics and injection signal (Abad, 2017)

The injected signal is given by:

$$V_3 = -\frac{\max\{v_a^*, v_b^*, v_c^*\} + \min\{v_a^*, v_b^*, v_c^*\}}{2} \quad (3.103)$$

Where;

$V_3$ : is the injected third harmonic signal

$v_a^*, v_b^*, v_c^*$  : are the reference signal for phase a, b and c respectively.

The block diagram of the third harmonics injection block is shown in figure 3.28:

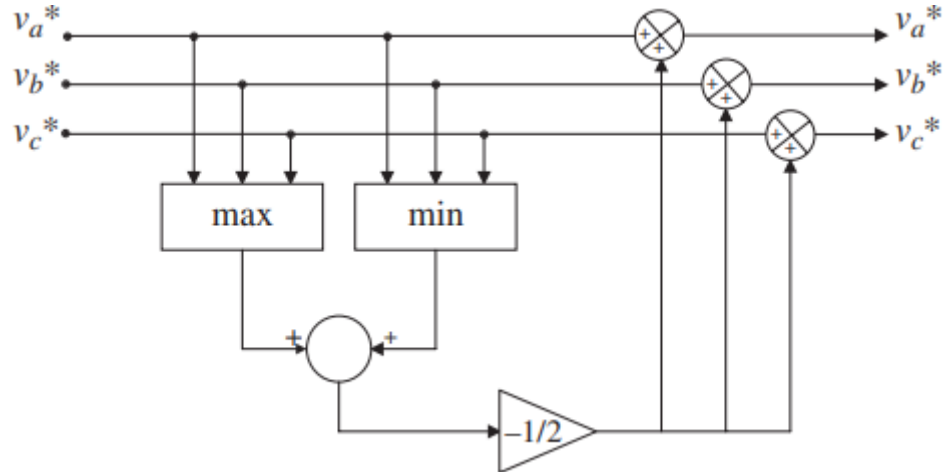


FIGURE 3. 28. Third harmonic injection simplified block diagram (Abad, 2017)

### 3.4.6. Angle Estimation

The angle estimation for grid connected DFIG based WECS is in responsible to estimate the rotor angle and the grid angle. The block diagram of angle calculation for rotor-side voltage is shown in figure 3.29. the grid voltage's angle can be expressed as:

$$\theta_g = \int \omega_g dt = \tan^{-1} \frac{v_\beta}{v_\alpha} \quad (3.104)$$

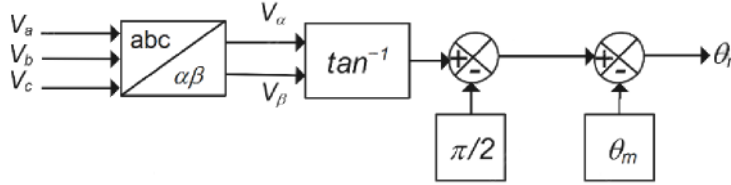


FIGURE 3. 29. Rotor side converter Angle calculation block diagram (Erdal B., 2022)

The rotor angle can be obtained by:

$$\theta_r = \theta_g - \frac{\pi}{2} - \theta_e \quad (3.105)$$

$$\theta_e = p\theta_m \quad (3.106)$$

Where;

$\theta_g$ : is the grid angle

$\theta_r$ : is the rotor angle

$\theta_e$ : is the electrical angle

### 3.4.7. Tuning of Current Loops regulator

#### Rotor Side Converter Controller Tuning

The equivalent block diagram for the closed loop current control in the rotor side control block is shown in the block diagram as below from

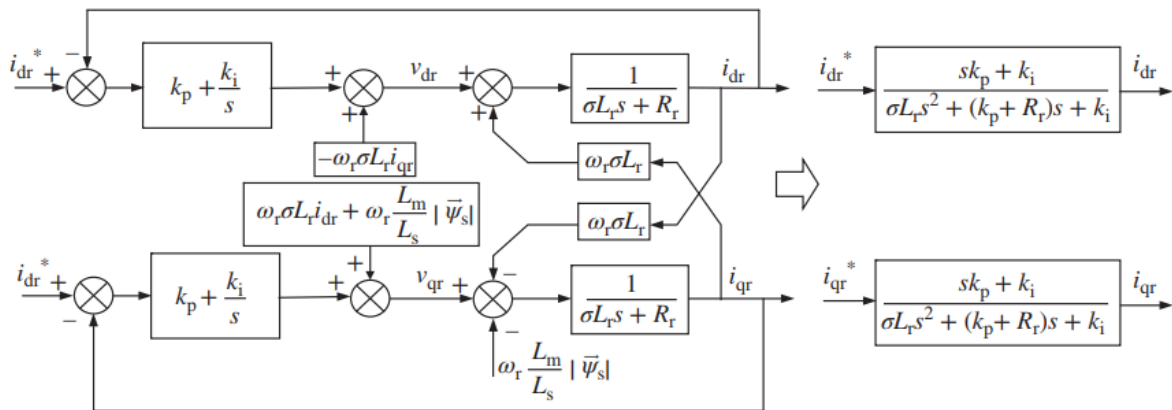


FIGURE 3. 30. Rotor side current control Loop (Rub, Malinowski, & Haddad, 2014)

the equivalent closed-loop systems of both current loops are equal to a second-order system with two poles and a zero that can be placed by classic control theory choosing the appropriate gains of the PI regulators.

$$\frac{i_{dr}(s)}{i_{dr}^*(s)} = \frac{sk_p + k_i}{s^2 L_r \sigma + s(R_r + k_p) + k_i} \quad (3.107)$$

$$\frac{i_{dr}(s)}{i_{dr}^*(s)} = \frac{sk_p + k_i}{s^2 L_r \sigma + s(R_r + k_p) + k_i} \quad (3.108)$$

the general control transfer function i.e.  $s^2 + 2\zeta\omega_n s + \omega_n^2$  we have,

$$k_i = \sigma L_r \omega_n^2 \quad (3.109)$$

$$k_p = 2\sigma L_r \omega_n^2 - R_r \quad (3.110)$$

### Grid Side Converter Controller Tuning

The equivalent block diagram for the closed loop current control in the grid side control block is shown in the block diagram as below from

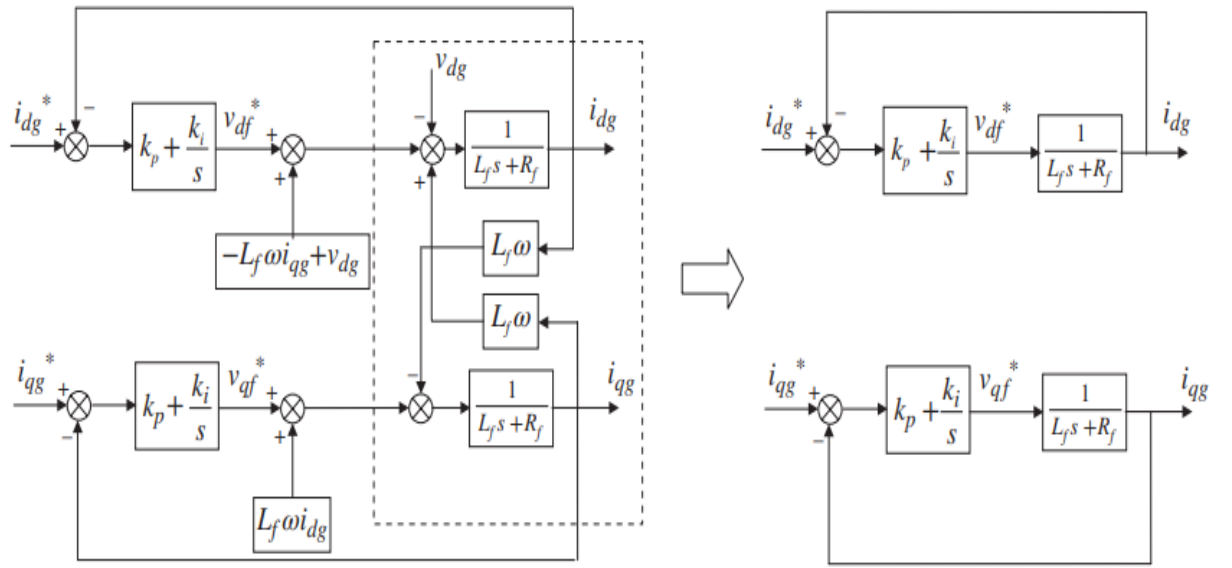


FIGURE 3. 31. Grid side converter current control loop (Rub, Malinowski, & Haddad, 2014)

The gains of the PI regulators for the closed loop current expressions have been tuned by equalizing the denominator of the derived transfer function with the standard second-order denominator of classic control theories. Thus, we obtain:

$$s^2(L_f) + s(R_f + k_p) + k_i \equiv s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (3.111)$$

Since our ultimate goals here are to find the required  $k_p$  and  $k_i$  values are:

$$k_i = L_f \omega_n^2 \quad (3.112)$$

$$k_p = L_f^2 \zeta \omega_n - R_f \quad (3.113)$$

## CHAPTER FOUR

### 4. RESULTS AND DISCUSSIONS

#### 4.1. Introduction

The results and discussion of optimization and design of grid connected solar PV and wind hybrid system had presented in this section. Homer and Matlab 2023a software has been used as a tool in order to optimal sizing and simulate the hybrid system respectively. The obtained result from it is classified in to four categories;

1. The first category discussed about the Optimal sizing and configuration of solar PV and wind hybrid system
2. The second category described how well a photovoltaic system operated under various temperature and solar irradiation conditions.
3. The third category demonstrated how the DFIG-based WECS behaved in different wind speeds scenarios.
4. The last category explained how a hybrid of PV and wind system operated in different weather conditions

#### 4.2. Optimal results from homer pro software

In this section, the simulation results of homer pro software discussion are presented. Figure 4.1 shown the overall optimization result of wind and solar energy hybrid system. the software presents the optimization results based on ascending costs of energy and capacity shortages. 16 scenarios are taken, the first scenario is selected due to less cost of energy and capacity shortages. Therefore, the finding optimization results for Dire Dawa city were calculated using daily radiation of  $6.05 \text{ kWh/m}^2/\text{day}$ , monthly average temperature of  $24.04^\circ\text{C}$  and an average wind speed of  $10.26\text{m/s}$ . thus, the suitable model for Dire Dawa city is solar PV-converter-wind-grid with 20MW of solar PV, 1.5MW of bi-directional inverter,  $1.5\text{MW} \times 15$  wind turbines and 10MW of grid. This hybrid system has used 80% renewable power, the power price was  $\$0.037/\text{kWh}$  and  $\$42.3$  million net present cost including a capital depreciation and levelized operation and maintenance costs. Figure 4.2 shown that the generation of energy from various energy sources such as solar PV, wind and grid elements. The overall energy need from all source is  $207,018,558 \text{ kWh/y}$ , wind turbine provides  $130,413,115 \text{ kWh/y}$  which is 63% of the total energy, solar PV provide  $34,110,573 \text{ kWh/y}$  of 16.5% of the total energy and grid provides  $42,494,870 \text{ kWh/y}$  which is 20.5% of the total energy for the Dire Dawa city. Even though, there were a surplus of

3,850,776 kWh which is 1.86% generated, and capacity shortage of 61,742,691 kWh which is 28.9% over the year

|                                                                                     | Architecture                                                                                                                                                                                                                                                                                                                                    |                    |         |                |              | Cost     |          |               |                        | System     |              | MTPVp-245 MSC     |           | GW 1500                    |                   |                     |               |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|---------|----------------|--------------|----------|----------|---------------|------------------------|------------|--------------|-------------------|-----------|----------------------------|-------------------|---------------------|---------------|
|                                                                                     |             | MTPVp-245 MSC (kW) | GW 1500 | Dire Dawa (kW) | SGI 500 (kW) | Dispatch | NPC (\$) | LCOE (\$/kWh) | Operating cost (\$/yr) | CAPEX (\$) | Ren Frac (%) | Total Fuel (L/yr) | CAPEX     | Energy Production (kWh/yr) | Capital Cost (\$) | Production (kWh/yr) | O&M Cost (\$) |
|    |             | 20,000             | 15      | 10,000         | 12,500       | CC       | \$42.3M  | \$0.0137      | \$339,722              | \$37.1M    | 79.0         | 0                 | 4,800,000 | 34,110,572                 | 30,750,000        | 130,413,112         | 190,120       |
|    |             | 20,000             | 15      | 10,000         | 15,000       | LF       | \$42.6M  | \$0.0138      | \$340,028              | \$37.4M    | 79.2         | 0                 | 4,800,000 | 34,110,572                 | 30,750,000        | 130,413,112         | 190,120       |
|    |             | 20,000             | 15      | 10,000         | 15,000       | CC       | \$42.6M  | \$0.0138      | \$340,028              | \$37.4M    | 79.2         | 0                 | 4,800,000 | 34,110,572                 | 30,750,000        | 130,413,112         | 190,120       |
|    |             | 20,000             | 15      | 10,000         | 20,000       | LF       | \$43.4M  | \$0.0140      | \$347,546              | \$38.1M    | 79.2         | 0                 | 4,800,000 | 34,110,572                 | 30,750,000        | 130,413,112         | 190,120       |
|    |             | 20,000             | 15      | 10,000         | 20,000       | CC       | \$43.4M  | \$0.0140      | \$347,546              | \$38.1M    | 79.2         | 0                 | 4,800,000 | 34,110,572                 | 30,750,000        | 130,413,112         | 190,120       |
|    |             | 2,000              | 20      | 10,000         | 12,500       | LF       | \$47.7M  | \$0.0149      | \$301,739              | \$43.1M    | 82.4         | 0                 | 480,000   | 3,411,057                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 2,000              | 20      | 10,000         | 12,500       | CC       | \$47.7M  | \$0.0149      | \$301,739              | \$43.1M    | 82.4         | 0                 | 480,000   | 3,411,057                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 4,000              | 20      | 10,000         | 12,500       | LF       | \$48.0M  | \$0.0148      | \$291,857              | \$43.5M    | 83.0         | 0                 | 960,000   | 6,822,114                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 4,000              | 20      | 10,000         | 12,500       | CC       | \$48.0M  | \$0.0148      | \$291,857              | \$43.5M    | 83.0         | 0                 | 960,000   | 6,822,114                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 2,000              | 20      | 10,000         | 15,000       | LF       | \$48.0M  | \$0.0150      | \$305,752              | \$43.4M    | 82.4         | 0                 | 480,000   | 3,411,057                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 2,000              | 20      | 10,000         | 15,000       | CC       | \$48.0M  | \$0.0150      | \$305,752              | \$43.4M    | 82.4         | 0                 | 480,000   | 3,411,057                  | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 6,000              | 20      | 10,000         | 12,500       | LF       | \$48.3M  | \$0.0148      | \$282,340              | \$44.0M    | 83.5         | 0                 | 1,440,000 | 10,233,172                 | 41,000,000        | 173,884,160         | 253,493       |
|    |             | 6,000              | 20      | 10,000         | 12,500       | CC       | \$48.3M  | \$0.0148      | \$282,340              | \$44.0M    | 83.5         | 0                 | 1,440,000 | 10,233,172                 | 41,000,000        | 173,884,160         | 253,493       |
|   |         | 4,000              | 20      | 10,000         | 15,000       | LF       | \$48.4M  | \$0.0149      | \$295,870              | \$43.8M    | 83.0         | 0                 | 960,000   | 6,822,114                  | 41,000,000        | 173,884,160         | 253,493       |
|  |     | 4,000              | 20      | 10,000         | 15,000       | CC       | \$48.4M  | \$0.0149      | \$295,870              | \$43.8M    | 83.0         | 0                 | 960,000   | 6,822,114                  | 41,000,000        | 173,884,160         | 253,493       |
|  |     | 8,000              | 20      | 10,000         | 12,500       | LF       | \$48.7M  | \$0.0148      | \$273,204              | \$44.5M    | 83.9         | 0                 | 1,920,000 | 13,644,229                 | 41,000,000        | 173,884,160         | 253,493       |

FIGURE 4. 1. Overall Optimization results for PV/wind/grid hybrid system

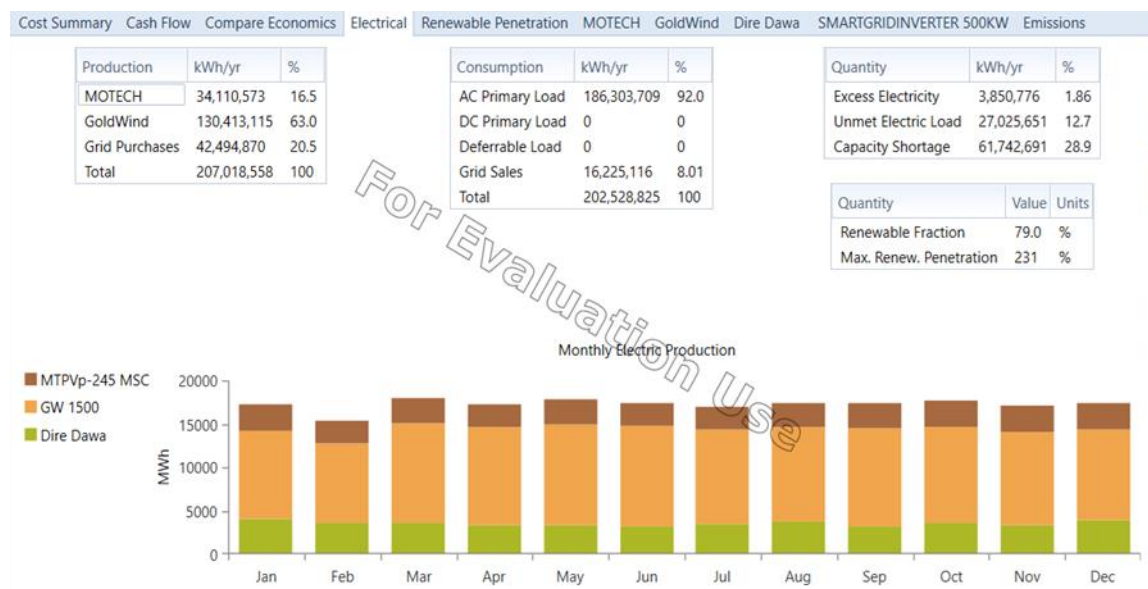


FIGURE 4. 2. A grid-connected hybrid of solar PV and wind energy system monthly average electric production

This project has required 25 years to complete, with an annual real interest rate of 7% and a nominal interest rate of 9%.

