Cape Peninsula University of Technology

BUILDING INTEGRATED SOLAR PV-WIND AND BATTERY HYBRID SYSTEM

By:

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A thesis submitted in partial fulfillment of the requirements for the degree:

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DECLARATION

I, OLIVIER KIRAGA CYUBAHIRO, declare that the contents of this thesis represent my unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it is my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed Date

28/Oct/2020

ABSTRACT

This thesis proposes an energy management system (EMS) of a Microgrid comprised of a solar photovoltaic array, wind turbine, and a battery energy storage system, for a residential building positioned in a remote area. The aim is to design a control system that will rightly manage generated energy to meet the load demand. The power generated by the Microgrid is modeled to supply the residential load and charge the battery simultaneously. The battery storage will only be dispatched as the last resource to meet the load demand deficit when the combined power generated from the Microgrid is unable to sustain the residential load demand. Modeling and simulation are performed using MATLAB/Simulink

ACKNOWLEDGEMENTS

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It is my opportunity to express my gratitude to my brother Mutunzi Kiraga Elie and his wife Liliane Uwera for their support and encouragement.

DEDICATION

This work is dedicated to the Almighty LORD who always has good plans for me, For I know the plans that I have for you, declares the LORD, ‘plans for welfare and not for calamity to give you a future and a hope’ Jeremiah 29:11

To my Parents

To my brother’s family and my Sisters

To my wife and Kids

I dedicate this work to all relatives and friends for their contribution

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ABBREVIATIONS AND ACRONYMS

DSM:	Demand Side Management
EES:	Energy storage System
HEM:	Home Energy Management
CO_2:	Carbone Dioxide
PV:	Photovoltaic
EVs:	Electric Vehicles
IRP:	Integrated Resource Plan
PMSG:	Permanent Magnetic Synchronous Generator
OECD:	Organization for Economic Co-operation and Development
IEA:	International Energy Agency
PID:	Proportional, integral, and derivative
UML:	Unified Modelling Language
CHP:	Combine heat and power
TFSC:	Thin-film solar cell
a-Si:	Amorphous silicon
INC:	Incremental Conductance
P&O:	Perturb and Observe
CAES:	Compressed air energy storage
PHPS:	Pumped hydropower storage
PHES:	Pumped hydroelectric Energy Storage
NaS:	Sodium-Sulphur
Li-ion:	Lithium-ion
VRB:	Vanadium-Redox Flow Battery
NiCd:	Nickel-cadmium
Ni-Zn:	Nickel-Zink
SMES:	Superconducting Magnetic Energy Storage
LTS:	Low temperature superconductors
HTS:	High Temperature Superconductor
LPG:	Liquefied Petroleum Gas
SOC:	State of Charge
AADG:	Autonomous Active Distribution Grid
HVAC:	Heating, ventilating, and air conditioning
COE:	Cost of Energy
HDI:	Human Development Index
MOEA:	Multi-objective Evolutionary Algorithm
OLTC:	On Load Tap Changers
SDUS:	Smart distribution and utilisation system
SFCL:	Superconducting fault current limiter
EDLC:	Electric Double Layer Capacitors
PMSG:	Permanent magnetic synchronous generator

CHAPTER ONE
INTRODUCTION
1.1 Overview

South Africa is recently facing an energy crisis due to the high demand above the current conventional power generation capacity. This situation is accompanied by the need to reduce carbon emissions, which increased the calls for the adoption of renewable energy systems. The adoption of a solar PV-wind-battery hybrid system for the residential building sector will reduce pressure on the main grid power since residential loads are the most demanding load types during winter and summer periods(Hossain et al., 2017). The adoption of a renewable energy-based micro-grid is more useful in terms of energy-saving.

Numerous studies have been done in terms of increasing the efficiency of the micro-grid system for residential buildings. Some studies focused on the application of micro-grid in either off-grid mode as in (Bouharchouchel et al., 2013; Baneshi and Hadianfard, 2016; Mirbagheri et al., 2014; Al-falahi et al., 2016), or grid-connected mode as in (Abo-Al-Ez et al., 2012; Baneshi and Hadianfard, 2016; Chen and Xu, 2017), while other studies such as in (Zahboune et al., 2014; Anayochukwu, Ani Vincent, 2013; Qiang et al., 2016; Kumaravel and Ashok, 2011), are based on the integration of a battery system as a back-up which in turns increase the reliability of the system in terms of generating continuous power. Therefore, this concern of a battery application in the microgrid system either off-grid or connected to the grid is the most preferred for those who need to have stable, and affordable microgrid renewable power systems. Therefore, the integration of the battery system for the PV-wind hybrid system will effectively sustain the residential building load. This will reduce the stress on the network and increase the efficiency of a residential building for both winter and summer season. Most of the residential buildings' loads are using for cooking, heating, cooling, and lighting, where the peak hours are always between 7 to 9 Am during the morning, while 6 to 8 pm is considered as evening peak hours of a residential building in South Africa.

The proposed system in this thesis is intended to supply a residential building situated in a remote area with a solar photovoltaic panels-small wind and battery system which will be able to fully supply the needs of the studied residential load. The major benefits of this system are free carbon emissions, and limited maintenance, and operating costs. Their drawback is that their initial high capital cost. Therefore, the energy from wind and photovoltaic is used to supply the residential load, in case of energy from wind and PV are more than the load the battery is charged to be used as a back-up in case the energy from wind and PV are not enough to sustain the load, particularly during the night hours.

In this study, the main contribution is the development of an energy management system for the proposed Microgrid which is composed of a cluster of renewable energy and storage system.

1.2 Problem statement

Modern microgrids are composed of a cluster of renewable energy and storage systems. These systems can work off-grid to supply the needs of local loads. Due to the intermittent nature of different renewable energy sources such as wind and solar systems, the use of storage systems such as batteries is inevitable to ensure high reliability and stability of the microgrid, especially in the off-grid mode, where there is no backup from the main utility supply. This requires the design of a suitable energy management system.

The research questions that we need to answer in this case study are:

1. What is the contribution of applying a reliable energy management system for a micro-grid system?
2. What is the effect of a proposed energy management system for the overall system?
3. How accurate is the proposed energy management system?
4. How is the performance of a proposed energy management system for different scenarios?

1.3 The aim of the research

This thesis aims to propose an energy management system (EMS) for a residential microgrid. The microgrid model will use a storage battery as a backup system to store energy from the intermittent sources (PV and wind), then in a case where energy from renewable energy systems is not enough to sustain the load, power will be drawn from the battery. MATLAB will be used to simulate and test the performance of the Microgrid energy management system.

1.4 Objectives of the research

The Objectives of this study are:

1. To investigate the Performance of the microgrid system formed of the solar photovoltaic-wind system combined with a battery hybrid system for a residential building.
2. To achieve the highest output of solar photovoltaic - wind and battery hybrid system.
3. To design the energy management system which will be able to sustain the demand at any time of a day
4. To extract the maximum of a solar photovoltaic panel.
5. To extract the maximum of a wind turbine.
6. To investigate the superiority of the proposed system by making a comparison of other studies related to it as mentioned in the literature.
7. To evaluate and test the efficiency of the proposed system.

1.5 Choice of Topic and Interest

Issues of operation and management of a micro-grid system had been studied by the author and have been applied in different countries all over the world due to its advantages. Thus, the energy management model for the microgrid system suitable for the off-grid system is developed and tested in Simulink/MATLAB. The results of the proposed model will be able to fulfill the following point:

1. The obtained results will help to increase electricity access in the rural area, especially in South Africa.
2. The results will increase the reliability of the micro-grid system
3. The model will extract the maximum energy from wind turbines and a photovoltaic panel.

1.6 Limitation of the research

This work is limited to the performance of a designed energy management system for a micro-grid hybrid system comprised of a Photovoltaic and wind system using battery storage as a back-up system for an off-grid system.

1.7 Contribution to the knowledge

This study develops a computer model that can perform an energy management of a solar photovoltaic, wind, and battery hybrid system for rural or island areas, and investigate the effectiveness of the proposed system model for rural areas. This study increases confidence in implementing a 100% micro-grid renewable energy system in a rural area, where they can depend only on renewable energy such as wind and photovoltaic, either in South Africa or other regions.

1.8 Discussion and test of the proposed system

This study develops a computer model that can perform an energy management of a solar photovoltaic, wind, and battery hybrid system for rural or island areas, and investigate the effectiveness of the proposed system model for rural areas. This study increases confidence in implementing a 100% micro-grid renewable energy system in a rural area, where they can depend only on renewable energy such as wind and photovoltaic, either in South Africa or other regions.

1.9 Methodology

The method of this research work is divided as follow:

1. Mathematical modelling of the case study components, PV, Wind, Battery, and loads, to gain a deep understanding of their performance.
2. Mathematical modelling of the proposed energy management algorithm based on the state machine method.
3. Computer modelling of the case study components using MATLAB/Simpower systems and Simulink, and program the state machine algorithm suing state flow tool in MATLAB.
4. Different scenarios are conducted for testing the validity of the results

1.10 Brief Layout of thesis by mentioning what will be done in the next chapters

Chapter One: Introduction

The chapter briefly explains the background concerning the energy management of a microgrid system, different aspect such as problem statement, objectives, aims, research approach, limitation, the contribution of the research, are sorted out to make clear the work that was done.

Chapter Two: Literature Review

In this chapter, we deeply go into detail concerning the theory necessary to understand the micro-grid system. However, the literature review is divided into two sections: the first section presents the description of different items and components such as photovoltaic system, wind turbines, and battery storage system, the second section presents the reviewing of various papers related to the micro-grid renewable system to be updated with the area of research regarding energy management of a micro-grid system based on the PV, Wind and battery hybrid system.

Chapter three: Mathematical Modelling of the Hybrid microgrid and the proposed state machine energy management system.

This chapter discusses the mathematical modelling of the case study microgrid, which helps to understand the performance parameters of each component of the microgrid. Modelling of each component has been done to determine the required value of each component such as input voltage, output voltage, output power, and input power, etc.