### 4.3. Solar PV system

This section examines at how well a PV system operates in different temperatures and sun irradiation conditions. Simulink environment has been used to simulates the model that was built in previous chapters. The PV system's simulation results are discussed below. The two-stage grid-connected photovoltaic system's Simulink model is shown in Figure 4.3.

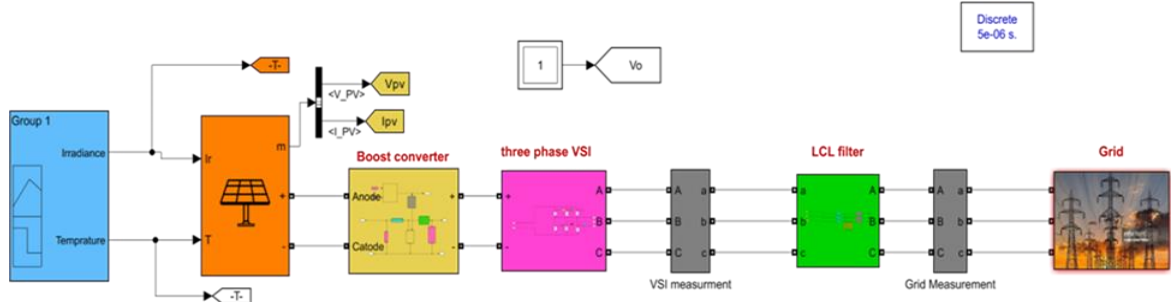


FIGURE 4. 3. A two-stage grid connected PV system Simulink model

#### 4.3.1. PV array

For this thesis work, Sunpower SPR-425E-WHT-D module has been used. The maximum power that this module can produce at 25°C temperature and 1000 w/m<sup>2</sup> irradiance is 425 W. In order to generate a power of around 500 KW, the PV array is built using a PV string, which is composed of 236 strings connected in parallel and five modules connected in series. Figure 4.4 and 4.5 showed the module's I-V and P-V characteristic curves at different sun irradiance and temperature respectively.

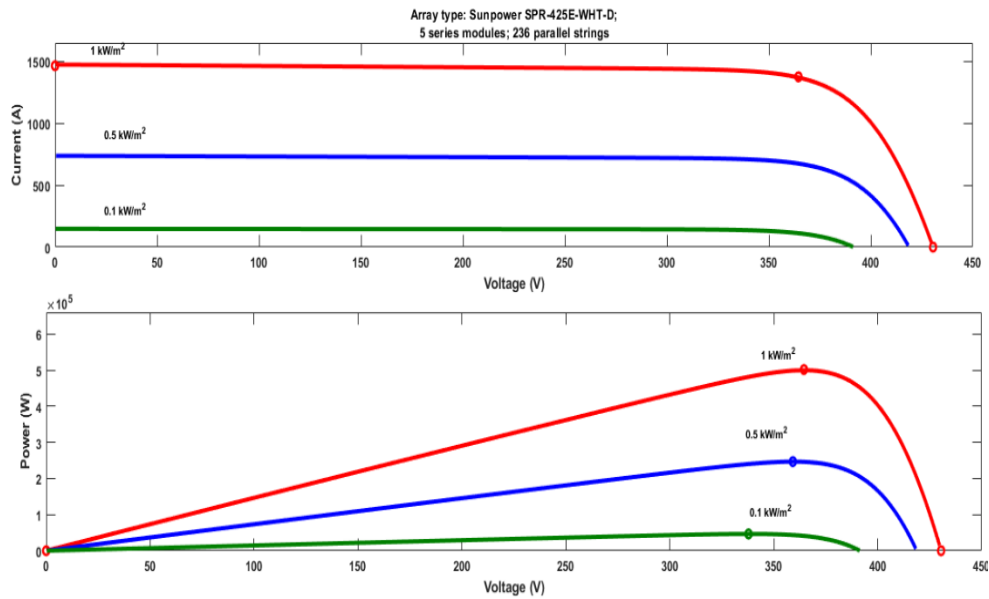


FIGURE 4. 4. I-V and P-V Curve under variable sun irradiation

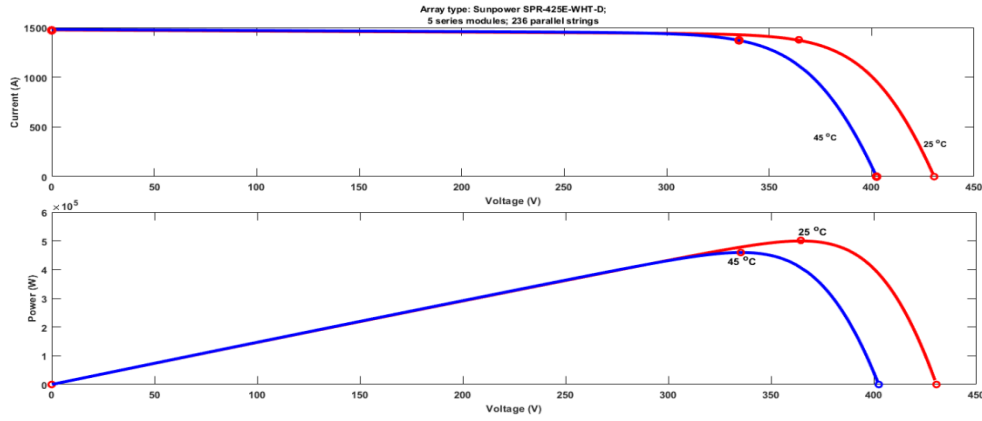


FIGURE 4. 5. I-V and P-V Curve under variable temperature

As shown in Figure 4.5, the PV array current decreased as the solar irradiance changed. This is due to that the irradiance value significantly affected the short-circuit current. Thus, the PV array current is also affected. The PV array voltage is also affected by the temperature, as the temperature increases the open circuit voltage of the PV array decreases, thus the Voltage of the PV array decreases.

For this system 5 seconds is taken to run the simulation with a sampling time of  $5 \mu\text{s}$ . Time-varying irradiance and temperature are the PV array's input signals. The value of the input irradiance signal is  $1000 \text{ W/m}^2$ ,  $750 \text{ W/m}^2$  and  $500 \text{ W/m}^2$  and the temperature signal is  $25^\circ\text{C}$  and  $45^\circ\text{C}$ . Figure 4.6 illustrates these signals, the x-axis represented time, while the y-axis represented sun irradiance and temperature respectively.

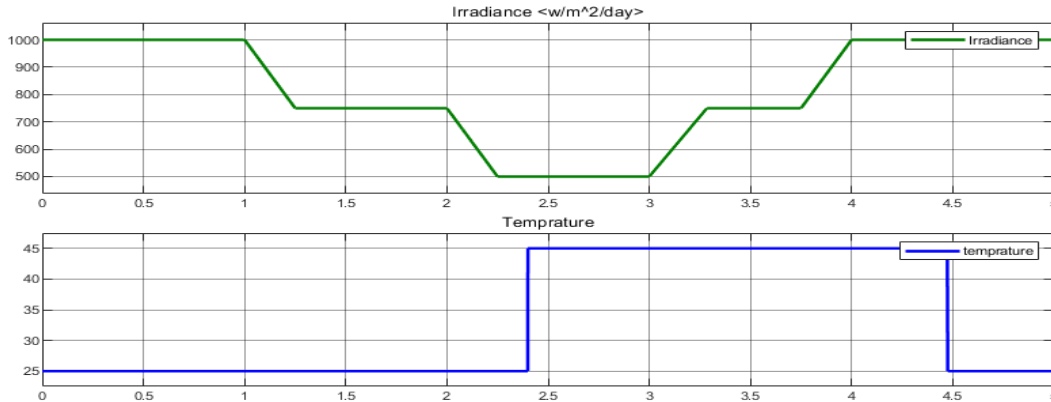


FIGURE 4. 6. Sun irradiance and temperature variation

#### 4.3.2. Boost Converter

The boost converter is employed in this thesis work operating in conduction mode. To track the maximum power point and increase the PV array's output voltage to the desired voltage level, which is approximately  $700 \text{ V}$ , PO and FLC-based MPPT algorithms are employed.

## 1. PO MPPT

PV array with PO MPPT controller simulation results is discussed below. Figure 4.6 shows the PV array voltage, current and power waveform at different sun irradiation and temperature. At standard test condition, the voltage and power of the PV array are 368.5V and 493kW respectively. At 25°C temperature and  $750\text{W}/\text{m}^2$  irradiance, the voltage and power of the PV array are 365.8V and 372.8kW respectively. As shown in the figure 4.7, when the irradiance decreases, the voltage and current of the PV array has decreased, and also the power of the PV array has decreased as well. Similarly, increase in temperature result in decreasing the voltage, current and power of the PV array.

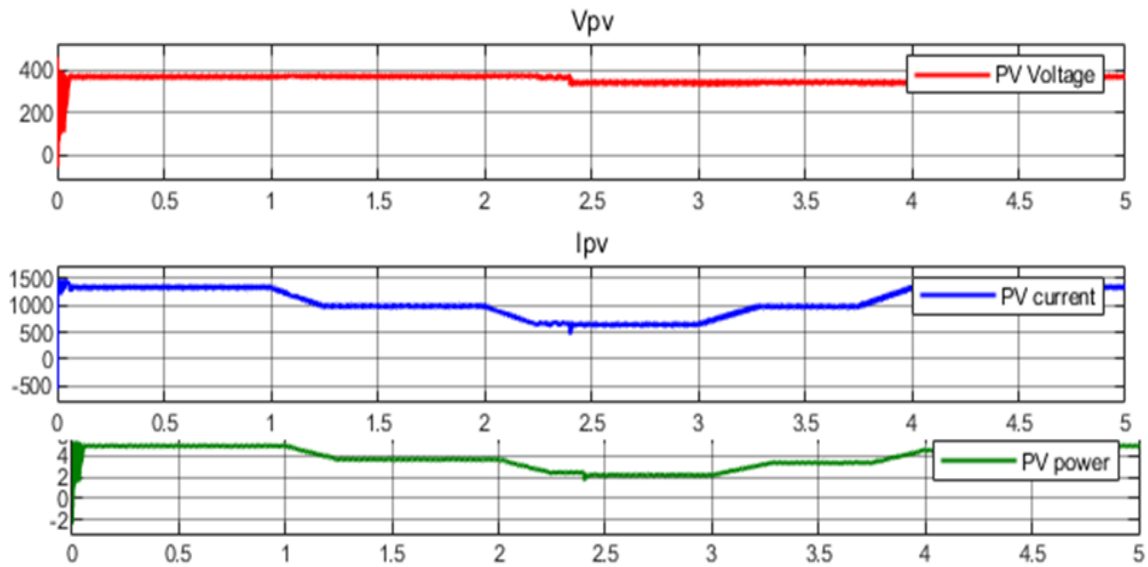


FIGURE 4. 7. PV array output with PO MPPT

As shown in figure 4.7, the x-axis represented the time, while the y-axis represented the PV array voltage, current and power through PO based MPPT controller.

## 2. FLC MPPT

Figure 4.8 shows the power, voltage, and current drawn from the PV array with FLC MPPT. The system successfully monitors the maximum output voltage and power of the PV array. At standard test condition, the input power and the maximum power point voltages are 500kW and 364.5V respectively. At 25°C temperature and  $750\text{W}/\text{m}^2$  of irradiance, the maximum power point voltage and power are reduced to 358.9V and 372.7kW respectively. The maximum power point voltage and power are further reduced 341.7V and 225.4kW at 25°C temperature and  $500\text{W}/\text{m}^2$  of irradiance. As the temperature increase, the voltage and power of the PV array decrease as well.

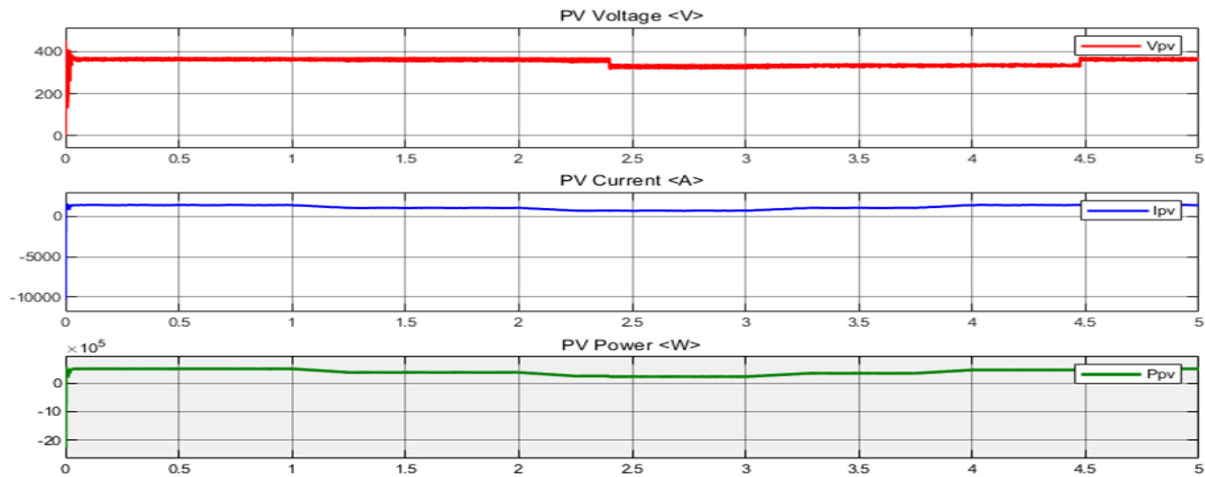


FIGURE 4. 8. PV array output with FLC MPPT

The PO and FLC based MPPT algorithms voltages compared with the PV array maximum power point voltages. Table 4.1 showed the comparison of voltage PO and FLC based MPPT with respect to the actual PV array.

TABLE 4. 1. Comparison of FLC and PO MPPT with the actual PV array

| Sun irradiance ( $w/m^2$ ) | Temperature ( $^{\circ}C$ ) | PO Voltage | FLC Voltage | PV array Voltage at MPP |
|----------------------------|-----------------------------|------------|-------------|-------------------------|
| 1000                       | 25                          | 368.5      | 364.5       | 364.5                   |
|                            | 45                          | 347.2      | 334.8       | 335.266                 |
| 750                        | 25                          | 370.8      | 363.7       | 362.717                 |
|                            | 45                          | 347.4      | 339.8       | -----                   |
| 500                        | 25                          | 361.7      | 358.9       | 359.19                  |
|                            | 45                          | 343.7      | 330.5       | -----                   |

As shown in table 4.1, FLC based MPPT voltage is near to the PV array maximum power voltage. at  $25^{\circ}C$  temperature and  $1000 w/m^2$  irradiance, the PV array voltage is 364.5V, FLC based MPPT voltage is 364.5V and PO MPPT voltage is 368.5V. similarly, at varying temperature and sun irradiance FLC based MPPT voltage is near to actual PV array maximum power voltage. Based on these results, in this thesis we proposed FLC based MPPT controller

#### 4.3.3. DC-Link Voltage

The voltage controller controls the voltage across the DC-link. Because of this, a PV array's maximum power output is nearly equal to the power added to the grid. Figure 4.8 shows the DC-link voltage and reference voltage signal results for the voltage controller. Temperature

and irradiance cause the DC-link voltage to fluctuate slightly, but the voltage controller keeps the voltage constant to restore the voltage to the desirable level. As shown in figure 4.9, at 4.5 seconds the temperature instantly dropped down from 45°C to 25°C during this time the dc-link voltage has fluctuated. The DC-link voltage tracks the reference voltage signal within the permitted range. The DC-link voltage error signal is relatively near to zero when compared to the reference voltage signal. As a result, the DC-link voltage's tracking of the reference voltage signal has minimal error.