Chapter Four: Computer modelling of the microgrid

In this chapter, the Modelling of each component particularly has been done and processed in detail in MATLAB/Simulink to give accurate results for our system.

Chapter Five: Research results and Discussion

In this chapter, the results are presented. The analysis and discussion of obtained results are conducted in detail in this chapter regarding the integration of energy management of a micro-grid renewable energy system for a residential house. The results discussion is used to confirm the proposed energy management system.

2.6 Chapter Six: Conclusion and Recommendation

This chapter gives the thesis conclusions and recommendations for future research work concerning microgrid control and operation.

2.7 Appendices

The appendices of this thesis present some of the diagram that we could not insert inside other chapters, but it includes different diagram from various system.

2.8 Summary

In this chapter, the introduction based on the topic is given and other issues related to the proposed system such as aims of the research, objectives of the research, choice of topic and Interest, the importance of the research, the contribution to knowledge, discussion and test of the proposed system, and methodology used to perform the research. A brief layout of the thesis is also included to easily help the reader.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

The interest in microgrid has grown tremendously due to its vital role in modern smart grid-architecture. Many operation and control strategies such as energy management within microgrids have been studied in several research works. This chapter presents a literature review related to the point of the study, where various papers related to renewable energy, microgrid, and the energy management system used for those microgrids have been reviewed. The literature review is divided into two sections. The first section presents different renewable energy systems in detail such as an overview of the availability, potential, interest, barriers, principal operational, and characteristics. The second section is reviewing papers related to microgrids and the energy management system used for those microgrids.

2.2 Renewable Energy Systems

Renewable energy technology has grown rapidly in the last decade due to its improvement and attractiveness. Therefore, studies show that renewable energy technologies have gained popularity for distributed generation for small power generation systems which are suitable for supplying electricity to the small sites. Therefore, the improvement of distributed generation, energy management, and energy storage systems have boosted the potential of renewable energy systems. Studies show that since the year 1990s, renewable energy technology systems have evolved significantly from focusing only on energy generation to energy storage and energy management (Liu and Su, 2008). The potential of renewable energy technology will strengthen energy security, improve the energy economy, and sustain the quality of the environment (Liu, and Su, 2008). Renewable energy systems differ from one to another, and their availability depends on several factors as the geographical background of the area, etc.

2.2.1 Availability of Renewable Resources

The availability of renewable energy resources depends upon the geographical location of the area (Karekezi and Kithyoma, 2002). Africa is considered as a continent filled with plenty of renewable energy resources such as wind, water, solar radiation, plant material, animal waste, and geothermal etc. (Karekezi and Kithyoma, 2002; Bugaje, 2006; Murenzi and Ustun, 2015). Since the topic of this thesis is focused on the microgrids involving solar and wind systems, we will introduce an overview of the potential of those systems in Africa along with a discussion of the battery technologies.

2.2.1.1 Solar potential

Solar energy resource is the most available renewable energy resources in the worldwide; it has known to have 23,000 TW of energy. Solar energy potential can sustain the whole energy required worldwide. However, according to OECD/IEA, (2014) the African continent is among the continent which receives a high amount of direct solar radiation. The Sahara Desert is considered as the area with high sunny in Africa which placing the continent in top position in terms of solar resources (Karekezi and Kithyoma, 2002). Researchers have found that 85% of African countries receive at least 2000kwh/m^2 per year of solar radiation (Anonymous, 2012). Therefore, Figure 2.1 shows the potential of solar resources in Africa, and the north of Africa has more potential than other areas.

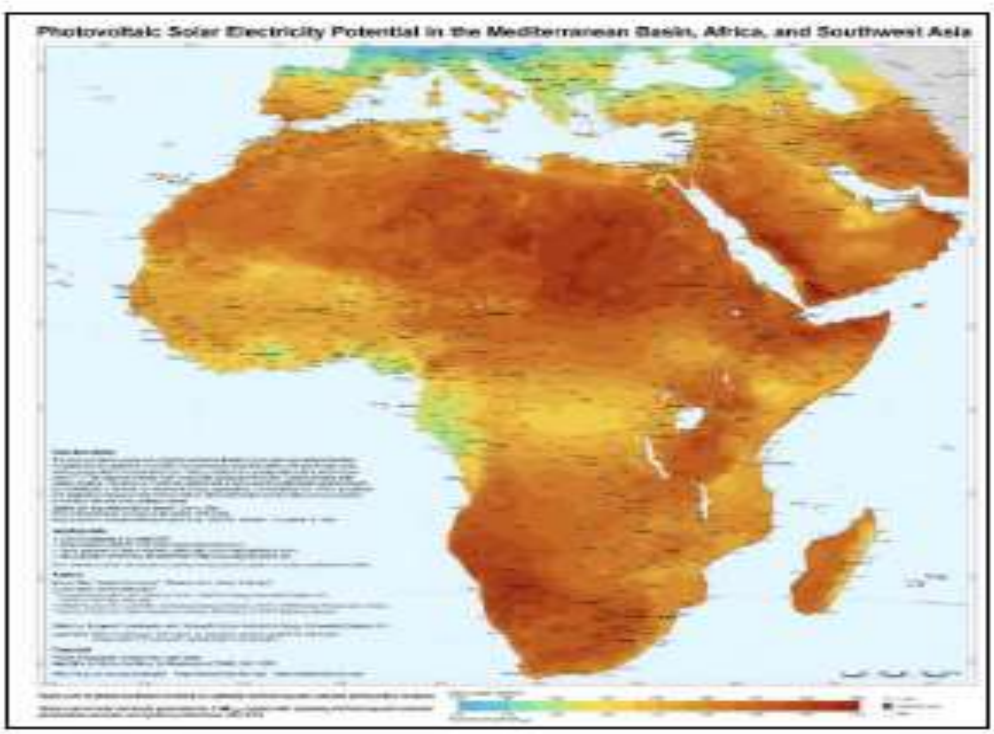

Figure 2. 1: Solar potential in Africa (Belward et al., 2011)

2.2.1.2 Wind potential

Currently, the potential of wind energy in Africa has been known worldwide, and some of the Asian, American, and European country have shown their interest to invest in wind energy generation farms in Africa (Mentis et al., 2015:111). The increase of wind energy extraction starts in 2006 (Mentis et al., 2015) However; the strong wind is in southern and northern Africa, but poor wind speed in the central of the African continent as seen in Figure 2.2. The African country with high wind energy production is Morocco with 1300 MW, Egypt with 550 MW, and Tunisia with 240 MW(OECD/IEA, 2014; Anonymous, 2012). Research made by Trevor M Letcher(2017) found that 70% of the energy demand of Europe can be covered by wind firm of North Africa and Europe, and stated that offshore wind firm can generate more power than the onshore wind firm.

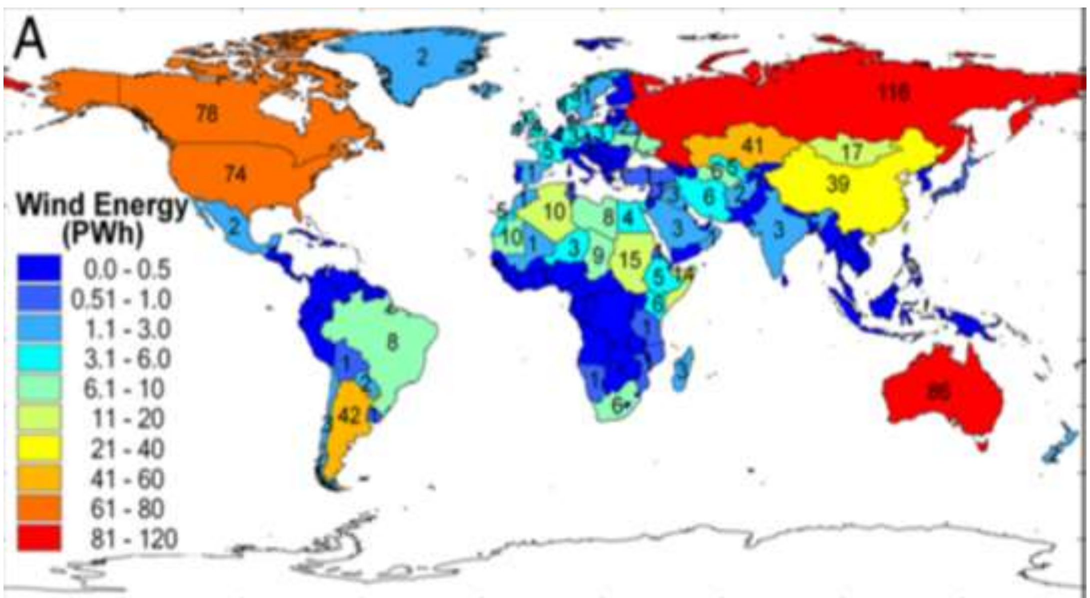

Figure 2. 2: Wind potential maps (Letcher., 2017)

2.2.2 What is driving the interest in Renewable Energy?

Various factors are collected and presented to prove the interest in renewable energy system, the main reason that is driving interest in renewable energy, is that its resources are all over the world, and has a very low (GHG) emission and has known as green energy production. Secondly the increasing prices of petroleum and the uncertainty of availability of petroleum for some areas in

Africa due to the lack of infrastructure such as roads, railways, etc. (Karekezi & Kithyoma, 2002:1; Abanda, 2012:2148). Thirdly, Some governments have cut off or lowered the tax paid for renewable energy devices used to generate electricity, for the private sector and different organizations involved in the renewable energy industry (Lesser, 2010).

2.2.3 Barriers to Renewable Energy Technology

The following aspects are considered as the major barriers to the penetration of renewable energy systems in Africa. Poor planning, lack of technician, clash of interests, High capital cost, poor efficiency, lack of private sector participation, lack of professional institution, and Lack of government plan to mobilize citizens to generate their electricity using renewable energy should have considered as barriers (Painuly, 2001:82; Slann, 2013).

2.3 Micro-grid

2.3.1 Introduction

A microgrid is a cluster of energy systems (Renewable and/or Non-Renewable) that can operate either independently or connected to the main grid, the purpose of a microgrid is to generate either AC power and/or DC power to the consumers (Justo et al., 2013). The microgrid system should be managed properly so that it can be able to supply generated energy economically and reliably. Microgrid systems should contribute to reducing global warming which is considered as currently a major problem. The other importance of microgrids is to supply local consumers who can work independently from the main grid so that at any time the generation meets the demand. Most problems of the microgrid system are power fluctuation due to the variability or uncertainty of renewable resources such as wind speed and solar radiation (Murenzi and Ustun, 2015). Therefore, in case of working independently, a proper battery system along with a reliable energy management system needed to be in place, and in the case of interconnection with the grid, the following condition is needed to be regulated in voltage regulation, frequency regulation. Both cases need a controlled power electronics system to manage islanded or grid-connected operation.

2.3.2 Micro-grid Structure system

Micro-grid is structured in such a way that it consists of Distributed Energy Resources (DER) and loads. Within the micro-grids system, energy sources and loads should be connected to and disconnected from the electrical power grid system without causing any disruption to the local loads (Liu and Su, 2008). Distributed Energy Resources (DER) can be divided into two groups, Distributed Generation (DG) and Distributed Storage (DS) as shown in Figure 2.3. Among the DERs are systems that produce thermal energy, electrical energy, or both electrical and thermal energy at the same time or Combined Heat Power (CHP) systems. DERs can be classified into two groups: a Controllable Distributed Generation (CDG) such as hydro-turbines, fuel cells, and microturbines, and Non-Controllable Distributed Generation (NCDG) such as photovoltaic (PV), wind turbines, and thermal collector. Therefore, for (CDG) they can only supply energy demand, the power output of (CDG) can be adjusted at a minimum and maximum value, whereas for (NCDG) their output power varies according to the variability of renewable resources such as wind speed and solar radiation. The Distributed Storage (DS) systems are the most key component of the microgrid due to their ability to store energy to meet the demand at any time. DS is such as batteries, electric vehicles, flywheels, etc. (Fikari et al.,2015; Liu and Su, 2008). Figure 2.3, shows a schematic diagram of the microgrid structure, comprised of DERs, DS systems, and loads.

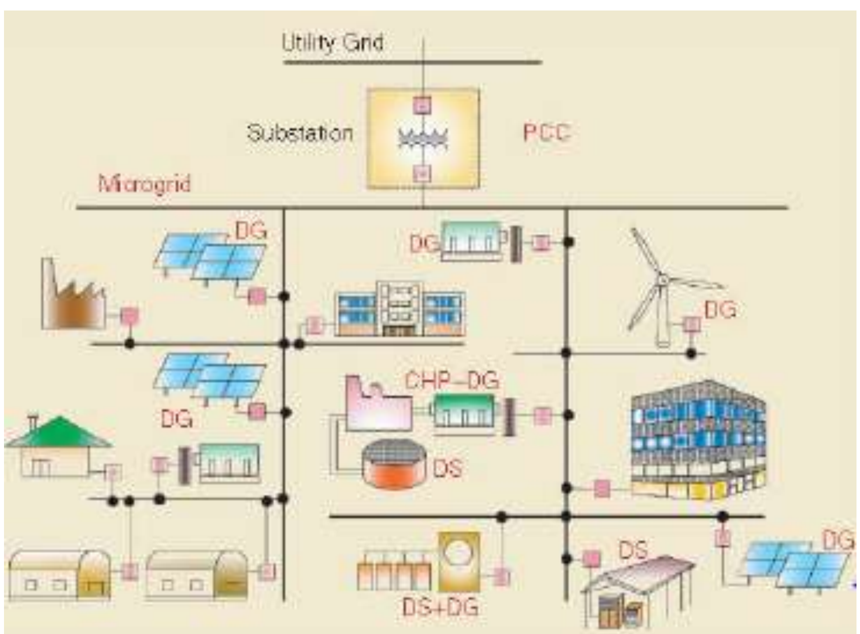

Figure 2. 3: Schematic diagram for Micro-grid structure (Fikari, Sigarchian, and Chamorro.,2015)

2.3.3 Micro-grid Types based on power generation

There are three different types of microgrid based on the power generated as shown in Figure 2.4, therefore, these three types of a microgrid are AC microgrid which generates AC power, DC microgrid which produces DC power, and both AC and DC powers which is known as a hybrid AC /-DC microgrid system (Moussavou, 2014).

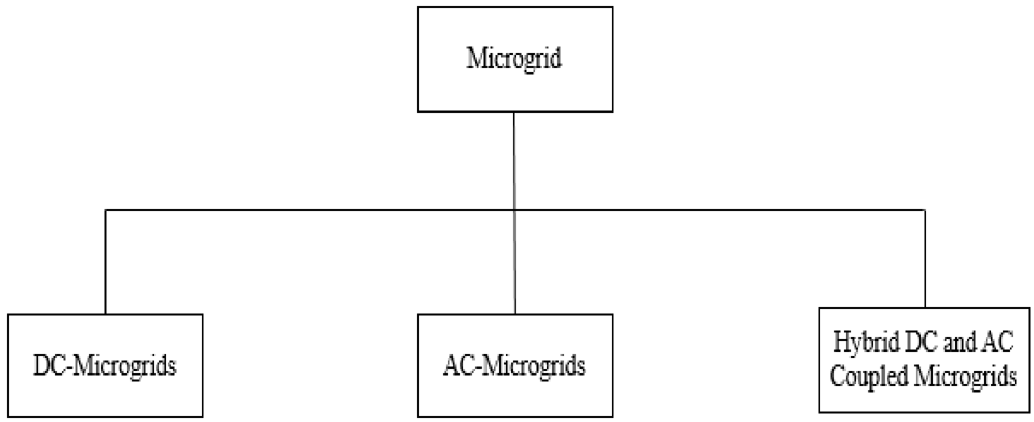

Figure 2. 4: Types of Micro-grid based on the types of generated power (Moussavou, 2014).

2.3.3.1 DC Micro-grid

DC microgrid is composed of generation units which produce a DC power as an output power connected straight to the DC bus bar such as photovoltaic panel, battery storage, and fuel cells, or it can be AC supply but connected to a DC bus bar via AC to DC rectifier (Lotfi, and Khodaei, 2017) DC microgrid can be used either in an off-grid or grid-connected mode, it has many advantages such as high efficiency, reliable and small size since DC microgrids don't use transformers, it also uses two cables instead of three or four cables as used by AC microgrids (Liu and Su, 2008). Most of the conventional loads are DC loads which can be connected straight to the DC micro-grid without any conversion of power. DC power can be transmitted with low losses (Chen and Xu, 2017). DC micro-grid still has many challenges, the most important is to handle faults, the lack of protective devices such as circuit breakers, protection relays as well as fuses, makes the DC microgrid system dangerous to control in case of faults (Liu and Su, 2008). Figure 2.5 shows the schematic diagram of a DC micro-grid system.

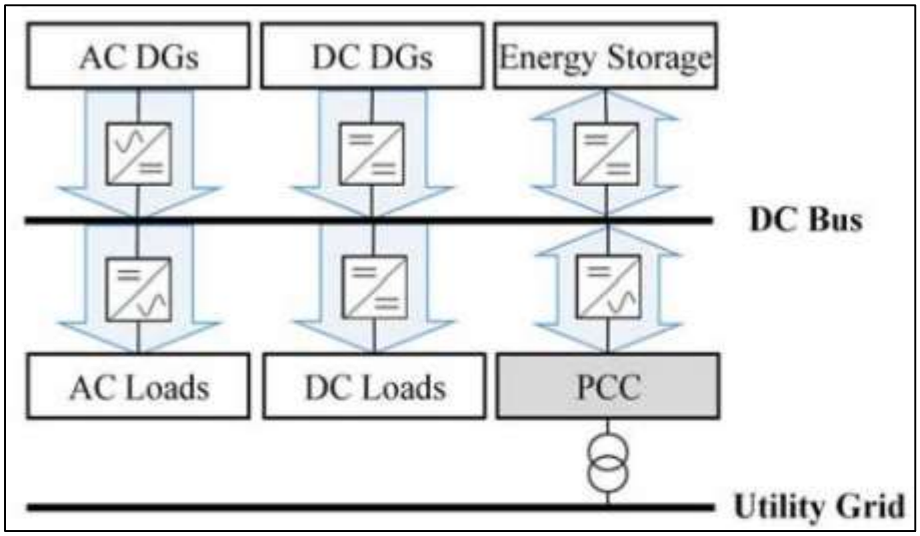

Figure 2. 5: Schematic Diagram of DC micro-grid (Lotf and Khodaei, 2015)

2.3.3.2 AC Micro-grid

AC microgrids produce AC power as an output connected straight to the AC bus bar. AC microgrid uses DERs such as biogas-based generation system, and wind energy conversion system. They can be in hybrid operation with the DC generation systems connected to an AC bus bar via DC to AC inverter (Lotfi and Hossein, 2017). AC microgrids have many advantages due to their nature, and the similarity in power with the grid which is always AC, and there are many components designed to use AC power (Chen and Xu, 2017). There are other advantages of using AC distributed generation, since AC microgrid can generate both active and reactive power for the consumer, to improve the power balance between generation and consumption (Moussavou, 2014). Figure 2.6 shows the schematic diagram of the AC microgrid system.