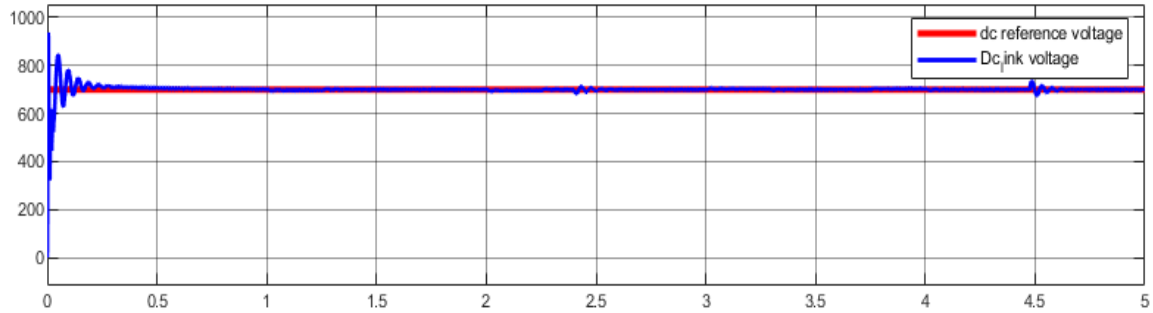


FIGURE 4. 9. Actual and reference DC link voltage

#### 4.3.4. Inverter

DC voltage from the boost converter is received by the inverter, which converts it to AC voltage. This AC voltage has two levels to it. Figure 4.10 illustrated the oscillation of the line voltage between the positive and negative of the DC-link voltage of the specified model.

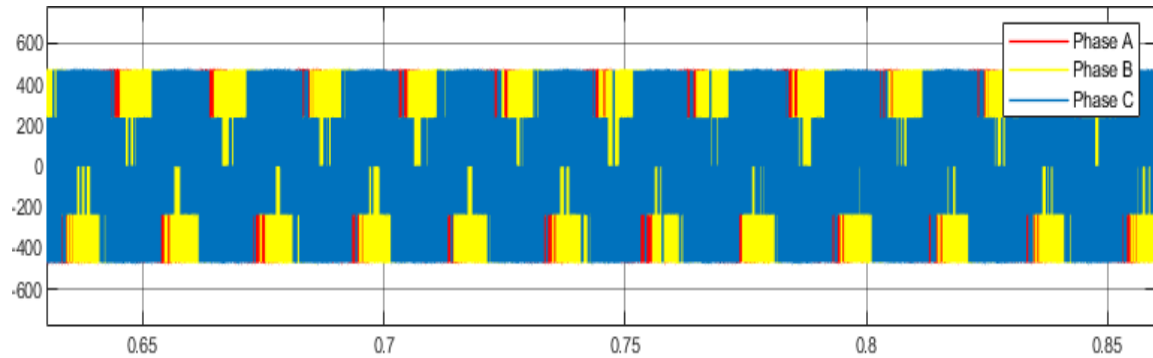


FIGURE 4. 10. Inverter output voltage

Through the use of Fast Fourier Transform (FFT) analysis, the output voltage and current of VSI with and without filter have been assessed. Voltage source inverter disturbances are common, which lowers the system's power quality and impacts all grid-connected photovoltaic systems. Because of this, the high-frequency harmonics are attenuated using an LCL filter to meet the recommended requirement. The impact of the LCL filter on reducing inverter current and voltage disturbances is depicted in Figures 4.11 and 4.12.

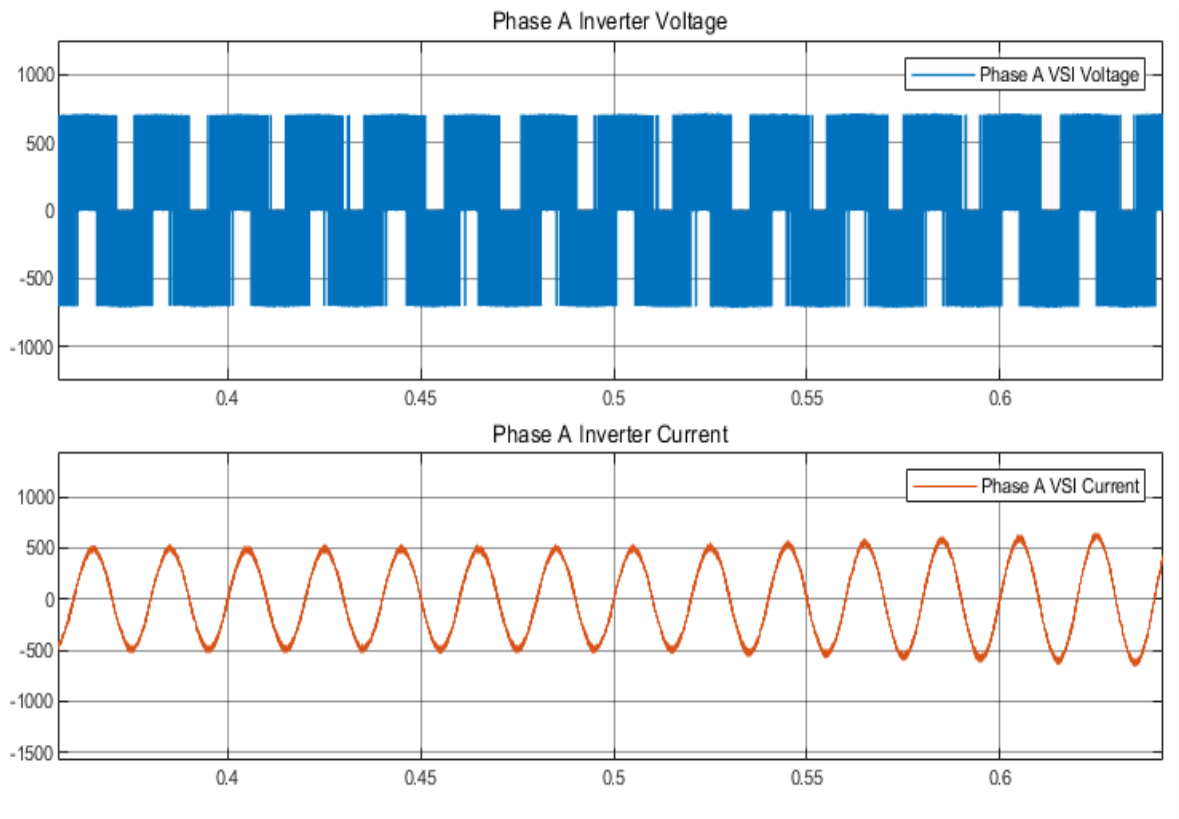


FIGURE 4. 11. Inverter Voltage and Current output waveform before filter

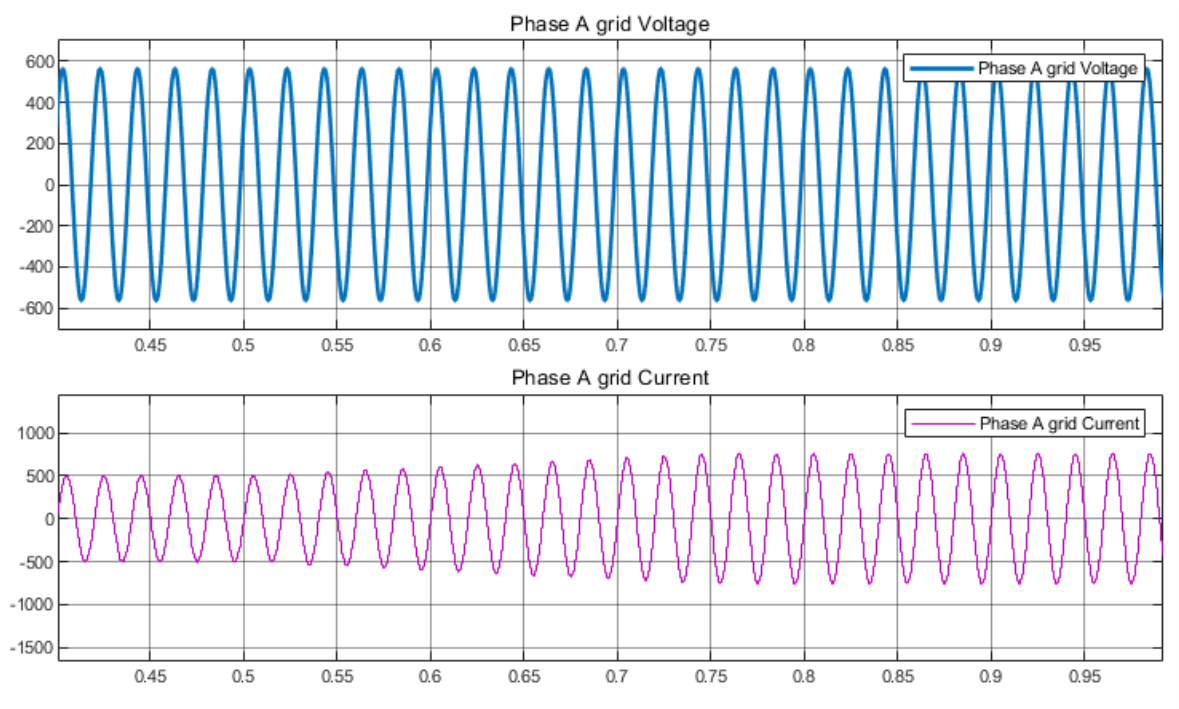


FIGURE 4. 12. Inverter Voltage and Current output waveform after filter

Figures 4.13 and 4.14, respectively, depict the output voltage and current of the inverter together with their FFT spectrums. According to IEEE standard 929-2000, the THD of the inverter voltage and current is 0.246% and 2.46%, respectively, which is less than 5%.

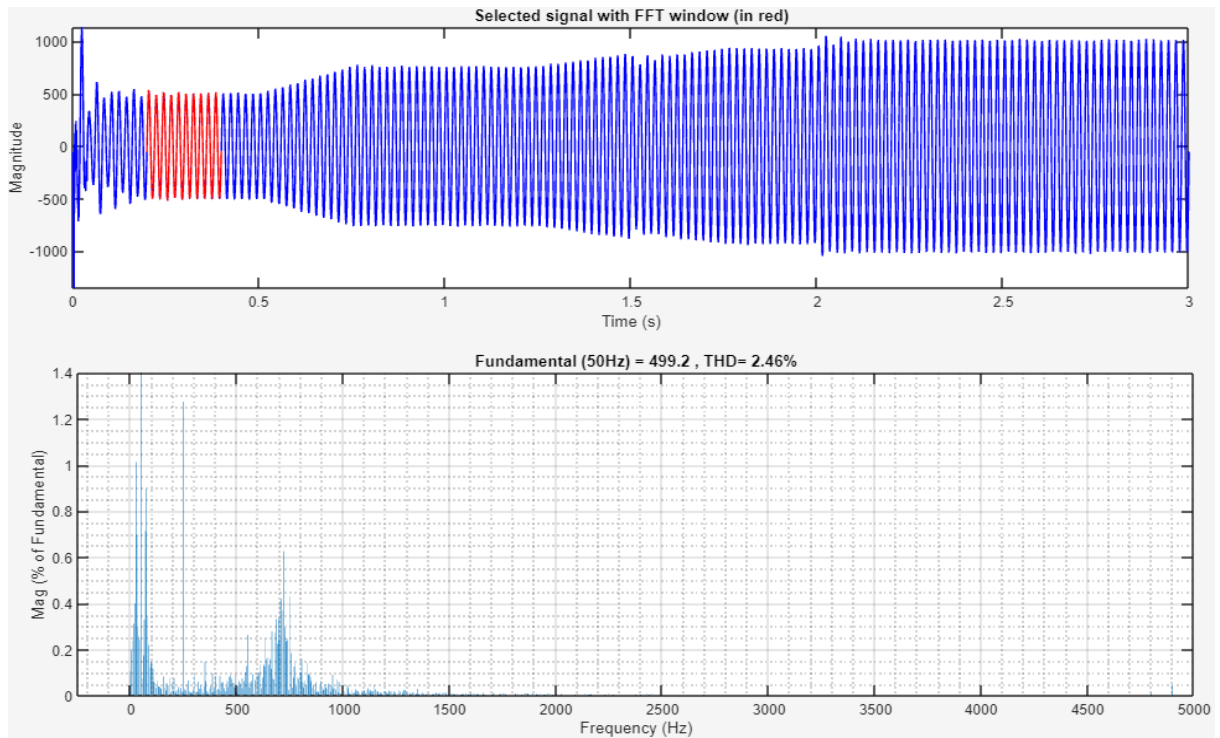


FIGURE 4. 13. Output Inverter Current FFT analysis

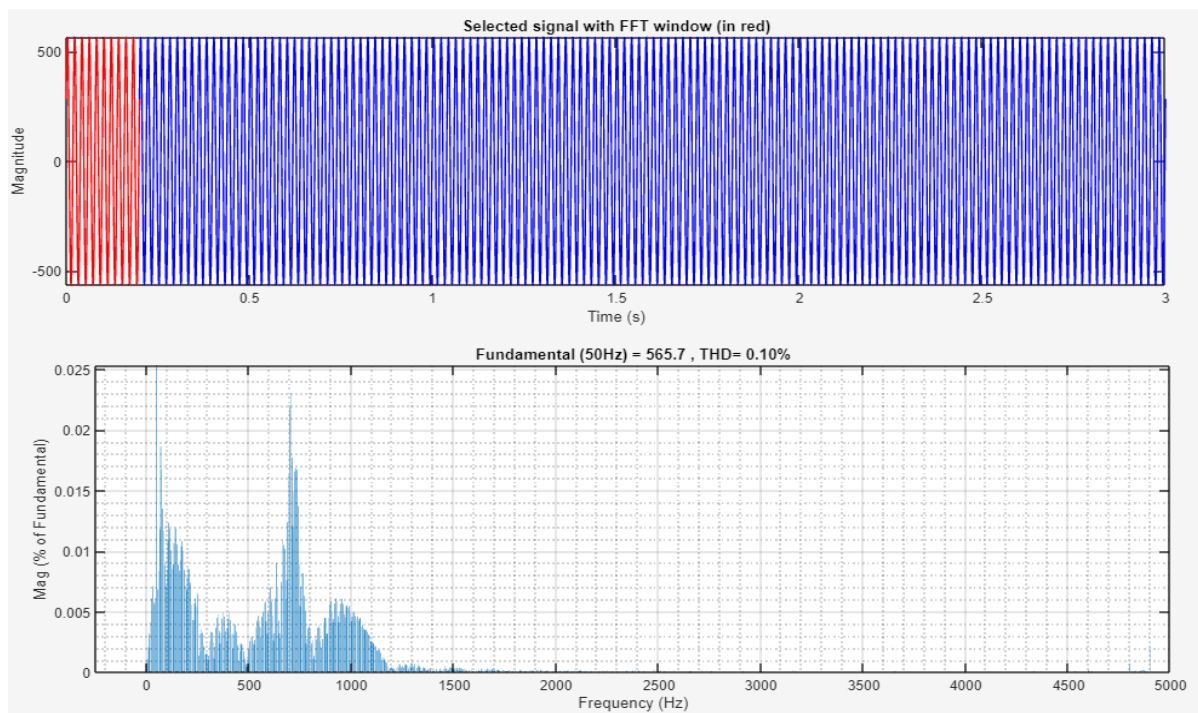


FIGURE 4. 14. Output Inverter Voltage FFT Analysis

#### 4.3.5. Three-Phase grid Voltage and Current Waveforms

Once the inverter's output synchronization with the grid is complete, the phase angle, frequency, and magnitude of both the grid and the inverter will be equal. To provide the phase angle required to synchronize the inverter and grid outputs using the grid voltage, a

phase-locked loop is necessary. Figure 4.15 shows the three phase voltage output waveforms of the grid and inverter at a frequency of 50Hz and a magnitude of 230V.

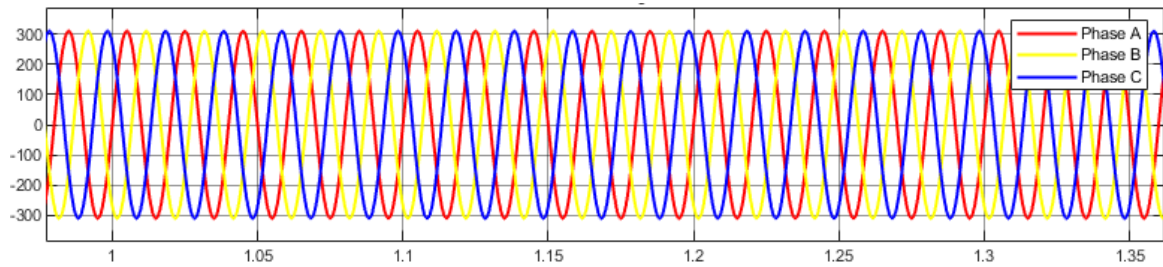


FIGURE 4. 15. Three-phase grid voltage waveforms

Figure 4.16 illustrates the result of the three-phase current that was fed into the grid and inverter.

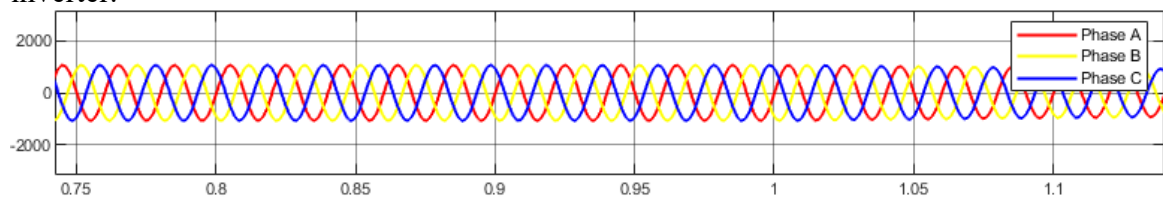


FIGURE 4. 16. Three-phase grid current waveform

The grid voltage and the three-phase inverter current are in phase, as seen in the figures above. The current magnitude of each phase is about 1253 A rms. The Fast Fourier Transform (FFT) analysis of the grid current and voltage as frequency spectrum, the magnitudes of harmonics available in the injected current concerning the fundamental frequency/harmonic order for phase A, and the total harmonic distortion (THD) of the injected grid current and voltage are shown in Figures 4.17 and 4.18. The current and voltage have THDs of 2.46% and 0.08%, respectively.

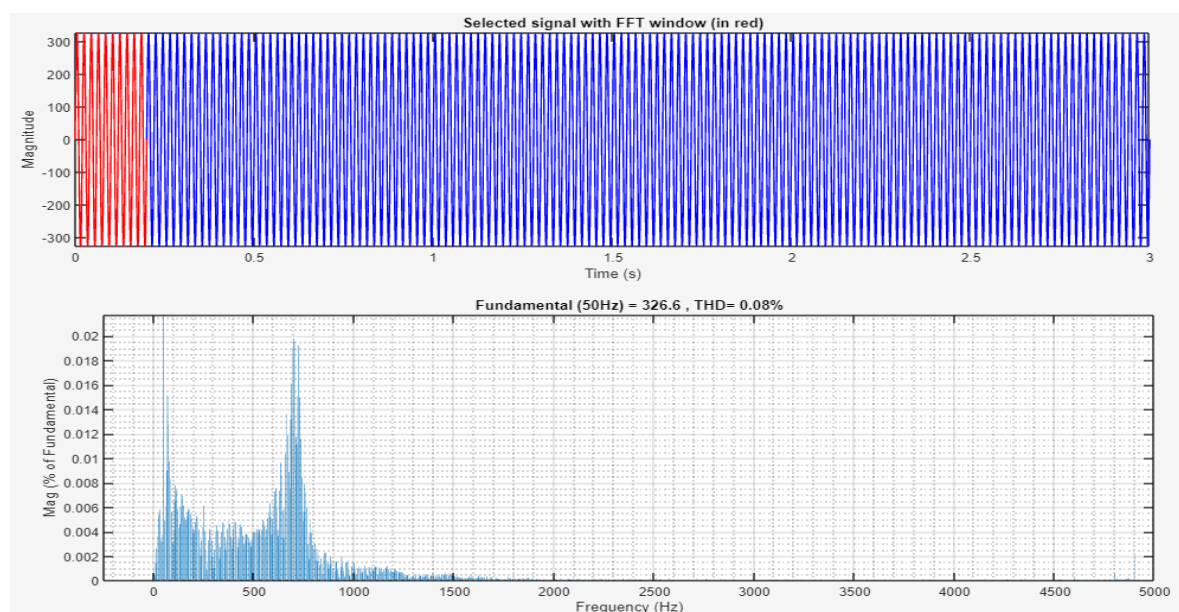


FIGURE 4. 17. Three-phase grid Voltage FFT analysis

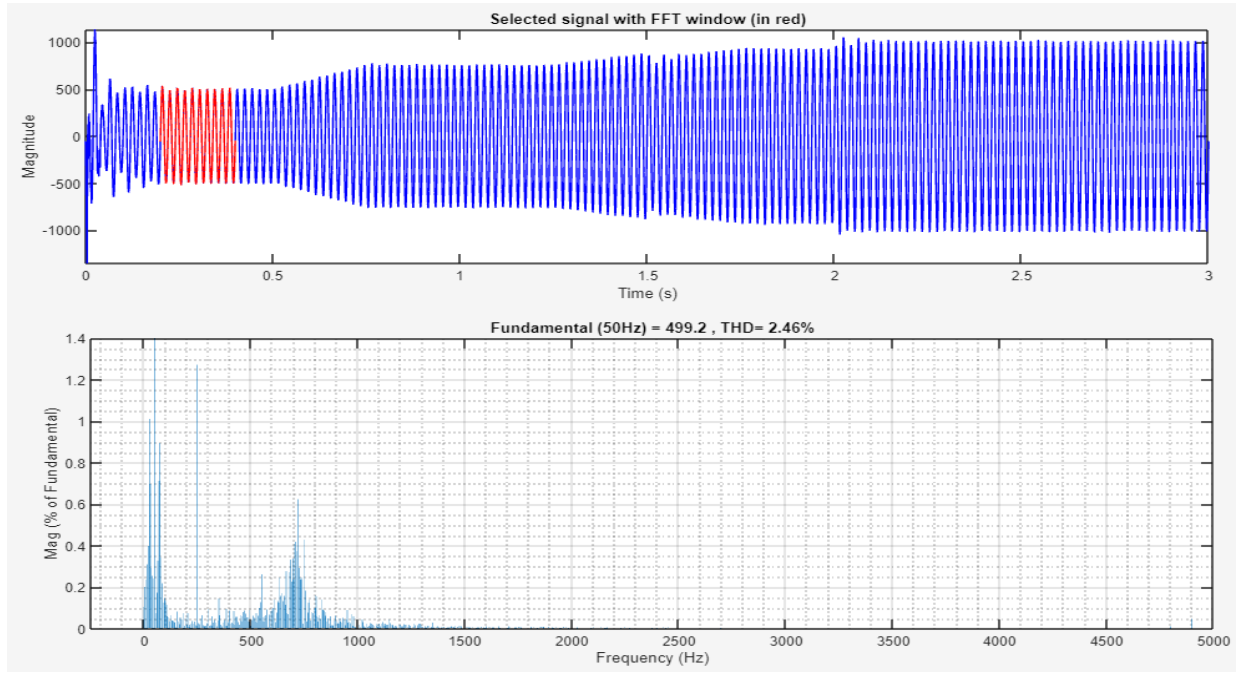


FIGURE 4. 18. Three-phase grids current FFT analysis

#### 4.3.6. Direct and Quadrature Reference Currents

The direct and quadrature reference currents,  $I_d^*$  and  $I_q^*$ , respectively have considerable effects on the system's active and reactive power. The direct current component is in charge of controlling the active power of the inverter, while the quadrature current component regulates the inverter's reactive power output, which must be reduced to zero in order to achieve a unity power factor. Figure 4.19 showed the actual and reference direct and quadrature current components.

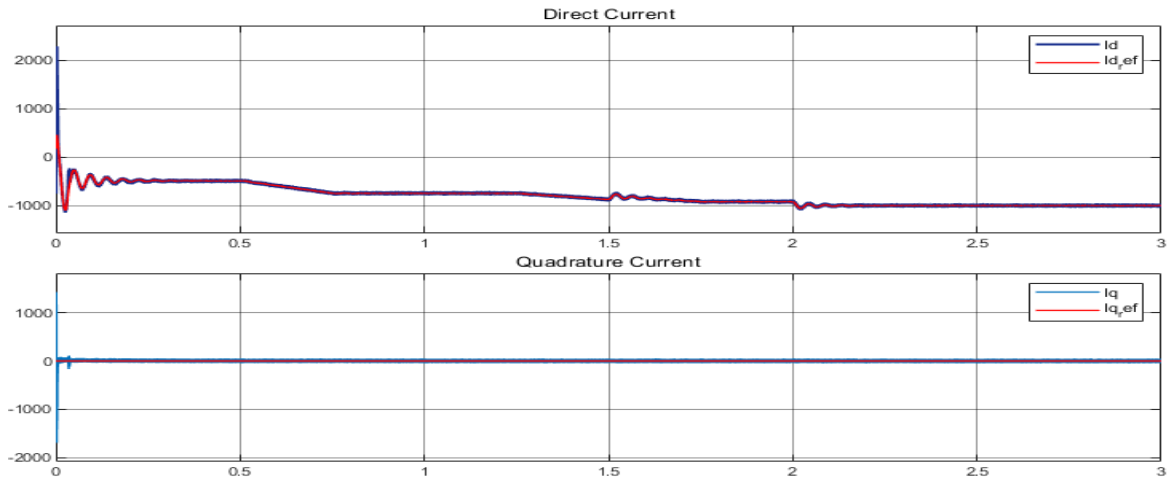


FIGURE 4. 19. Direct and Quadrature Reference Current

#### 4.3.7. PV System's Output power

At constant solar irradiation and temperature, the maximum output power from the solar array is 497kW, and 476kW power is transmitted to the grid. Since, the grid only receives

an addition of active power, while the reactive power is reduced to zero. During variations in weather, the grid can be supplied with both reactive and active power. At  $45^{\circ}\text{C}$  and  $1000\text{W}/\text{m}^2$ ,  $457.6\text{kW}$  is the maximum power delivered to the grid. Figure 4.20 illustrates the active power and reactive power added to the grid.

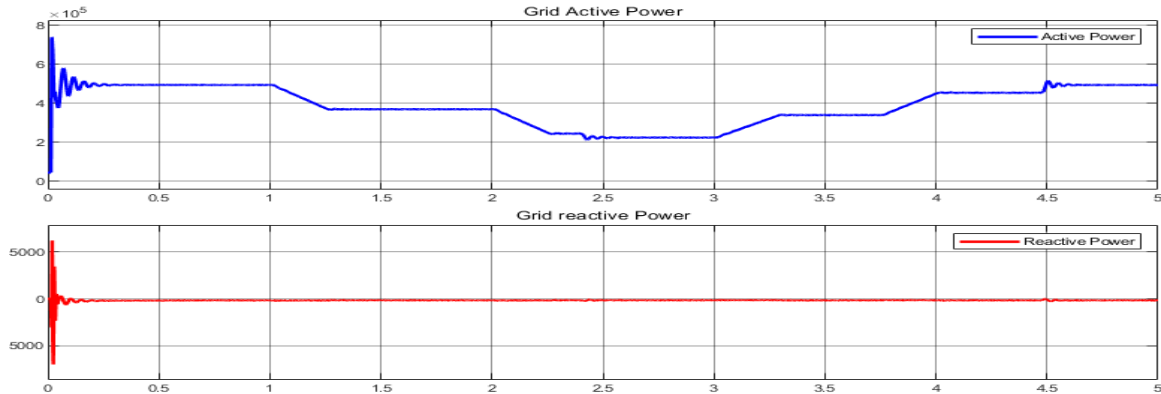


FIGURE 4. 20. Injected Active and Reactive Power

#### 4.4. Doubly Fed Induction generator (DFIG) based WECS

This section investigated the performance of wind energy conversion at different wind speed. the simulation results of this WECS were discussed below. The grid connected DFIG based WECS Simulink model is shown in Figure 4.21. In this system, voltage-oriented control is applied to control the RSC and GSC, and an indirect OTC is employed to optimize the wind turbine's power output.

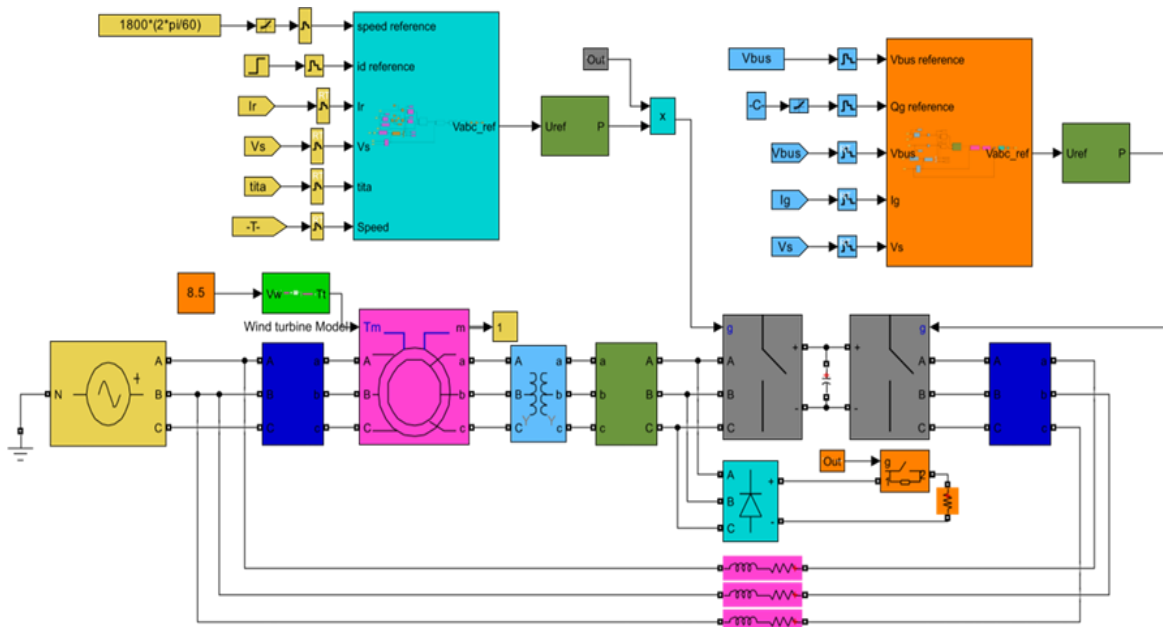


FIGURE 4. 21. Grid-connected DFIG-based WECS Simulink model

#### 4.4.1. Wind turbine

For this thesis work, Acciona AW-70 wind turbine has been used. The maximum mechanical power extracted by this wind turbine at a rated wind speed of 12 m/s is 1.5 MW. This wind turbine's power curve is displayed in figure 4.22.

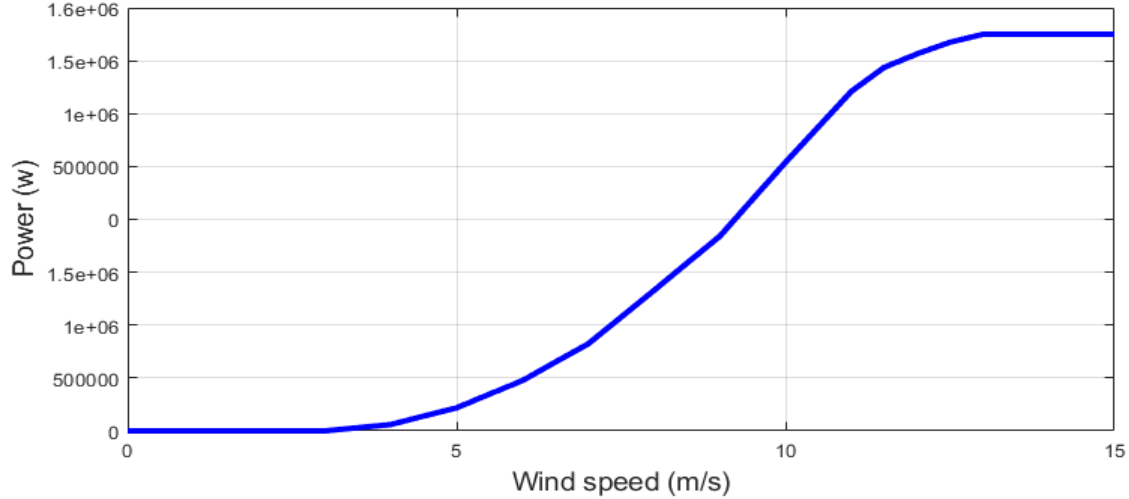


FIGURE 4. 22. Power curve of DFIG

Figure 4.23 shows the wind speed profile that is applied to the system. The profile of wind speed fluctuates between 9 and 13 m/s, which is a broad range of speeds. In this simulation study, the ramp increase and reduction in wind speed are considered. At the start of the simulation, the system starts with the stand steel condition and considers a wind speed of 9 m/s.