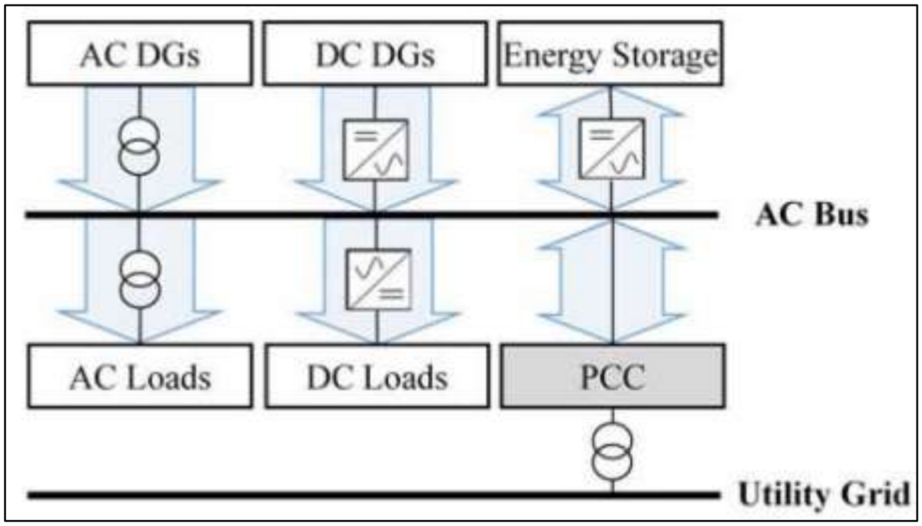

Figure 2. 6: Schematic Diagram of AC micro-grid system (Lotf and Khodaei, 2015)

2.3.3.3 Hybrid Micro-grid

Hybrid micro-grids hold both AC microgrid and DC microgrids. This type of micro-grid can operate with different kinds of loads. This is possible due to its hybrid nature which can provide both AC and DC powers. Within the microgrid system, the consumer can be able to generate electricity and sell it back to the main grid, in the case of grid-connected operation, this helps consumers to boost their economy. The only disadvantage of a hybrid microgrid system is the requirement of a coordinated control algorithm (Moussavou, 2014). Figure 2.7 shows the hybrid microgrid system comprised of both AC and DC systems.

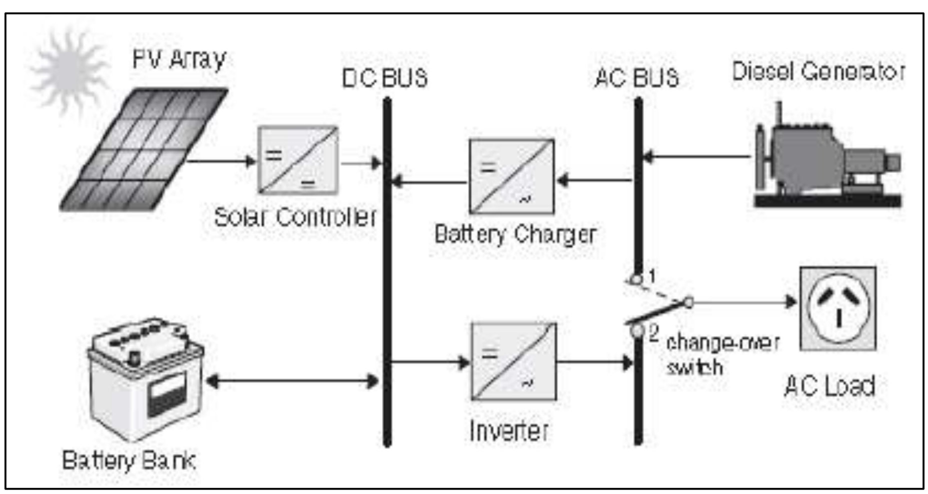

Figure 2. 7: Hybrid micro-grid system (Fikari, 2015)

2.3.4 Microgrid Types based on the operation model

There are two types of microgrids according to their operation model: grid-connected mode and off-grid (stand-alone or island).

2.3.4.1 Grid Connected Mode

Grid-connected mode has the exchange of active and reactive power with the main grid. Grid-connected operation increases the stability of the microgrid system since the system can still operate even in the absence of one of the microgrid DERs. Therefore, the advantages of a grid-connected microgrid are more attractive than off-grid microgrids, on top of that, the energy generated by renewable energy DERs can be either used directly or stored in batteries and back to the main grid. Therefore, a storage system is not necessary for grid-connected microgrids (Luu, 2015). Figure 2.8 shows the schematic design of a grid-connected system.

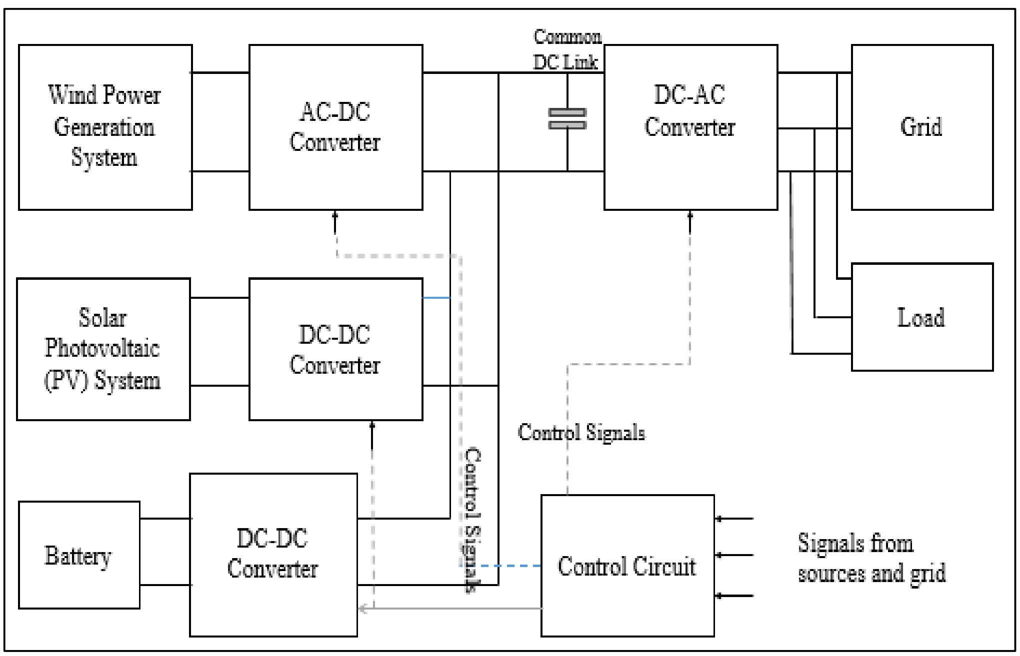

Figure 2. 8: Schematic Diagram of Grid-Connected system(Luta, 2014)

2.3.4.2 Off-Grid Model

Off-grid microgrids need a storage system to operate reliably because in case of energy generation exceeds the load demand, the excess energy is stored in the storage system, while in case the generated energy is not enough to meet the load demand the storage system will be required to sustain the load (Luta, 2014). Therefore, the off-grid microgrids need an energy storage system as a back-up. The main advantage of the off-grid microgrid is that it can be implemented anywhere regardless of the availability of infrastructures, and the main disadvantages are the uncertainty of renewable resources such as photovoltaic system operated only during the day due to the availability of solar irradiation, and wind which is not available all the time (Luu, 2015). The structure of the off-grid microgrid is shown in Figure 2.9.

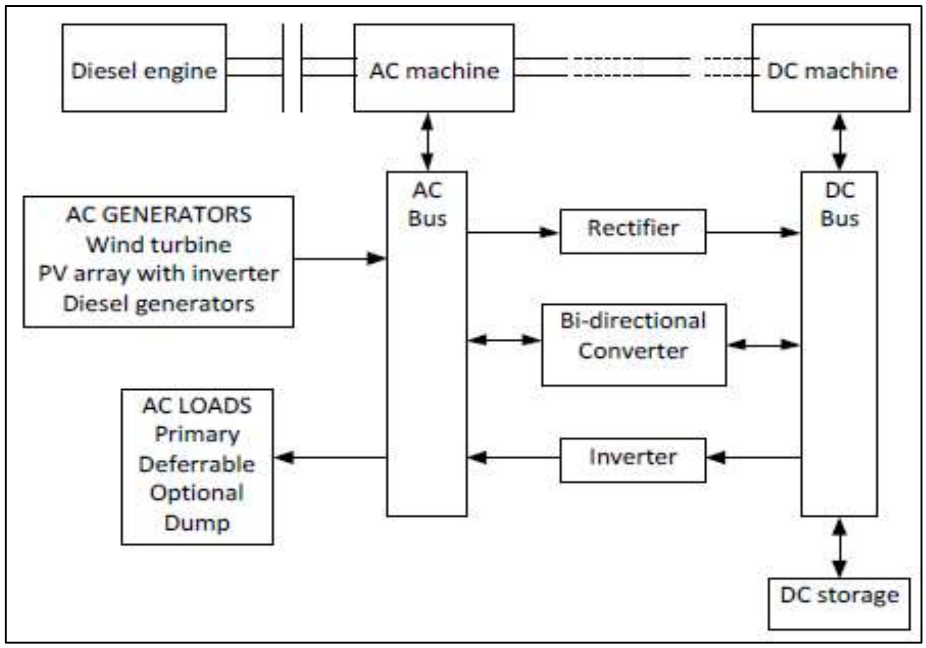

Figure 2. 9: Off-grid model (Luu, 2015)

2.3.5 Energy management of microgrid

Despite the tremendous increase in energy generation technologies, the energy needs to be managed to avoid a mismatch between load and generation. Therefore, different energy management systems can be implemented to make sure that the available energy is shared and managed such as: State machine, PID controller, fuzzy logic, etc. These energy management techniques have the same principle objectives, but each technique has its way of managing energy. In the following sections, details of the most important energy management methods are introduced.

2.3.5.1 State Machine

A state diagram, also known as a statechart diagram or a state machine diagram, is a transition between states an object can reach as well as an illustration of the states in the Unified Modelling Language (UML) (Swain et al., 2012). The statechart diagram can also model the behavior of a single object, specifying the sequence of events that an object goes through during its lifetime in response to events (Choi and Lim, 2018). However, statechart can be applied to many applications due to its simplicity. Statechart diagrams can show how an entity responds to different events by changing from one state to another as seen in Figure 2.10 (Golson, 1993; Wu, 2012).