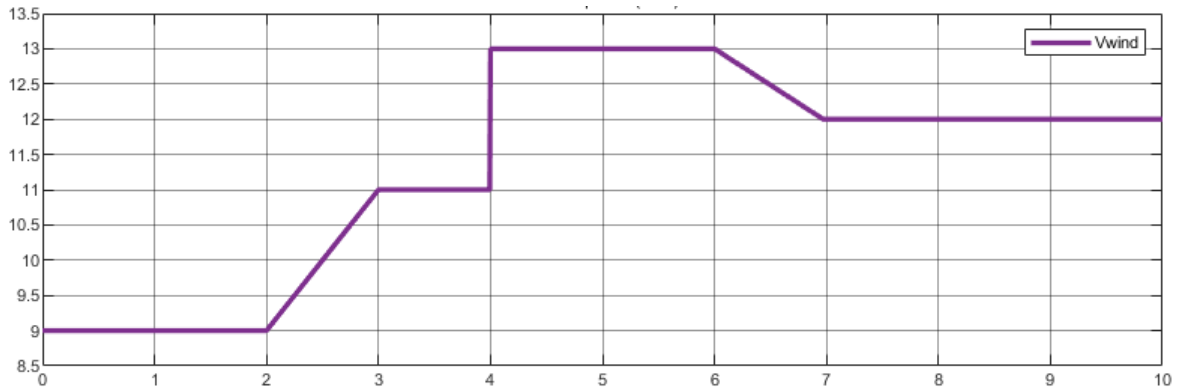


FIGURE 4. 23. Variations in wind speed input to the system

13 m/s is the rated wind speed of a wind turbine. At a wind speed of 13 m/s, the turbine, gearbox, and generator system are designed to enable the generator reach its synchronous speed. At the generator's synchronous speed, the rotor current is almost constant because there is no system slip. The actual and reference tracking speed of rotor at a variation wind speed simulation result is illustrated in figure 4.24. machine rotor rated speed is taking as a

reference rotor speed which is 183.167 rad/s. It is shown that the suggested control strategy tracks speed quite effectively.

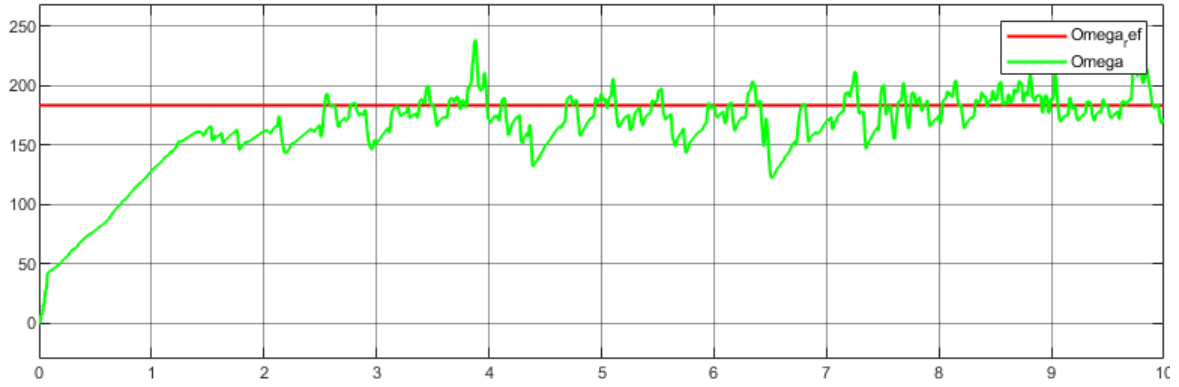


FIGURE 4. 24. Response of actual rotor speed

In this thesis, we used tip speed ratio controller to control the pitch angle of the wind turbine. Figure 4.25 illustrates the variations of the power coefficient ( $C_p$ ) and tip speed ratio ( $\lambda$ ) at different pitch angles. As shown in the figure, the yellow line indicated that the variations of ( $C_p$ ) and ( $\lambda$ ) at a pitch angle of  $0^\circ$ . Similarly the red line and the blue represents the relation of ( $C_p$ ) and ( $\lambda$ ) at pitch angles of  $1^\circ$  and  $5^\circ$  respectively. Due to the higher-performing perturbation of the MPPT controller, the suggested controllers maintain this value close to optimal throughout the simulation, with a minimum change  $C_p$  between 0.42 and 0.45.

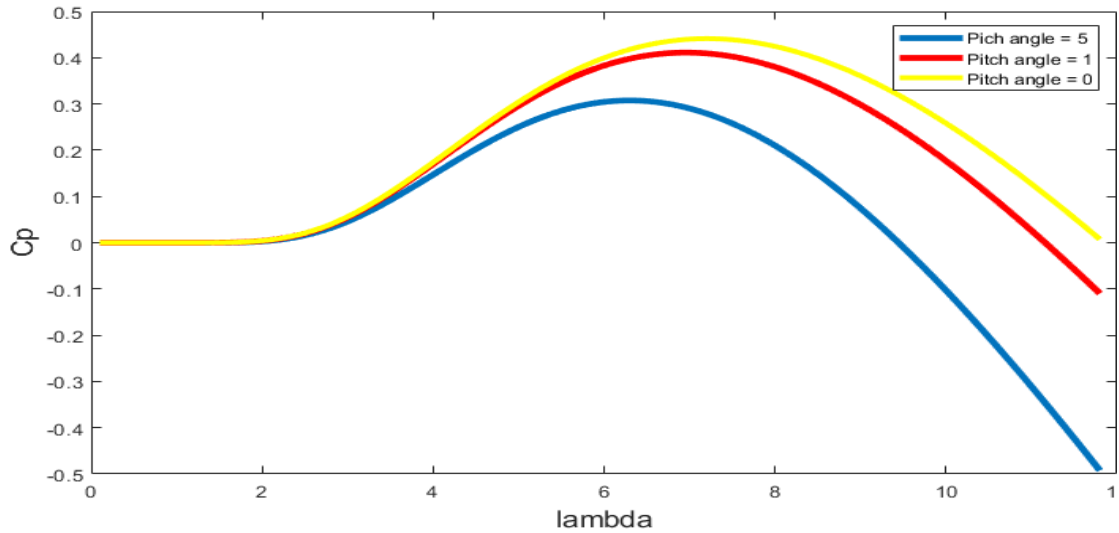


FIGURE 4. 25. Power coefficient and tip speed ratio variations at different pitch angles response

As shown in figure 4.25, at  $0^\circ$  pitch angle the blades are aligned parallel to the wind direction, thus the rotor's exposure to the wind, allowing for maximum energy capture. At  $1^\circ$  pitch angle the blades are slightly angled away from the wind. This small adjustment can help optimize performance in slightly higher wind speeds or reduce the load on the turbine

while still allowing for effective energy capture. At  $5^\circ$  pitch angle the blades are significantly angled away from the wind; thus, the turbine can maintain safe operating conditions and protect against mechanical stress and potential damage.

An indirect optimal torque controller used; the controller generates the reference torque which is represented by the red line, while the actual torque is developed by the machine represented by the blue line. Figure 4.26, which depicts the actual and reference torque responses.

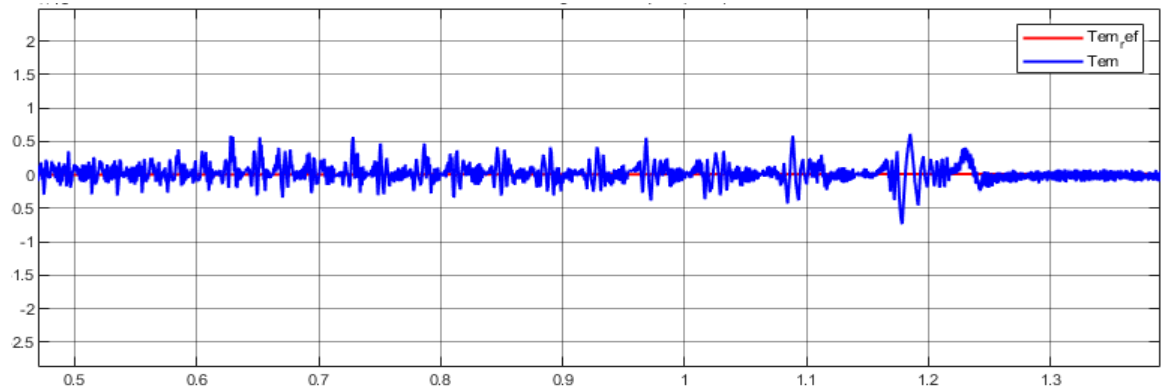


FIGURE 4. 26. Tracking the performance of actual and reference electromagnetic torque  
As shown in Figure 4.26, the reference torque followed and aligned with the actual torque. Thus, the proposed controller operates effectively.

Figure 4.26 and Figure 4.27 showed simulation results of the stator and rotor current waveform.

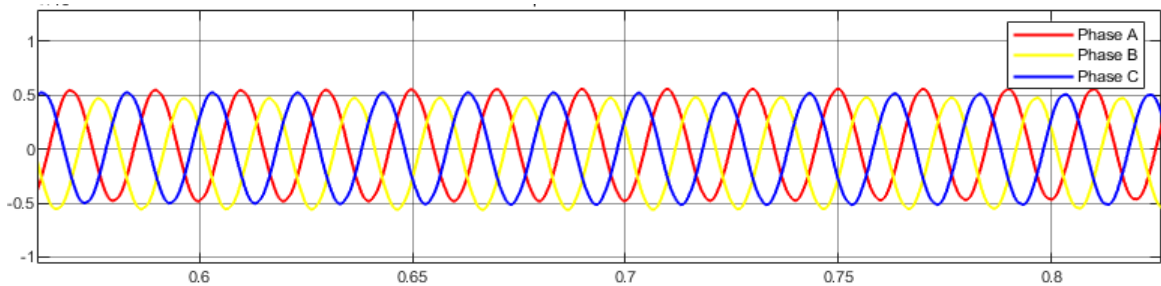


FIGURE 4. 27. The waveform of stator current

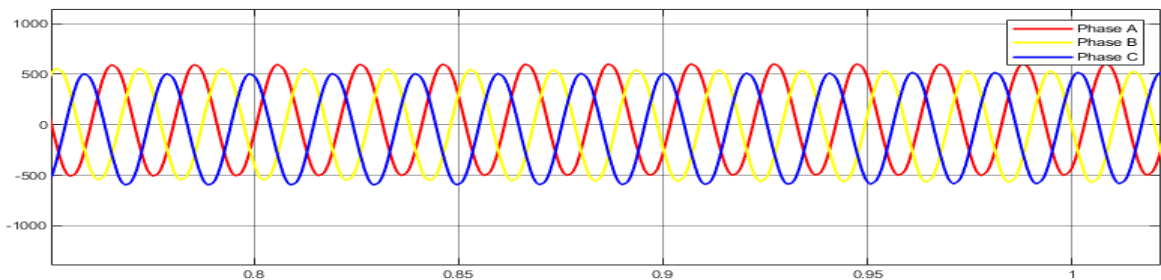


FIGURE 4. 28. The waveform of rotor Current

Figure 4.28 and 4.29 illustrates that the voltage and current of a single-phase stator are sinusoidal and balanced in accordance with IEEE 519 standards.

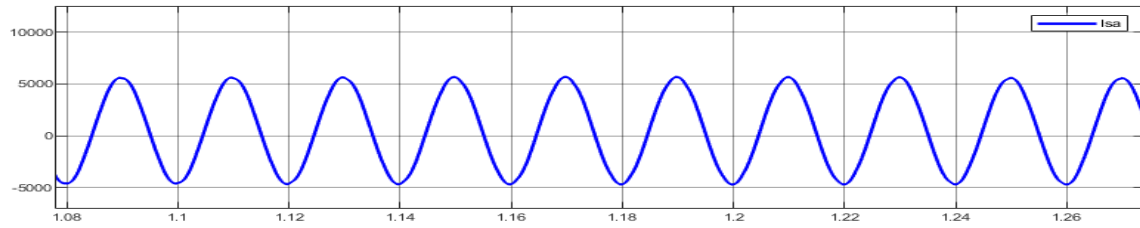


FIGURE 4. 29. Single-phase stator current

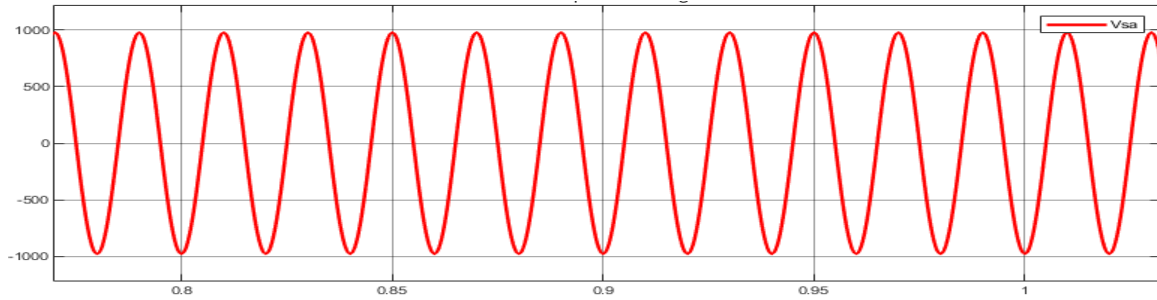


FIGURE 4. 30. Single-phase stator Voltage

The stator active power performance at different wind speed is depicted in Figure 4.30. The MPPT controller performs well dynamically even at variable wind speed.

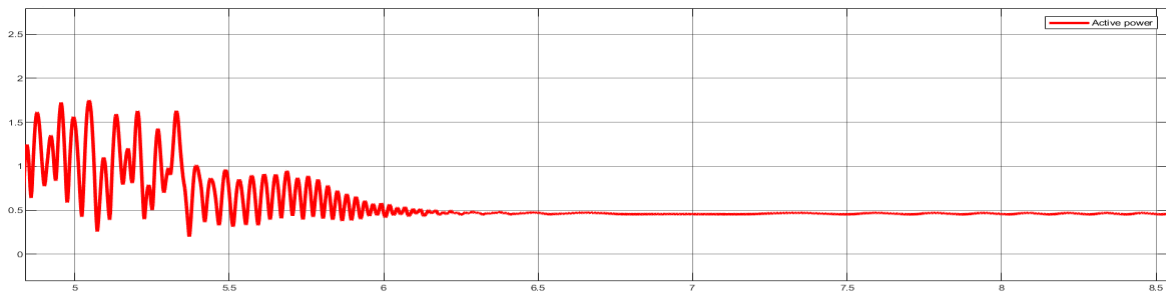


FIGURE 4. 31. Machine stator active power response

Figure 4.31 illustrates tracking performance of grid side reactive power in relation to reference power. When the reference for reactive power is changed from 0 to -400kVar at  $t = 5$  s, the controller behaves well and follows the reference reactive power without significantly overshooting.

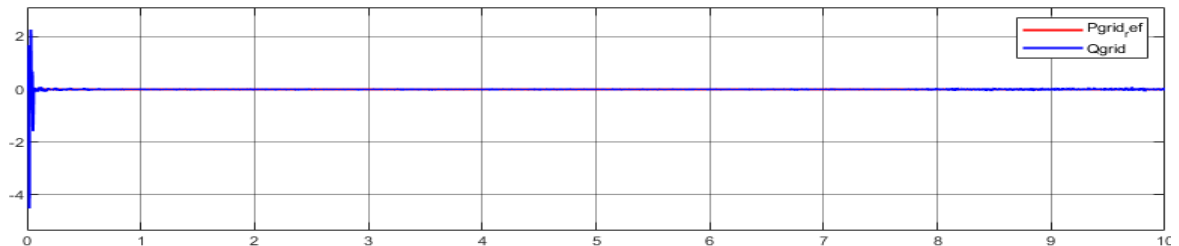


FIGURE 4. 32. DFIG grid side reactive power variation.