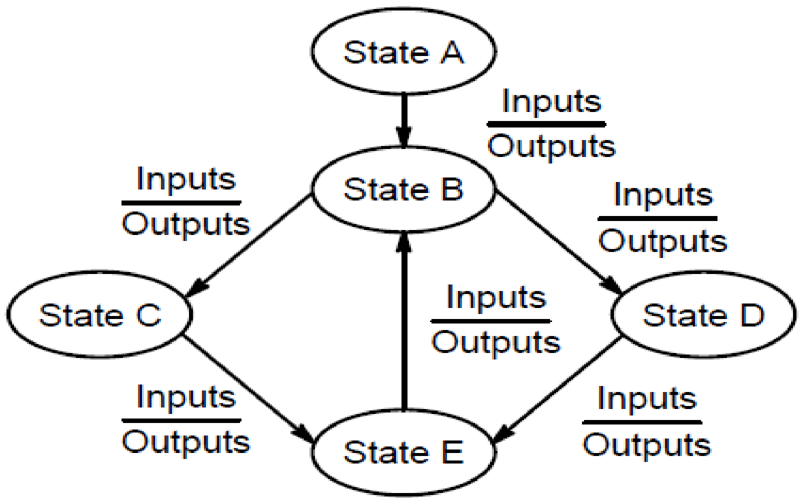

Figure 2. 10: Representation of State Machine (Golson, 1993)

2.3.5.2 Fuzzy Logic

Fuzzy logic is a machine that uses a transformed natural human language in a form of mathematical logic in which truth can assume a continuum of values between 0 and 1, and was invented by professor Lotfi Zadeh in the mid-1960s (Rojas, 1996). It uses variable linguistic and can provide a straightforward way to obtain the defined conclusions from both ambiguous and vague information. It is built-in with multi-state values such as (False/ True/partly false/ absolutely true etc.). As seen in Figure 2.11 the structure of fuzzy logic is presented and comprised of various parts including Input, fuzzifier, inference engine, demulsifier, output, and fuzzy knowledge base. Due to its ability to consider uncertainty and inaccuracies, the fuzzy logic gives a high valuable flexibility for reasoning (Dernoncourt, 2013).

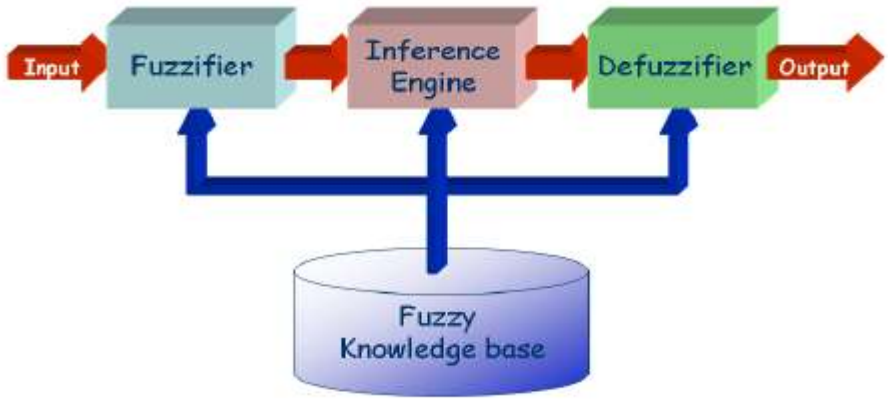

Figure 2. 11: Schematic Diagram of Fuzzy Logic structure (Dernoncourt, 2013)

2.3.5.3 Comparison between State machine and Fuzzy logic

There are many differences between the state machine program and the Fuzzy logic system, the most common things are that both are used to manage the energy between different sources and different load. In terms of variable load fuzzy logic react faster than the state machine program, and is more robust in case of measuring the ambiguity (Motapon et al., 2014). For the case of fixed load and big load state machine is more accurate. State machine has much more advantages such as easy to develop, easy to add other states, easy to test, and easy to predict (Choi and Lim, 2018).

2.4. Solar energy conversion system

Solar panels systems are used as energy conversion systems of sun radiation into light or heat (Sanaye and Sarrafi, 2015). Solar photovoltaic (PV) systems convert solar radiation into electric power feeding DC or AC loads using power electronics converters and solar thermal systems which convert solar radiation into heat which is used to warm up water and combined heat and power (CHP) (Cho et al., 2014). The three types of solar energy conversion systems are shown in Figure 2.12 (Energy Maret Authority and Building and Construction Authority). In this chapter, we will focus on the solar photovoltaic (PV) systems, as it is a main component of the residential microgrid case study.

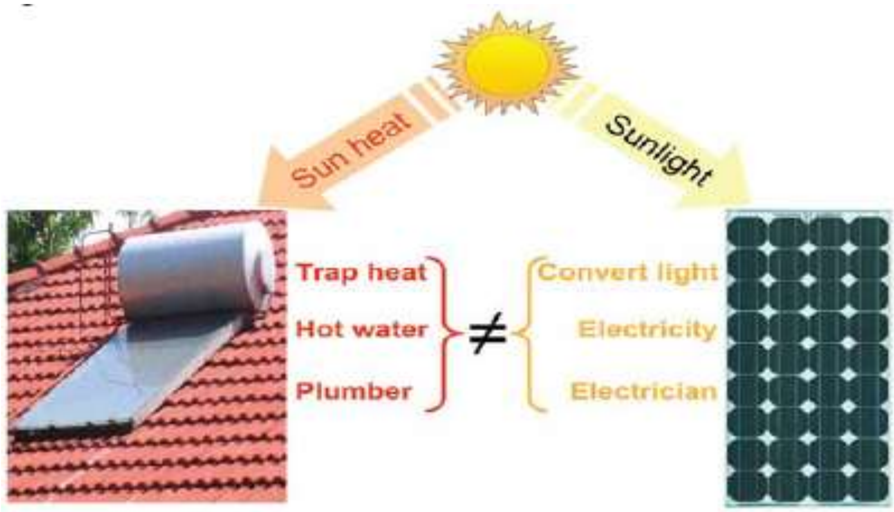

Figure 2. 12: Solar photovoltaic and solar thermal system (Energy Market Authority and Building and Construction Authority).

2.4.1 PV system

A photovoltaic system relies on the conversion of sunlight into a DC and voltage and current at the cell's terminal (Liu and Su, 2008). The amount of solar radiation fallings on the surfaces of the photovoltaic cells, the area occupied by the photovoltaic cell, and the efficiency of the photovoltaic cell determine the amount of DC voltage and current that the photovoltaic system can produce (Liu and Su, 2008). A photovoltaic system can be mounted in such a way that it uses a fixed or tracking system of the sunlight at any time; this tracking system can either be a single axis or double axis. However, the tracking system has some advantages over the fixed one, due to the reason that tracking system can track the sunlight at any time and it can extract the maximum possible from sunlight direction, but the disadvantage is that requires some added features and material which make the system more expensive. Low efficiency is still a major problem for researchers and manufacturing companies.

2.4.2 Technology of Solar PV

The technology of solar photovoltaic is differing from cell to cell, it is mostly comprised of two categories, the first one is the crystalline silicon, and the second one is a thin film which in turn considered to be new and is always gaining popularity due to its advantages. Crystalline silicon is the most used PV cell nowadays since is the first PV cell technology used before the other one, this crystalline silicon is divided into two groups such as monocrystalline and polycrystalline. In terms of efficiency monocrystalline is a little bit in advance compared to the other kind of PV cells. (Energy Market Authority, and Building and Construction Authority; Lasnier, 2017). Contrary to the efficiency of technologies, the thin film silicon has a low loss compared to the other technology such as crystalline silicon both monocrystalline and polycrystalline which has a high loss if the temperature exceeds the normal one of $25°C$ (Energy Market Authority, Building and Construction Authority; p:8.).Therefore, Figure 2.13 shows different categories of technologies of PV cells such as the crystalline silicon, and a thin film (Energy Market Authority, Building and Construction Authority; p: 7).

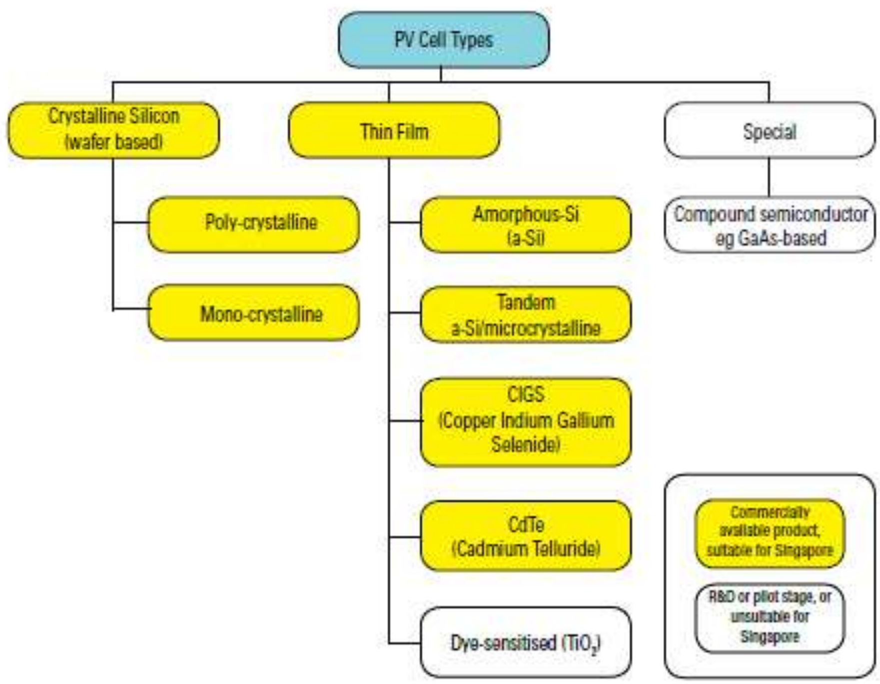

Figure 2. 13: Technology of Solar PV system (Energy Market Authority, and Building and Construction Authority; p: 7)

2.4.5 Maximum Power Point Tracking System Techniques for Solar System

For a photovoltaic system to be able to operate at the highest level, the maximum power point tracking techniques needed to be able to extract the maximum possible from the photovoltaic system. However, there are many techniques of maximum power point tracking system which can be applied and make the photovoltaic system to operate at its maximum possible. Such methods are the perturb and observe (P&O), incremental conductance (INC), Fuzzy Logic, Neural Networks, DC-link capacitor droop control, Load Current Maximisation, Fractional short circuit current, fractional open-circuit voltage, Current Sweep, Ripple Correlation Control, dP/dV or dP/dI Feedback control, etc. (Sumathi et al., 2015). Each of these techniques differs in many ways such as speed, cost of application, right tracking for changing temperature or irradiance, required sensors, etc. Therefore, the most used algorithm for maximum power point (MPPT) according to (Sumathi et al., 2015:115; Moussavou, 2014) is Perturb and Observe (P&O) and Incremental Conductance.

2.4.5.1 Perturb and Observe Algorithm (P&O)

The 'perturb and Observe' method is a cost-effective technique since its operation is based on the application of one voltage sensor which is used to sense the voltage of a photovoltaic voltage array. According to Moussavou (2014), the perturb and observe is a fast technique in case we have changing temperature and irradiance due to its possibility to adapt to the changing, while the drawback of the technique is that the perturb and observe technique due to its unstable state is not able to operate at a high perturbation rate (Sumathi et al., 2015). Figure 2.14 shows the P&O flow chart diagram.

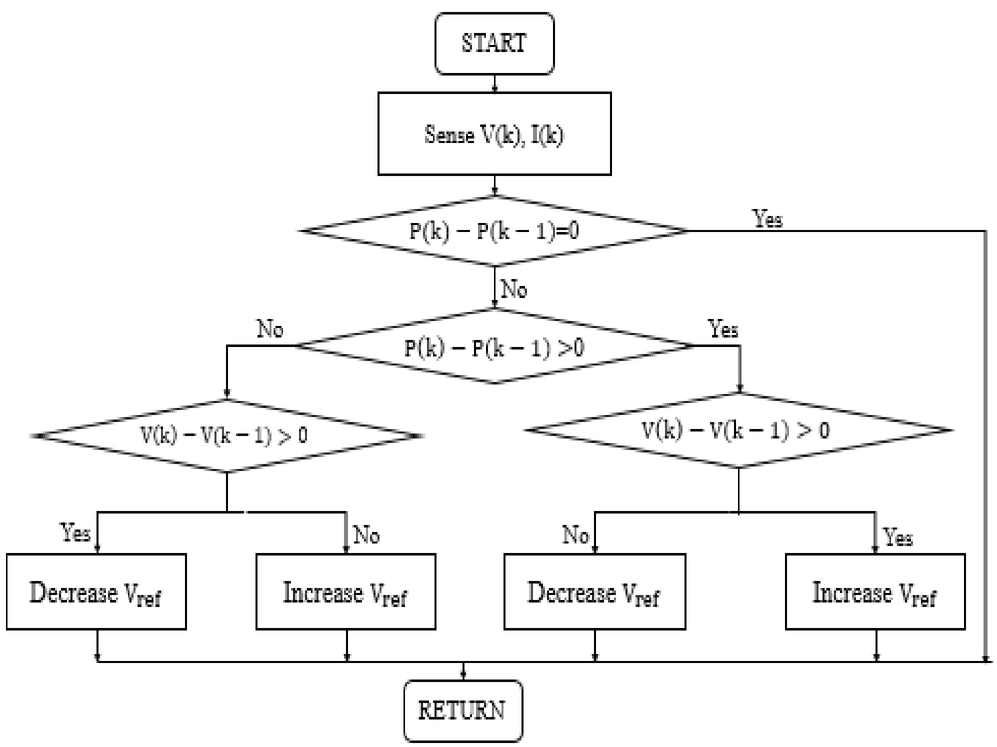

Figure 2. 14: P&O flow Chart Diagram (Sumathi, Kumar and Surekha., 2015)

2.4.5.2 Incremental conductance

The incremental conductance algorithm is based on the adjustment of the PV array voltage to the MPP voltage. It senses the output current and voltage of the PV array by using two current and voltage sensors. However, the system is based on the instantaneous and incremental conductance of the PV module (Lokanadham and Bhaskar, 2012). Therefore, Figure 2.15, shows that the incremental conductance is zero at the MPP, while on the right side is decreasing and the left side of MPP is increased as shown with equations below, the instantaneous conductance is represented by the right side, while the incremental conductance represents by the left side, whereas Figure 2.16 shows the flowchart of an Incremental Conductance (Lokanadham and Bhaskar, 2012).

$\frac{dI}{dV} = -\frac{I}{V}$ at the MPP 2.1

$\frac{dI}{dV} > -\frac{I}{V}$ at the left side of MPP 2.2

$\frac{dI}{dV} < -\frac{I}{V}$ at the right side 2.3

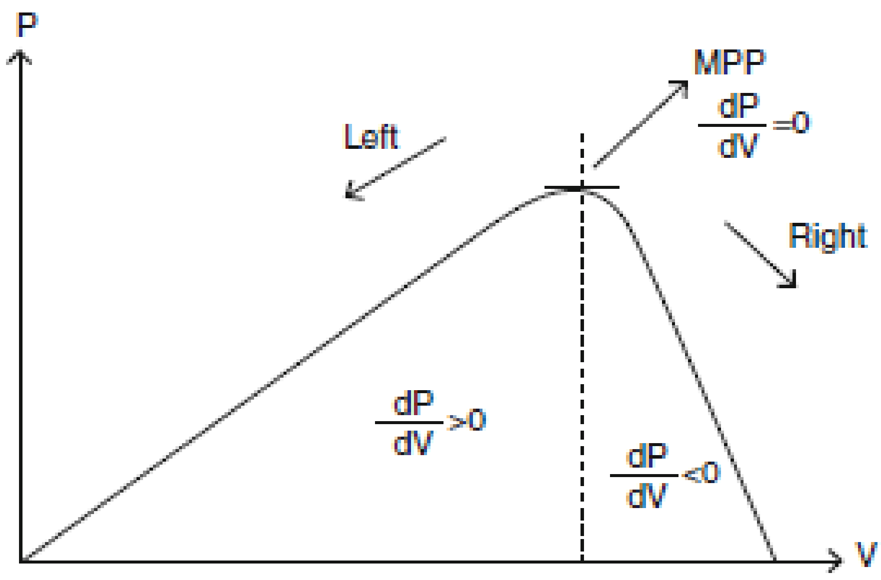

Figure 2. 15: PV Curves for Incremental Conductance (Lokanadham, M and Bhaskar, 2012)

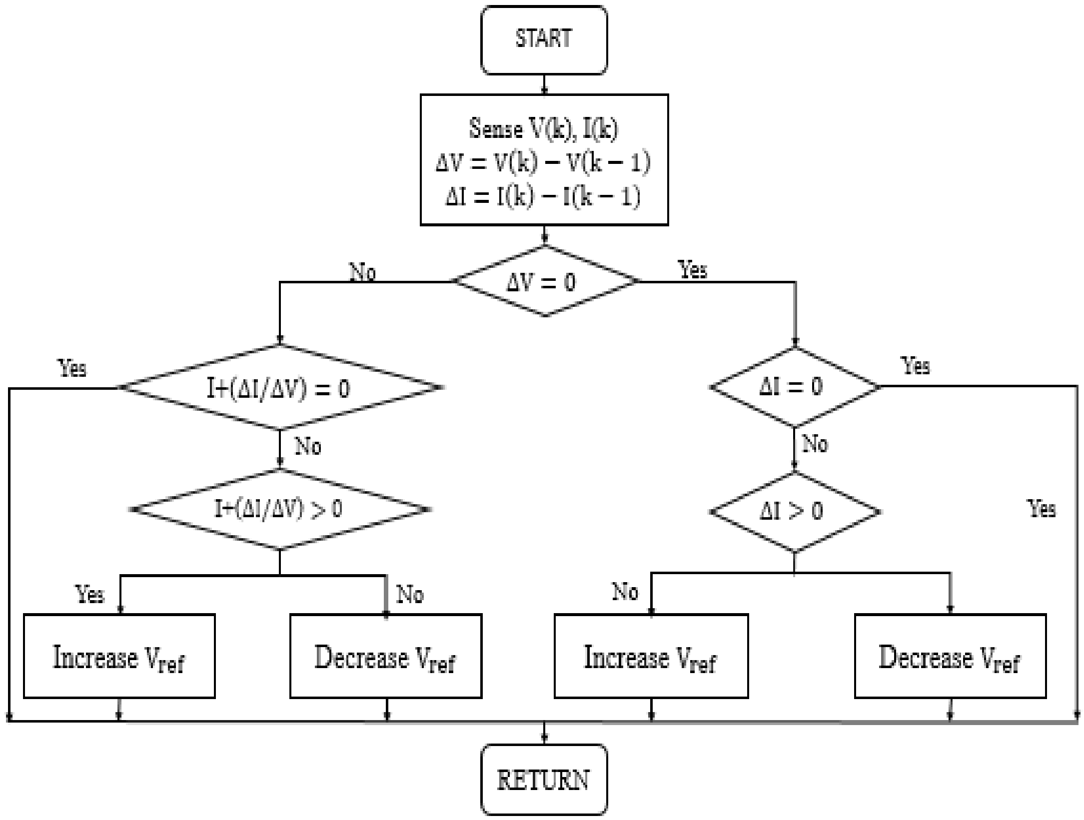

Figure 2. 16: Incremental Conductance flow chart (Sumathi, Kumar and Surekha., 2015)

2.5 Wind energy conversion system

Wind energy conversion system works when the wind blows and hits the rotor blades, this creates kinetic energy, then there will be a conversion of this kinetic energy into mechanical energy, during this conversion there will be some losses due to friction, then the rotor blade is connected to a generator via a gearbox and it will run to produce electricity (Johnson, 2006). The generation of electricity by wind turbine depends on different factors including the length of the blades, the height of the tower, rotor blades, types of the turbines, and the generators and can depend on various other factors including wind speed, and other environmental concerns (Letcher, 2017). Figure 2.17 shows the different parts of the wind energy conversion system.