The flow of active and reactive power independently is provided by the direct and quadrature components respectively. Reference rotor quadrature current component is shown in figure 4.32.

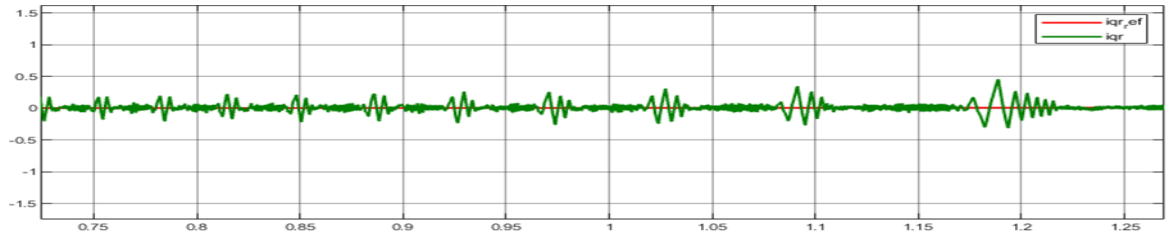


FIGURE 4. 33. Actual and reference rotor quadrature current tracking performance

The grid side currents direct and quadrature components are illustrated in figure 4.33 and figure 4.34 respectively. As shown in figure 4.33, the red line has indicated that the reference grid direct current and the actual grid direct current is indicated by green. Similarly, the grid side actual and reference quadrature current component is shown in figure 4.34. thus, during the simulation both the grid side direct and quadrature reference current component varies. Therefore, the proposed controllers have better tracking performance even under variations.

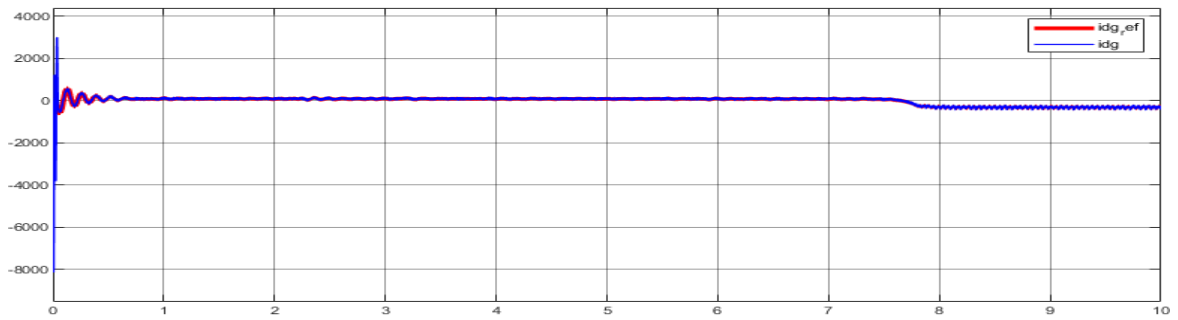


FIGURE 4. 34. GSC direct current component tracking performance

Since The quadrature components regulates the reactive power. In this thesis, for testing the controller performance grid side reactive power varied from 0 to 400kVar, the reference quadrature component varied accordingly and followed the actual quadrature component as shown in figure 4.35. Thus, the controller performed well.

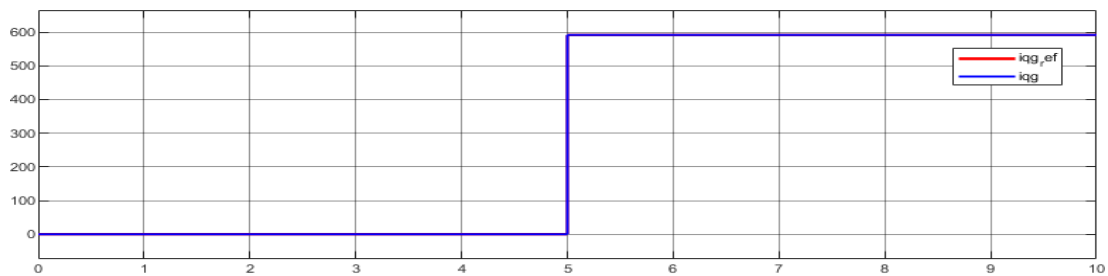


FIGURE 4. 35. GSC quadrature component tracking performance

1150V is taken as the DC link's reference voltage. Figure 4.36 showed the reference and actual DC link voltage variations. The actual and reference dc link voltage waveforms are matched without exceeding it.

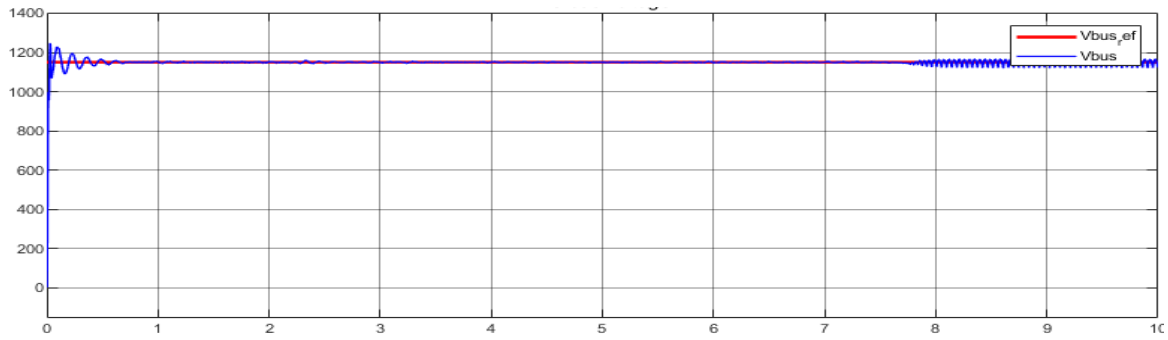


FIGURE 4. 36. DC link voltage tracking performance

The THD analysis of the stator current during five cycles at a fundamental frequency of 50 Hz, encompassing the frequency range of 0 Hz to 1 kHz, is shown in Figure 4.37. It is evident from this that at its rated speed, the generator's stator current has a THD content of only 0.79%.

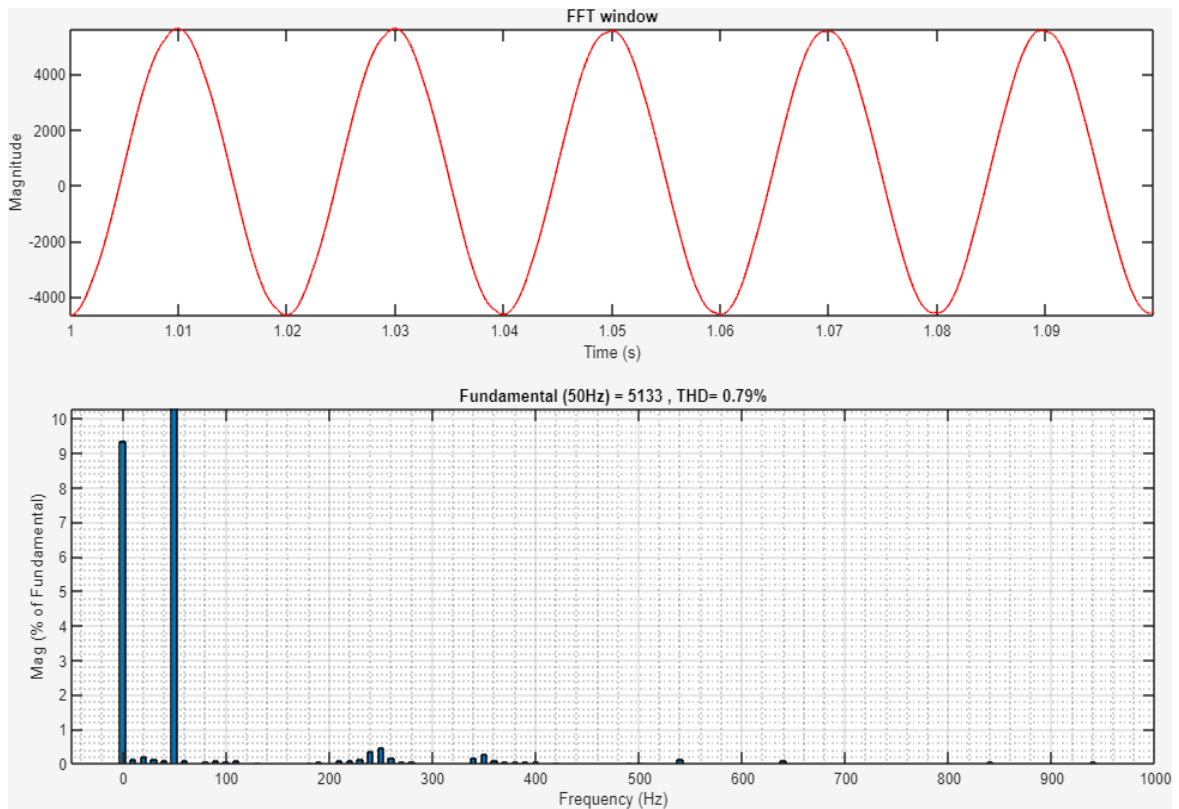


FIGURE 4. 37. Single phase stator current THD performance

Figure 4.38 displays the THD analysis for five grid current cycles with a fundamental frequency of 50 Hz and a frequency range of 0 Hz to 1 kHz. Figure 4.38 illustrates that grid current satisfies IEEE requirements with a THD content of only 1.42%.

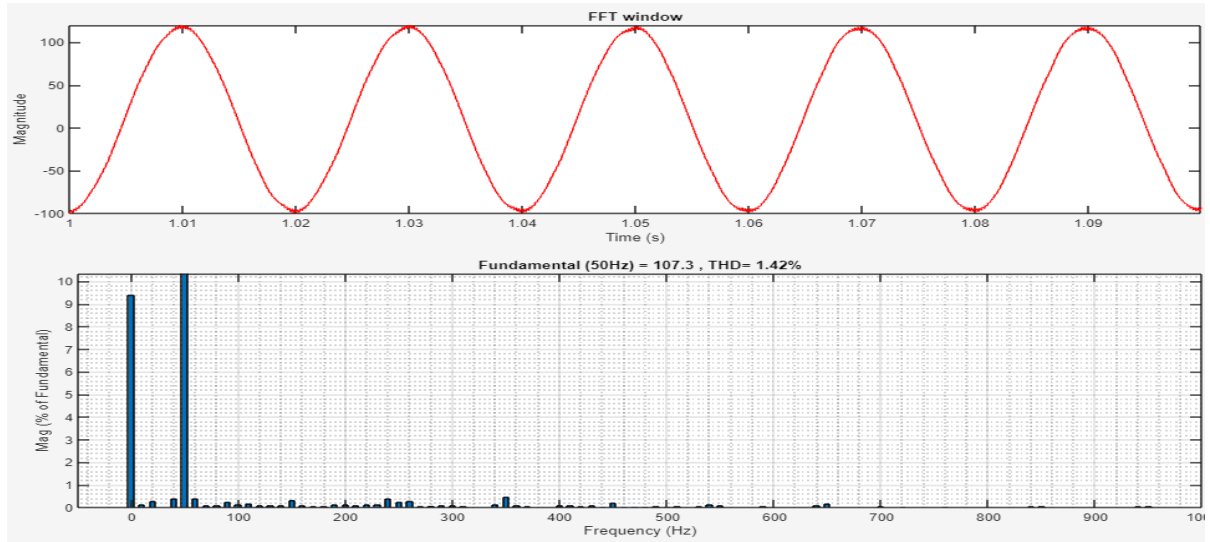


FIGURE 4. 38. Single phase grid current THD performance

We conclude from the simulation analysis and all the data that MPPT control works effectively for power tracking under a variety of wind speed conditions. In terms of dynamic performance and overshooting-free reference tracking, the RSC and GSC vector control technique with PI regulators performs well. Thus, the designed controller optimal power extraction from the wind in addition ensuring good dynamic and transient performance.

#### 4.5. Solar PV and wind hybrid system

In this scenario, the PV and wind hybrid system's performance was discussed under various sun irradiation and wind speed conditions. The Simulink model of the grid-connected PV and wind hybrid system is shown in Figure 4.39.

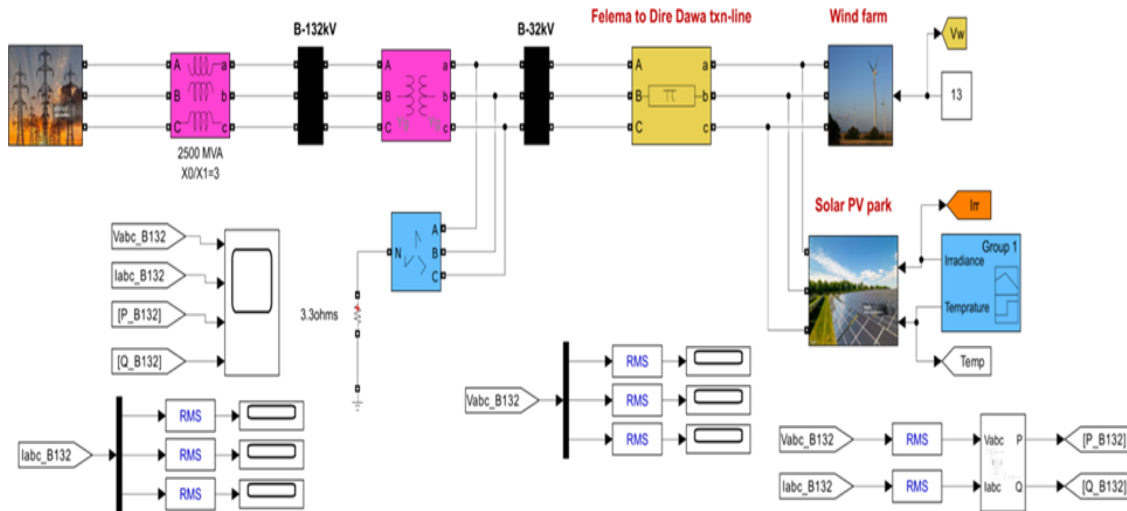


FIGURE 4. 39. Grid-connected photovoltaic and wind hybrid system Simulink model

The three-phase grid voltage's waveforms are shown in Figure 4.40, and it is clear that the grid voltage maintained constant.

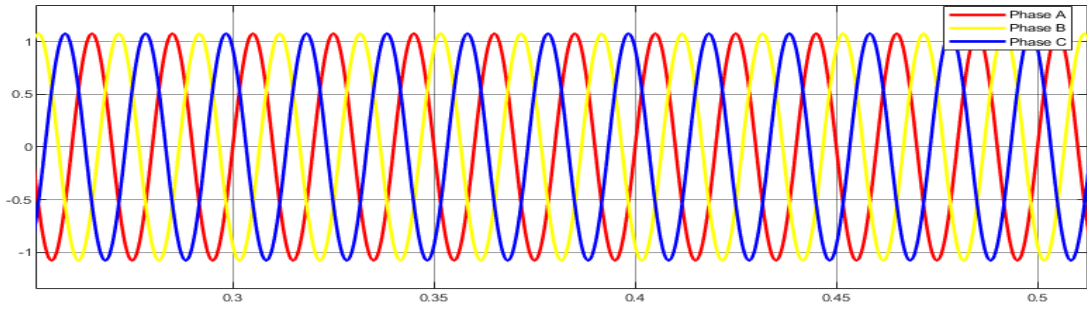


FIGURE 4. 40. Three-phase grid voltage

The grid side's current, which is sinusoidal, is shown in Figure 4.41.

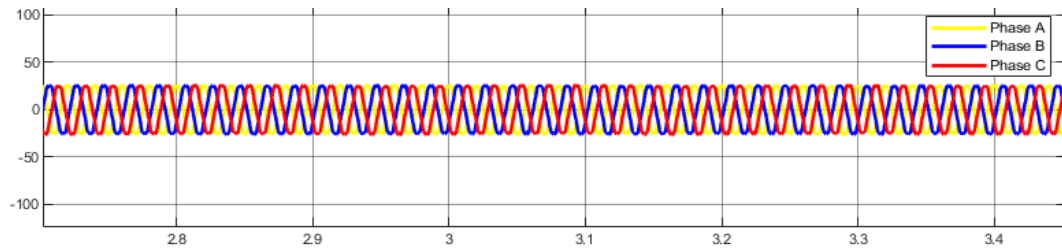


FIGURE 4. 41. Three phase injected grid current

Figure 4.42 shows the single-phase injected grid current waveforms.