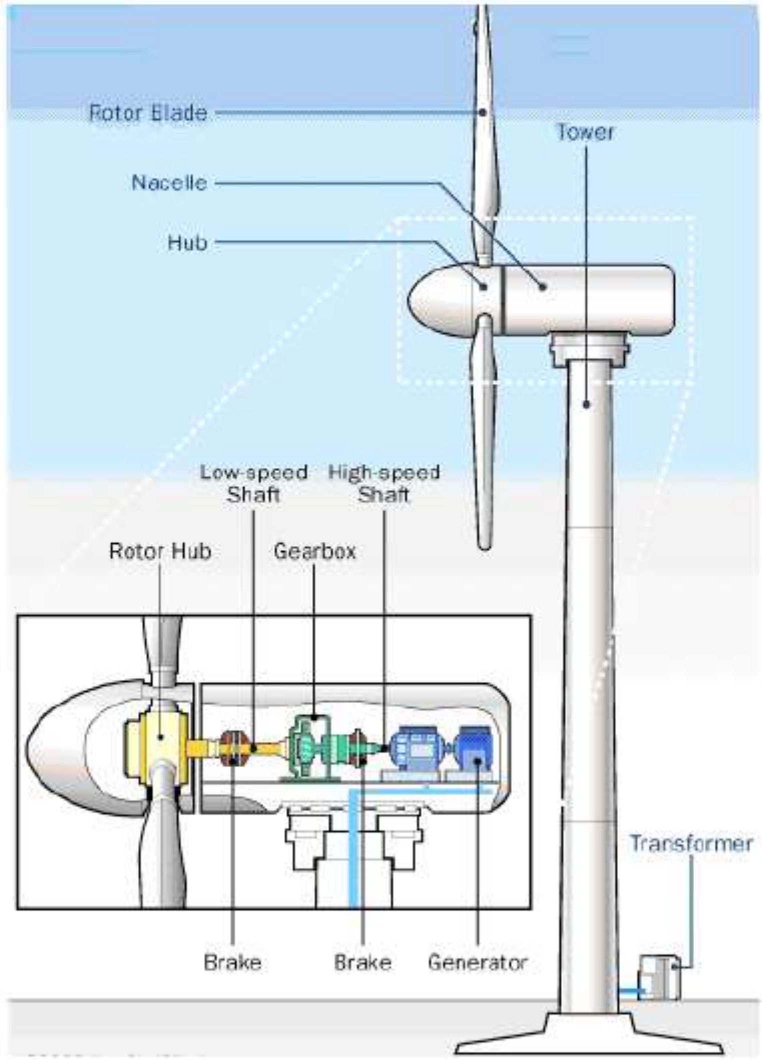

Figure 2. 17: Overview of wind turbines (Al-Shemmeri, 2012. p. 22)

2.5.1 Globally Installed Wind Capacity and Consumption

German followed by Spain is leading Europe in terms of installed wind capacity, while globally China and the USA are the leaders in terms of high installed wind turbine generation capacity. According to the following diagram as illustrated in Figure 2. 18, it is sure that apart of USA and China the main country with high installed wind capacity is based in Europe while the other area is very scarce or limited due to various reason including poverty, lack of expert in wind farm and lack of full information regarding the wind farms (Al-Shemmeri, 2010; Walker et al., 2014 p. 19). However, the worldwide wind energy production was occupied 4%, and 9% in Europe, 4% in North America, and 2% in Asia (Letcher, 2017).

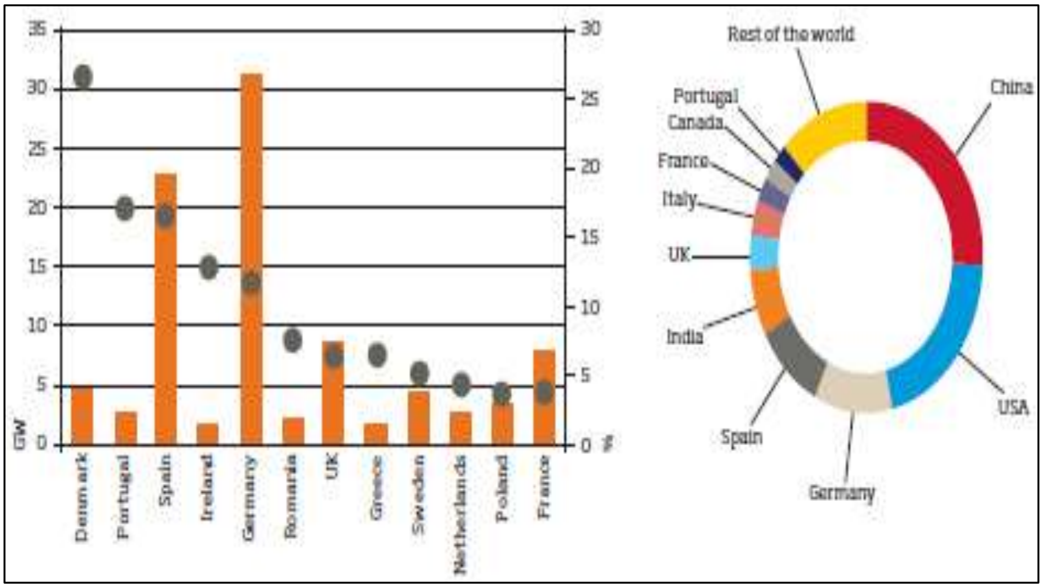

Figure 2. 18: Worldwide Installed wind capacity and Consumption of energy (Walker et al., 2014, p. 19)

2.5.2 Types and components of Wind Turbines

2.5.2.1 Types of Wind Turbines

Currently, there are only two main types of wind turbines, Vertical Axis Wind Turbines, and Horizontal Axis Wind Turbines (Giraneza., 2013).

2.5.2.1.1 Vertical Axis Wind Turbines

The vertical axis wind turbine is designed in the way that the rotor shaft is fixed vertically, and at the bottom of the turbines, there is a gearbox and generator. This vertical axis wind turbine is placed in a position that it can face the speed of the wind at any time due to its design. Therefore, the advantages of this kind of wind turbine are that its gearbox and generator are located to the ground as seen in Figure 2. 19. They can be modeled and supported easily, and they do not need anything to rotate it to face the direction of the wind, which helps to minimize the need for wind orientation mechanism and sensing (Hemami, 2012).

Figure 2. 19: Vertical wind turbine position (Hemami., 2012)

2.5.2.1.2 Horizontal Axis Wind Turbines

The horizontal axis wind turbines have a rotor shaft which is set in a horizontal position, and its electrical generator and rotor shaft are located on top of the tower, it is designed in a way that it can be fixed in one direction so that in case the wind change direction will need other added mechanism to be able to face the direction of the wind hence increases the price of the system (Hemami, 2012). Therefore, Figure 2.20 shows the position of the horizontal axis wind turbines.

Figure 2. 20: Horizontal wind turbine position (Hemami., 2012).

2.5.2.2 Wind Turbines Components

As illustrated in Figure 2.21, six major components formed wind turbines and each one is different from the other (Al-Shemmeri, 2010).

1. The rotor converts kinetic energy of wind to mechanical energy through a shaft.
2. The gearbox connects the rotor and the generator to regulate the rotation of a shaft to suit the generator.
3. Generator converts mechanical energy from rotor and gearbox to electrical energy.
4. Protection and control system to ensure the safety of the turbines since high wind cause damage of a wind turbine.
5. A tower, as a support of the system, because the rotor, gearbox, and generator are all hanging on the tower, and is used to increase the height of the system to reach the maximum wind speed.
6. A foundation to supports the whole system which is in charge of carrying all the systems together.

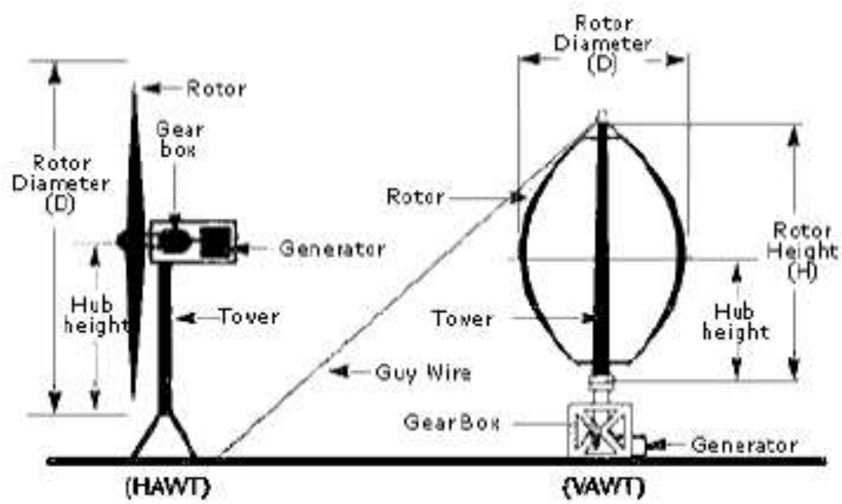

Figure 2. 21: Schematic of Wind Turbines Components (Al-Shemmeri, 2010).

2.5.3 Classification of Wind System based on the Environment

2.5.3.1 Onshore

There has been a tremendous increase in the deployment of wind energy in the entire worldwide, it has grown up to 1.5 % of global generating electricity. However, the onshore wind system is leading compared to the offshore wind energy system due to several factors such as cheap maintenance, easy and cheap to implement, easy to synchronize with the electrical grid, etc. A study conducted by (Archer and Jacobson, 2005; Luta, 2014) shows that onshore wind potential is much higher than the current energy demand of the entire world (Dai et al., 2015). Due to different reasons such as high building and environmental impact such as trees, hills and waste materials, debris all contribute to the slowdown of wind speed which in turn have a significant impact on the onshore wind farm or energy generation by a wind turbine.