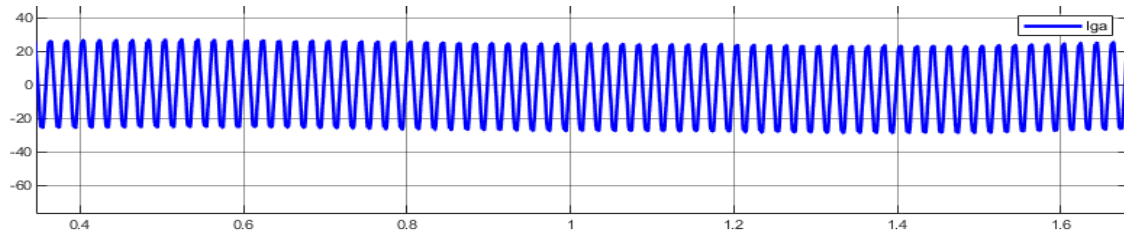


FIGURE 4. 42. Single phase injected grid current

Figure 4.43 illustrates the THD analysis for 25 grid current cycles with a fundamental frequency of 50 Hz and a frequency range of 0 Hz to 1 kHz. Grid current has a THD of 4.51%, as shown in the figure, which is below the IEEE standard of 5%.

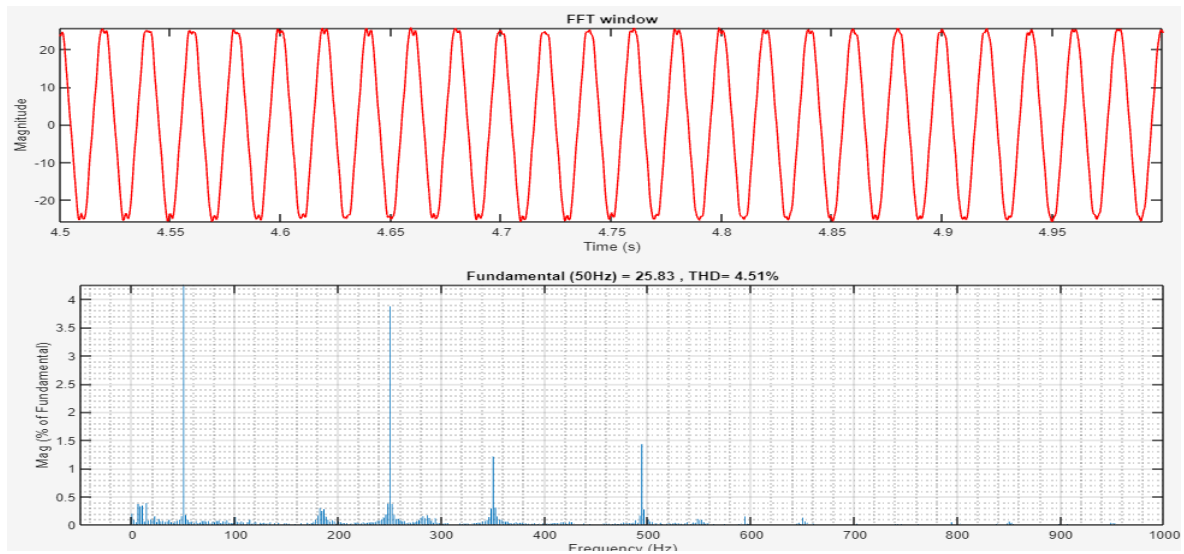


FIGURE 4. 43. THD performance of three injected grid current

The PV and wind hybrid system's power balance is shown in Figure 4.44. at STC, the PV's injected power was equal to 0.5 MW, while at base wind speed, the maximum power of the wind was equivalent to 1.5 MW.

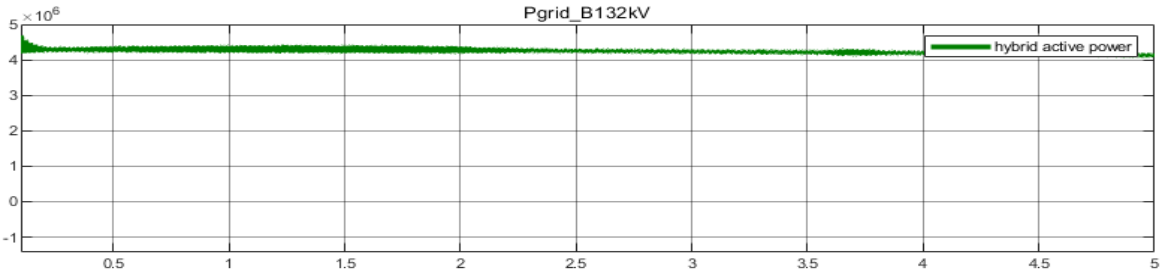


FIGURE 4. 44. PV and wind hybrid system active power

As shown in figure 4.44, the x-axis represented the time while the y-axis represented the injected active. Figure 4.45 showed the PV and wind hybrid system reactive power

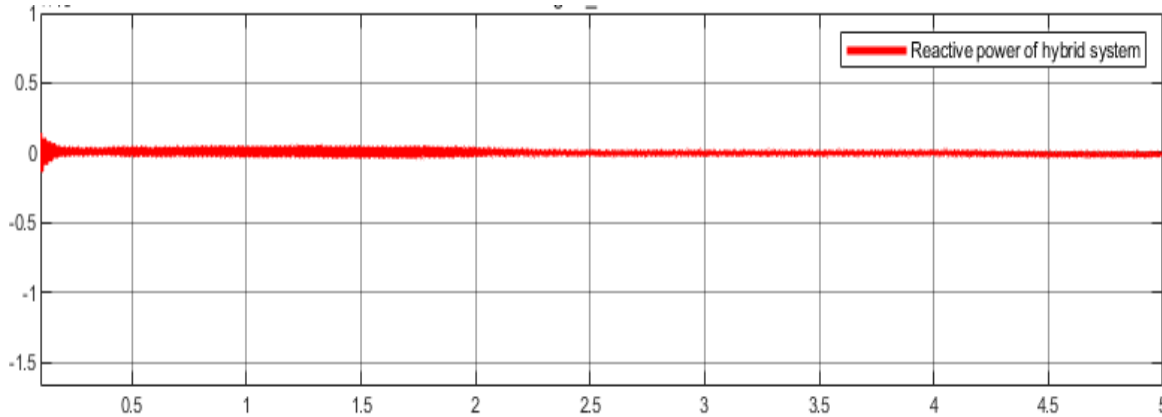


FIGURE 4. 45. PV and wind hybrid system reactive power

## CHAPTER FIVE

### 5. CONCLUSION, RECOMMENDATIONS AND FUTURE WORKS

#### 5.1. Conclusion

The design, modelling and optimization of grid connected solar PV and wind hybrid system has done successfully. This system comprised, both solar PV system and DFIG based WECS.

The Daily load demand of Dire Dawa city is obtained from EEP SCADA system which is 52.5MW. In order to supply this power to the city, an optimal configuration and sizing of renewable energy resources are required. Homer pro software is used as a tool to find the optimal configuration and sizing of renewable energy systems such solar and wind. The result showed that 20MW from PV, 22.5MW from wind and 10MW from grid satisfied the city load demand. Felema District is selected for this thesis study, due to proximity of the existing grid infrastructure, cheap and vast land availability, high wind speed and sun irradiance potential and ease access to transportation. The optimal system net present cost and levelized cost of energy is 42.3 million dollar and \$0.037/kWh respectively.

For further validation, Matlab/Simulink software is used as a tool for modelling and simulating the hybrid system. a two-stage grid connected PV system is designed, for the sake of simulation 500kW is taken. The PV array has used PO and FLC based MPPT for the purpose of comparison, the result showed that the latter MPPT has better tracking efficiency than the former. Thus, FLC based MPPT is recommended to be used. The PV inverter is connected to the grid via LCL filter and PLL. A decoupled VOC is used to control the grid connected PV inverter. Thus, the designed FLC based MPPT and decoupled VOC with LCL filter track and control effectively and efficiently.

1.5MW DFIG based WECS is designed and modelled. The rotor side converter is controlled by an indirect optimal torque controller track effectively and efficiently. The rated wind speed of the wind turbine is 13m/s, at this speed the wind turbine generated the rated power of 1.5MW. once the PV system and WECS is designed done, then connected to the grid via transformer and transmission line as per IEEE standards. finally, I conclude that, the finding of this thesis work satisfies the load demand of Dire Dawa city. Since, both solar and wind are renewable, sustainable and complementary to each other's, therefore they increase the country power reliability and security.

## **5.2. Recommendation**

In this thesis work the following recommendation has been given

- The study's encouraging findings support the start of an experiment to confirm the grid-connected solar PV and wind hybrid system in Dire Dawa's technical and financial feasibility. To find suitable locations for such hybrid systems, comparable feasibility studies ought to be carried out for other Ethiopian regions with abundant renewable energy resources.
- The government should think about enacting supportive laws and financial incentives, such as feed-in tariffs, tax credits, or subsidies, to help pay for the initial capital expenditures of renewable energy hybrid systems and increase their appeal to investors and project developers.
- As the proposed hybrid system is designed to be grid-connected, it is essential to ensure the reliability and stability of the existing grid infrastructure. Comprehensive grid integration studies should be carried out to identify any necessary upgrades or reinforcements to the transmission and distribution network to accommodate the increased renewable energy generation.
- To enable the successful implementation and long-term operation of these hybrid systems, it is crucial to invest in capacity building and knowledge transfer programs. This could include training for engineers, technicians, and local authorities on the design, installation, and maintenance of solar PV and wind energy systems.
- The findings of this thesis highlight the potential of advanced control strategies, such as the fuzzy logic-based MPPT algorithm, to enhance the overall performance of the hybrid system. Further research and development in this area can lead to even more efficient and cost-effective renewable energy solutions for Ethiopia.

## **5.3. Future Work**

By addressing these areas, future work can contribute to the continued advancement and implementation of efficient and sustainable energy solutions.

- Explore advanced optimization algorithms to improve system efficiency and cost-effectiveness.
- Investigate the use of battery storage systems to enhance reliability and manage demand fluctuations.
- Conduct comprehensive studies on the environmental impacts and benefits of the hybrid system over its lifecycle.

- Analyze the impact of government policies and incentives on the adoption and sustainability of hybrid energy systems.

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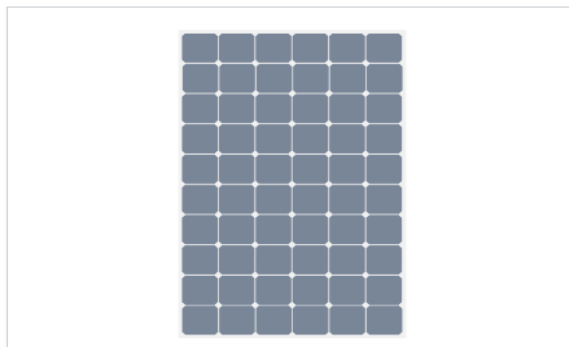
# APPENDICES

## Appendix A

### A-1: SunPower SPR-425E-WHT-D solar panel data sheet

#### SunPower SPR-425E-WHT-D solar panel

Updated: May 11, 2020



#### SunPower review score



4.53 1273 Reviews

Industry average score: 4.41

### A-2: Acciona AW-70/1500 wind turbine datasheet



#### Acciona AW-70/1500

[Start](#) / [Turbines](#) / [Acciona](#) / [AW-70/1500](#)

[Pictures](#)

[Datasheet](#)

[Power curve](#)

[Marketplace](#)

[Spare parts](#)

[Service](#)

[Models](#)

# 1,5 MW



X Power data

✓ 12 Pictures

X Models

#### Power

|                         |            |
|-------------------------|------------|
| Rated power:            | 1,500.0 kW |
| Flexible power ratings: | -          |
| Cut-in wind speed:      | 4.0 m/s    |
| Rated wind speed:       | 11.6 m/s   |
| Cut-out wind speed:     | 25.0 m/s   |
| Survival wind speed:    | -          |
| Wind zone (DIBt):       | -          |
| Wind class (IEC):       | -          |

## Appendix B: Parameters

### B-1: PV system parameters

| Data                                    |                                                               | Value                      |
|-----------------------------------------|---------------------------------------------------------------|----------------------------|
| Module type                             |                                                               | Sunpower SPR-425E<br>WHT-D |
| Sun irradiance ( $w/m^2$ )              |                                                               | 1000                       |
| Cell temperature ( $^{\circ}\text{C}$ ) |                                                               | 25, 45                     |
| Array data                              | Number of Parallel strings                                    | 236                        |
|                                         | Number of Series connected modules per strings                | 5                          |
| Module data                             | Power at MPP ( $P_{mp}$ )                                     | 425.007 W                  |
|                                         | Voltage at MPP ( $V_{mp}$ )                                   | 72.9 V                     |
|                                         | Current at MPP ( $I_{mp}$ )                                   | 5.83A                      |
|                                         | Number of Cells per module ( $N_{cell}$ )                     | 128                        |
|                                         | Open circuit voltage ( $V_{oc}$ )                             | 85.6 V                     |
|                                         | Short circuit current ( $I_{sc}$ )                            | 6.18A                      |
|                                         | Light generated current ( $I_L$ )                             | 6.1907A                    |
|                                         | Diode saturation current ( $I_0$ )                            | 5.6723e-11 A               |
|                                         | Diode identity                                                | 1.0248                     |
|                                         | Shunt resistance ( $R_{sh}$ )                                 | 825.5551 Ohm               |
|                                         | Series resistance ( $R_s$ )                                   | 0.38594 Ohm                |
|                                         | Temperature coefficient $V_{oc}$ ( $\%/^{\circ}\text{C}$ )    | -0.326                     |
|                                         | Temperature coefficient of $I_{sc}$ ( $\%/^{\circ}\text{C}$ ) | 0.019304                   |
| DC-DC boosts parameters:                | PV-link capacitor, $C_{pv}$                                   | 100 $\mu\text{F}$          |
|                                         | Boost inductance [ $L$ (mH) $R$ ( $\Omega$ )]                 | [0.5 0.05]                 |
|                                         | Boost capacitance, $C_{dc}$                                   | 10204 $\mu\text{F}$        |
|                                         | PWM Switching frequency                                       | 5 kHz                      |
| LCL filter parameters:                  | Converter side inductance ( $L_i$ )                           | 100 $\mu\text{H}$          |
|                                         | Grid side inductance ( $L_g$ )                                | 100 $\mu\text{H}$          |
|                                         | Filter capacitance ( $C_f$ )                                  | 500100 $\mu\text{F}$       |
|                                         | Damping resistance ( $R_f$ )                                  | 0.0509 $\Omega$            |
| PWM                                     | Switching frequency ( $f_{sw}$ )                              | 5 kHz                      |

**B-2: DFIG based WECS parameters**

| Data                    |                                             | Value                 |
|-------------------------|---------------------------------------------|-----------------------|
| Wind turbine parameters | WTG Version                                 | GW 1.5/77             |
|                         | Wind turbine nominal power (MW)             | 1.5                   |
|                         | Number of wind turbines                     | 1                     |
|                         | Rotor diameter (m)                          | 84                    |
|                         | Wind turbine rotor radius(m)                | 42                    |
|                         | Cut-in wind speed                           | 4 m/s                 |
|                         | Rated wind speed                            | 11.6 m/s              |
|                         | Cut-out wind speed                          | 25 m/s                |
|                         | Optimal speed ratio ( $\lambda_{opt}$ )     | 7.2                   |
|                         | Maximum Power coefficient ( $C_{p_{max}}$ ) | 0.44                  |
|                         | Number of blades                            | 3                     |
| Generator data set      | Generator Type                              | DFIG                  |
|                         | Rated Mechanical Power                      | 1.6 MW                |
|                         | Rated Apparent Power                        | 1.5 MVA               |
|                         | Generator inertia                           | 98.8 kgm <sup>2</sup> |
|                         | Speed Range                                 |                       |
|                         | Rated speed                                 |                       |
|                         | Damping constant                            | 0.001                 |
|                         | Number of Pole Pairs                        | 2                     |
| RSC controller          | Rated Rotor Flux Linkage                    | 1.7933 Wb             |
|                         | RSC Switching frequency                     | 4 kHz                 |
|                         | $K_{p_{id}}$                                | 0.52337               |
|                         | $K_{i_{id}}$                                | 232.61                |
|                         | $K_{p_{iq}}$                                | 0.52337               |
|                         | $K_{i_{iq}}$                                | 232.61                |
|                         | $K_{p_n}$                                   | 7904                  |
|                         | $K_{i_n}$                                   | 316160                |
| DC-link parameter       | Voltage                                     | 1150 V                |
|                         | Capacitance                                 | 100.73 mF             |

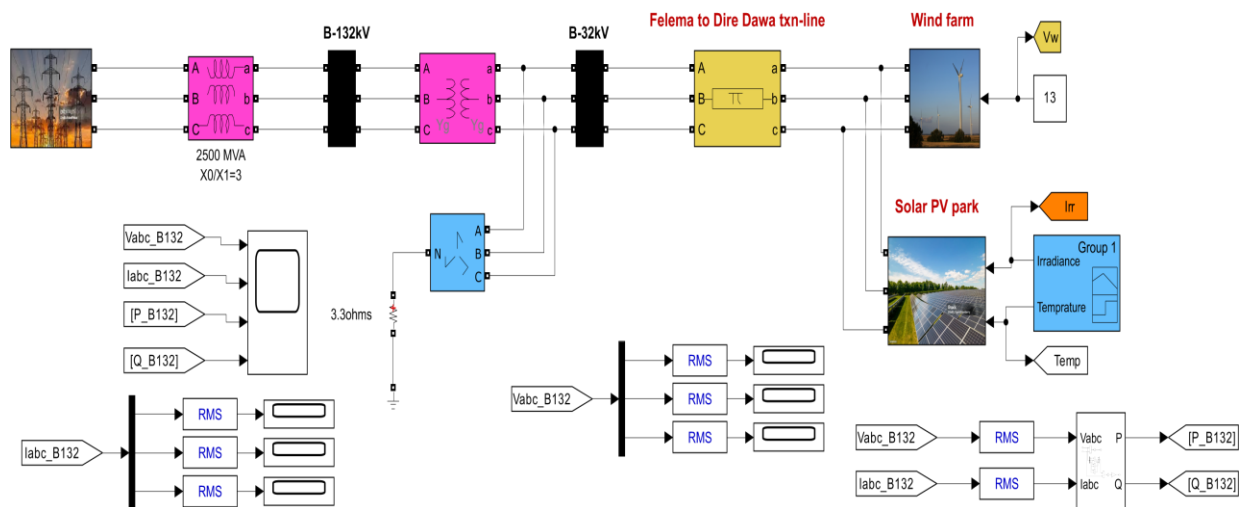
|                   |                         |                  |
|-------------------|-------------------------|------------------|
| GSC controller    | GSC Switching frequency | 4 kHz            |
|                   | $K_{p\_idg}$            | 0.1256           |
|                   | $K_{i\_idg}$            | 19.739           |
|                   | $K_{p\_iqg}$            | 0.1256           |
|                   | $K_{i\_iqg}$            | 19.739           |
|                   | $K_{P\_V}$              | -1000            |
|                   | $K_{i\_V}$              | -300000          |
| Filter Parameters | $L_g$                   | 200 $\mu H$      |
|                   | $R_g$                   | 0.001 m $\Omega$ |

### B-3: Transformer and transmission Line Parameter

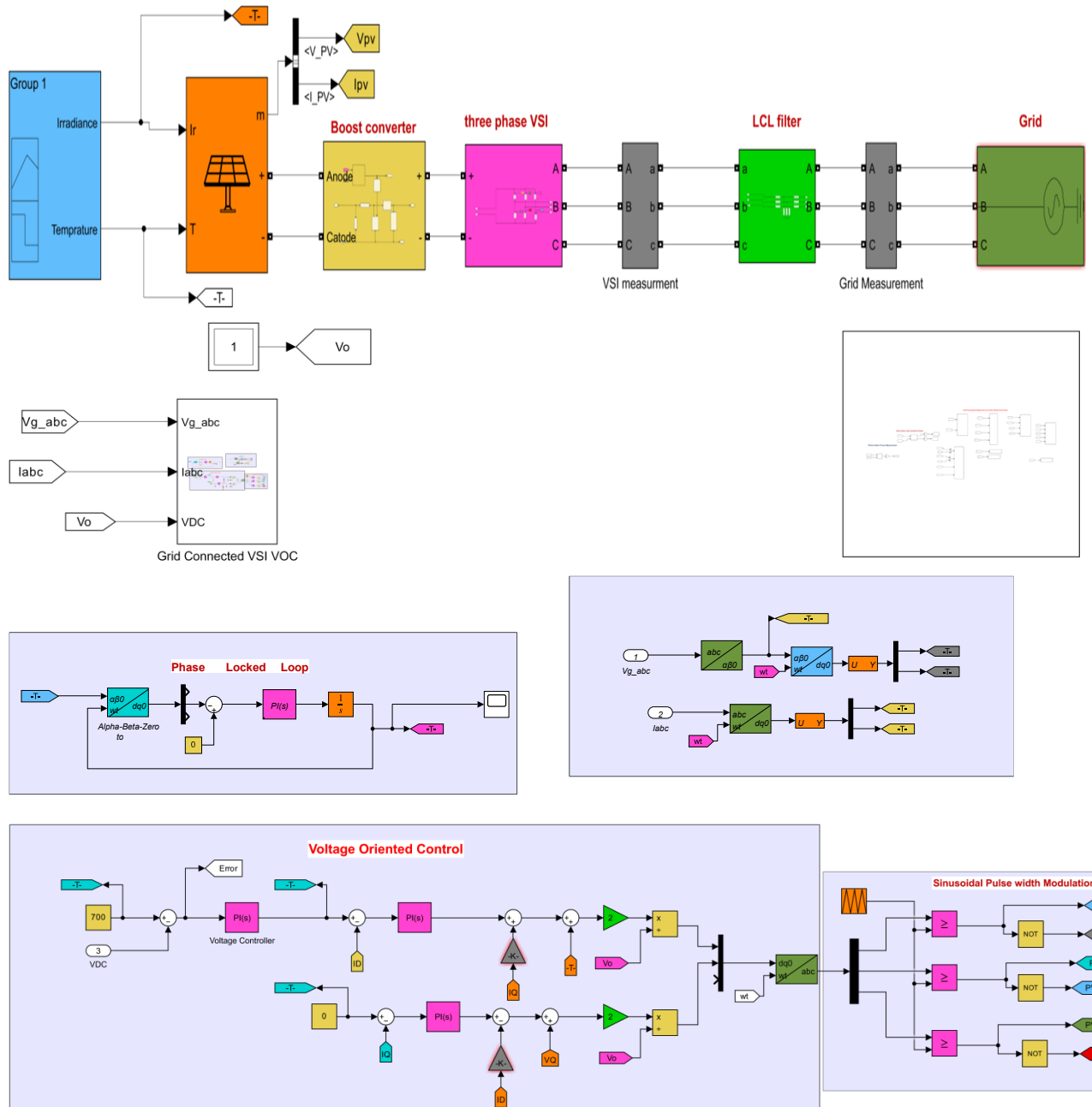
| Data              |                              | Value   |
|-------------------|------------------------------|---------|
| Power transformer | Three phase power            | 2.2 MVA |
|                   | Frequency                    | 50 Hz   |
|                   | Primary side L-L voltage     | 132 kV  |
|                   | Primary side total leakage   | 0.6     |
|                   | Secondary side L-L voltage   | 33 kV   |
|                   | Secondary side total leakage | 0.6     |

## Appendix C: Simulink Model

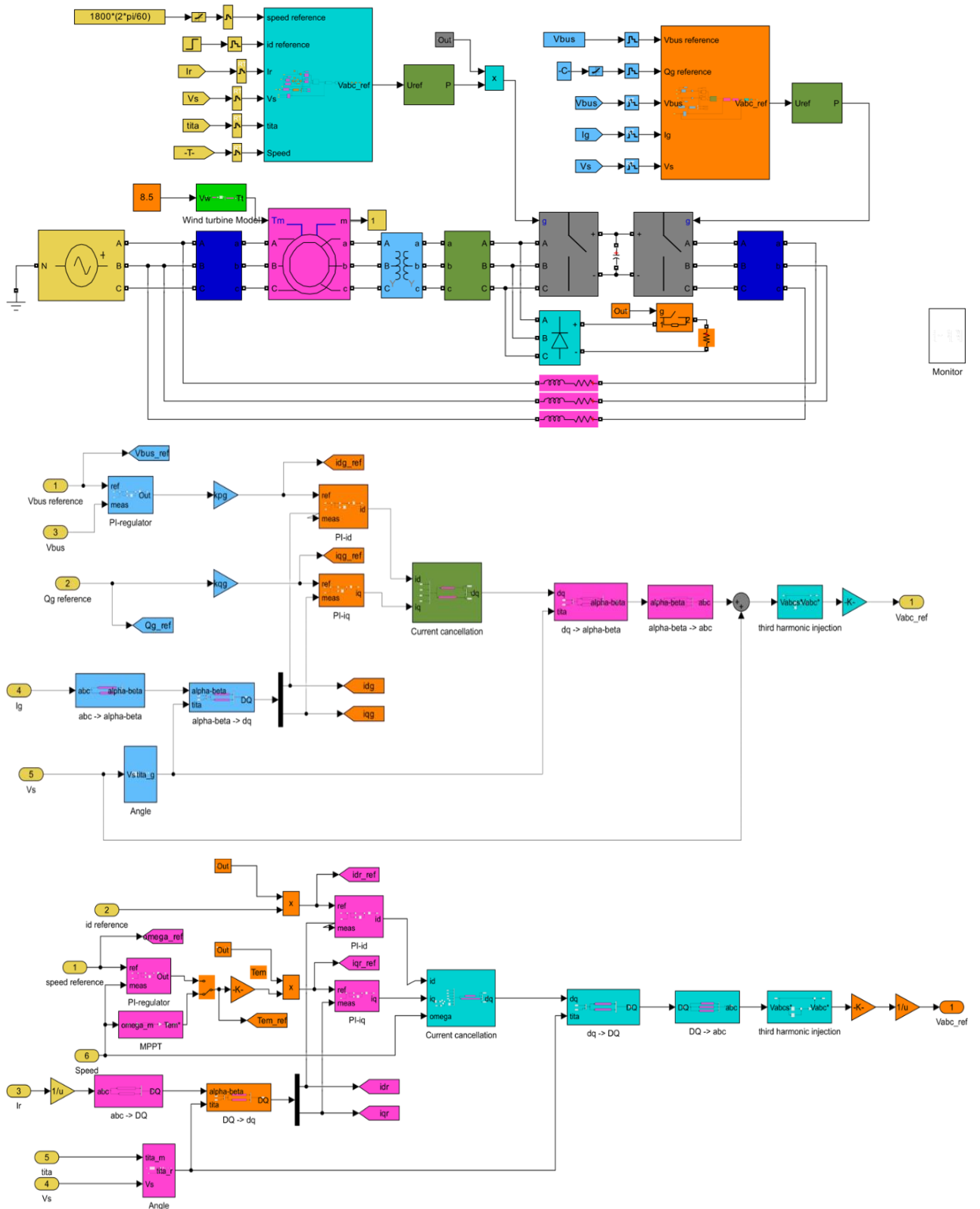
## Appendix C-1: Grid connected PV and wind hybrid system



## Appendix C-2: Grid connected PV system



## Appendix C-3: Grid connected DFIG based WECS



## Appendix D: MATLAB Code

### Appendix D-1: 500kW grid connected PV system parameters

```
clear
close all
clc
%%parameter of 500kw grid connected PV system
%%Boost converter parameter
Cpv=100e-6;           %%Decoupling capacitance value
Lb=0.5e-3;           %%boost inductance
Cdc=10204e-6;        %%DC link capacitance
fsw_b=5000;          %%Boost converter switching frequency
%%LCL Filter
Li=100e-6;           %%Inverter side filter inductance
Ri=1e-4;             %%Inverter side filter resistance
Lg=100e-6;           %%Grid side filter inductance
Rg=1e-4;             %%Grid side filter resistance
Lt=Li+Lg;            %%Total filter inductance value
Cf=500e-6;           %%Filter Capacitance
fsw_in=4000;         %%Switching frequency of inverter
Tpow=1/fsw_in/50;    %%Sampling period
%grid Parameter
Vg=400;              %%Grid line voltage
fg=50;              %%Grid frequency
```

### Appendix D-2: 1.5MW wind turbine power curve

```
%Cp and Ct curves
beta=0;             %pitch angle
ind2=1;
for lambda=0.1:0.01:11.8
    lambdai(ind2)=(1./((1./(lambda-0.02.*beta) + (0.003./(beta^3 + 1)))));
    cp(ind2)=0.73.*(151./lambdai(ind2)-0.58.*beta-0.002.*beta^2.14-13.2).*(exp(-
18.4./(lambdai(ind2))));
    ct(ind2)=cp(ind2)/lambda;
    ind2=ind2+1;
end
tab_lambda=[0.1:0.01:11.8];
%Kopt for MPPT
```

```

cp_max=0.44;
lambda_opt=7.2;
Kopt=((0.5*ro*pi*(Radius^5)*cp_max)/(lambda_opt^3));
P=1.0e+06*[0,0,0,0,0.0240,0.0560,0.0870,0.1390,0.1900,0.2600,0.3290,...
    0.4300,0.5310,0.6340,0.7360,0.8760,1.0160,1.1500,1.2840,1.3750,...
    1.4260,1.4700,1.5000,1.5000,1.5000,1.5000,1.5000];
V= [0.0000,1.0000,2.0000,3.0000,4.0000,4.5000,5.0000,5.5000,6.0000,...
    6.5000,7.0000,7.5000,8.0000,8.5000,9.0000,9.5000,10.0000,...
    10.5000,11.0000,11.5000,12.0000,12.5000,13.0000,13.5000,...
    14.0000,14.5000,15.0000];
figure
subplot(1,2,1);
plot(tab_lambda,ct,'linewidth',1.5)
xlabel('lambda','fontsize',14)
ylabel('Ct','fontsize',14)
subplot(1,2,2);
plot(V,P,'linewidth',1.5)
grid
xlabel('Wind speed (m/s)','fontsize',14)
ylabel('Power (w)','fontsize',14)

```

### Appendix D-3: 1.5MW DFIG based WECS Parameters

%%DFIG Parameters ->Rotor parameters referred to the stator side

```

f=50;                %stator frequency (Hz)
Ps=1.5e6;            %Rated stator Power (W)
n=1500;              %Rated rotational speed (rev/min)
Vs=690;              %Rated stator voltage (V)
Is=1068.2;           %Rated stator current (A)
Tem=8185;            %Rated torque (N.m)
p=2;                 %Pole pairs
u=1/3;               %stator/rotor turns ratio
Vr=2070;             %Rated rotor voltage (non-reached) (V)
Smax=1/3;            %Maximum slip
Rs=2.65e-3;          %Stator resistance (ohm)
Lsl=0.1687e-3;       %Leakage inductance (stator and rotor)(H)
Lm=5.4749e-3;        %Magnetizing inductance (H)
Rr=2.63e-3;          %Rotor resistance referred to stator (ohm)
Lrl=0.1337e-3;       %Rotor leakage inductance

```

```

Ls=Lm + Lsl;           %stator inductance
Lr=Lm + Lrl;           %Rotor inductance
Vbus=1150;             %DC bus voltage referred to stator (V)
sigma=1-Lm^2/(Ls*Lr);
Fs=Vs*sqrt(2/3)/(2*pi*f); %stator flux approx. (Wb)
J=98.8;               %Inertia
D=1e-3;               %Damping
fsw=4e3;              %switching frequency
Ts=1/fsw/50;          %sampling
%PI regulators
tau_i=(sigma * Lr)/Rr;
tau_n=0.05/4;
wni=100*(1/tau_i);
wnn=1/tau_n;
kp_id=(2*wni*sigma*Lr)-Rr;
kp_iq=kp_id;
ki_id=(wni^2)*Lr*sigma;
ki_iq=ki_id;
kp_n=(2*wnn*J)/p;
ki_n=((wnn^2)*J)/p;
%Three blade wind turbine Model
N=100;                %Gear ratio
Radius=42;            %Radius
ro=1.225;              %Air density
%GRID SIDE
Cbus=100.73e-3;
Rg=10e-6;
Lg=200e-6;
Kpg=1/(1.5*Vs*sqrt(2/3));
Kqg=-Kpg;
kp_v=-1000;
ki_v=-300000;
%PI REGULATORS—Grid side
tau_ig=Lg/Rg;
wng=50*2*pi;
kpidg=(2*wng*Lg)-Rg;
kpiqg=kpidg;

```

$$K_{iig} = (\omega_{ng}^2) * L_g;$$

$$K_{iiqg} = K_{iig};$$

$$R_{crowbar} = 0.1;$$

$$K_t = (-1.5 * P * (L_m / L_s) * F_s);$$