2.5.3.2 Offshore

Offshore wind has a higher potential than the onshore wind system, this could be the answer to the energy crisis in the world in case it is used in an effective way (Firestone and Kempton, 2007). However, the offshore wind system is not reliable in terms of the cost of implementing the system, due to the high capital cost of implementing the system, but reliable in terms of generating more power compared to the onshore wind system, this is because the area is wide and without any obstacle to avoid the movement of the wind such as building, trees, etc. (Dai et al., 2015; Luta, 2014). In the UK almost around 35% of the energy generated from wind is coming from offshore wind system, whereas 2% of worldwide energy generated from wind is from offshore wind system (Walker et al., 2014), this shows that the offshore wind system is still at earlier stage globally compared to onshore wind system but contrary to the UK (Walker et al., 2014). Despite being in the process of improving its technology, the offshore wind system has the following disadvantages which could otherwise be considered as a problem in the future. The first disadvantage of the offshore wind system is the uncertainty of wind availability since wind is not constant at all the time as well as onshore wind system, the other disadvantage is connecting the energy generated from offshore wind system to the grid is quite complicated compared to the onshore wind system (Walker et al., 2014).

2.5.4 Globally Barriers to Wind Energy

- Poor Grid Connectivity
- Lack of Demand Response and Energy Storage
- Lack of Stability

2.6 Distributed Energy Storage (DES)

Distributed energy storage is considered as a pillar for micro-grid system technology since most of the micro-grid systems operate at a certain hour of a day more than other hours depending on the availability of resources such as wind and solar radiation which is not constant at any time of the day. This is considered as an obstacle for a renewable energy system. However, because the storage of large-scale energy is not efficient, in case we manage to store energy efficiently the goal of renewable energy will be successfully achieved (Slann, 2013). Therefore, the main objectives of distributed storage technology are to store the generated energy at the time where there is a high excess of generated energy of generation devices such as PV and wind turbine and keep it and use it at the time when the power generated by those generated devices becomes smaller than the energy required or load. Distributed storage also helps to increase the stability and reliability of the system by balancing both load and generation. Therefore, distributed technology differs from one technology to another, there are many kinds of distributed technology such as the battery, flywheel, pumped hydro, super-capacitor energy storage. Therefore, some of the technologies used for storing energy provide long-term energy storage whereas others provide short-term energy storage, while some discharge quickly and other discharge slowly. Hence, the way of storing energy is still an unsolved question due to the reason that most of the energy stored is from small-scale energy, but in the case of large-scale energy is not efficacy, as stated in Slann (2013). One of the most known ways of storing the large-scale energy generation system technology which is still in use till now is compressed air storage and pumped hydro, but the efficiency is not too good, require big space, and they discharge quickly, another storage system is a flooded lead-acid battery which is the most used in the renewable energy system, but with some disadvantages such as short life spans, low energy density, and is not suitable for repeated discharge and charge cycles (Slann, 2013). Therefore, we can conclude that there is a significant improvement in decentralization due to its unlimited advantages. Hence, there are still many researchers regarding the development of energy storage for large scale systems. Distributed energy storage is categorized as follow:

2.6.1 Mechanical energy storage

Mechanical energy storage technology is a mechanism used to store energy generated by the movement of a substance at a given time, this kind of energy storage systems are reliable in terms of storing energy and used it for a short moment or discharge quickly but in the case of storing energy and use it for a long time is not suitable. The system can be used in different areas such as in the car, etc. Therefore, there are different kinds of mechanical energy storage such as flywheel system, gravitational energy storage, compressed air energy storage (CAES), and pumped hydropower storage (PHPS) (Sharma et al., 2009). However, the above-stated energy storage system differs from each other depending on their application, some of them such as flywheel are better for a medium storage system, whereas CAES is suitable for large storage system, and pumped hydroelectric energy storage store energy for a lengthy period from days to years due to its design, with low capital cost (Sharma et al., 2009; Chen et al., 2009; Ferreira et al., 2013).

2.6.2 Electrochemical energy storage

The electrochemical energy storage system was invented by Alessandro Volta in the year 1800s and is known as animal electricity, which was formed with a pile of cells that is like the galvanic cell. The duties of electrochemical energy storage are to convert the chemical energy to electrical energy (Sharma et al., 2009). Therefore, the system uses a chemical reaction to generate electricity, the process starts with the transfer of an electron from an ion or molecule changing its oxidation state, this reaction is possible just only by applying the external voltage sources, or through the releasing of chemical energy. Therefore, the electrochemical storage system has two main branches known as electrochemical capacitors and electrochemical batteries, the nature of electrochemical energy storage types vary according to various features such as design, structural, and chemical reaction types (Guney and Tepe., 2017). Based on the principle of operation of the electrochemical battery, there are discharge depth, deep cycle batteries, or shallow. Therefore, for renewable energy application is better to use deep cycle battery such as Lead-acid batteries, Nickel-Zink (Ni-Zn), and Nickel-Cadmium, due to their high efficiency in terms of charging, discharging, and long-life cycle (Guney and Tepe, 2017; Amrouche et al, 2016). The other classification is based on the types of electrolyte inside the battery, such as sealed, wet, and flooded. Therefore, there are many types of electrochemical energy storage system such as Flow batteries or Vanadium-Redox Flow Battery (VRB), Lithium-ion (Li-ion) batteries, Sodium Nickel Chloride Batteries, Sodium-Sulphur (NaS) batteries, Lead-acid batteries, Nickel-zinc batteries, Nickel-Metal Hydride batteries, Nickel-Hydrogen batteries, Nickel-cadmium (NiCd) batteries (Liu et al., 2010).

2.6.3 Electrical energy storage system

The electrical energy storage system is a system with two terminals of electrical components that are used to store the energy electrostatically. However, the electrical energy storage system should be categorized into two types such as super-capacitor, and capacitors (Kumar et al., 2017). Based on the storage types there are current energy storage or magnet energy storage system. However, a supercapacitor should be used to replace a capacitor unless the capacitor offers a high capacitance in a small package and it can be charged and discharged quickly without losing its performance, whereas the capacitor should be used to store energy and used it for a brief time, and it is suitable for high currents. Hence, a superconducting magnetic energy storage system can be a favorite for the industry and can be used to stabilize the output of the power plant by simply apply it at the exit of the power plant (Guney, and Tepe, 2017).

2.6.4 Thermochemical Energy Storage

The thermochemical energy storage system is based on the absorption of heat energy by thermal chemical material and convert it chemically into two components A and B. However, the reverse reaction is when the two components A and B are combined to form C (Guney and Tepe., 2017). Therefore, three reasons including the extent of conversion, endothermic heat of reaction, and the amount of storage material have an impact on heat storage (Sharma et al., 2009).

2.6.5 Chemical energy storage

The chemical energy storage system is such important technology based on the storage of electrical energy and transforms it through a chemical process to electrical energy again so that it can be reused again. However, the system is done by storing energy into the bonds of molecules and atoms. It can only release in the presence of a chemical reaction (Guney and Tepe, 2017). There are different types of chemical energy storage but the most dominant of this energy storage is the chemical fuel both in energy transportation and in electrical generation. However, natural gas, coal, liquefied petroleum gas (LPG), gasoline, butane, propane, diesel fuel, biodiesel, hydrogen, and ethanol, are the most used chemical fuels (Guney, and Tepe, 2017).

2.6.6 Thermal energy storage

The thermal energy storage is used to store electricity in the form of thermal energy by cooling or heating a storage medium, both with high temperature or low temperature, in case there is a need for electricity, this stored energy which is in the form of either high heat temperature or low heat temperature can be used for cooling or heating at a later time, or transformed into electricity through heat engines and then be used as electricity. However, the system consists of two thermal storage processes which are based on the phase change of the storage medium, and another one based on the heat capacity of the storage medium as seen in Figure 2.22 (Sharma et al., 2009). Some of the materials used for the storage medium are lithium fluoride, water, and molten salt. Therefore, most of this technology use freeze water, or ice which is made during the off-peak hours and being stored in ice bank energy storage tanks, and used at the proper time when electricity is not cheap (Ferreira et al., 2013). The thermal energy which has been collected and stored in a thermal energy storage can be used for a later time such as days, weeks, months, season, and it can be used in various areas, residential buildings, industries, towns depending on the used technology. However, the energy stored during the day can be used during the night to heat, while the heat stored by the solar collector during the summer period can be used to heat during the winter period, and also the ice or cold air for the winter period can be stored and used it in the summer period to cool inside the house or any other area.

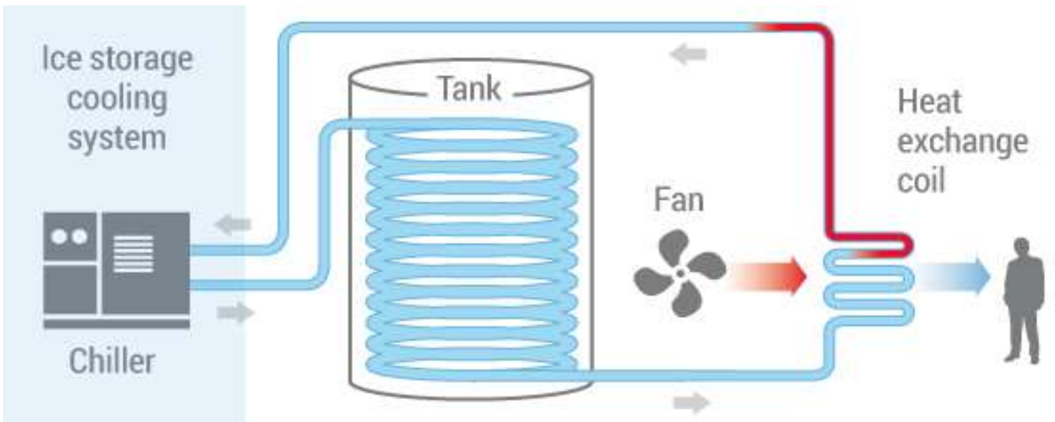

Figure 2. 22: Schematic design of Thermal energy storage (Sharma et al., 2009)

2.7 Power electronics systems

2.7.1 The power electronics inverter

The inverter is a power electronic devices that have the duty of converting the DC Current to AC in a microgrid system or any other system of application, the power produced by a micro-grid component such as a PV system is DC which needs to be converted to be able to connect it to an AC residential load, industrial or any other load. Hence, the inverter is designed in a such way that it can connect the system with a high efficiency which reduces the loss that occurred during the conversion of energy into one form to another form (Sumathi, et al., 2015). The inverter is controlled with a control system that is used to turn the inverter's switches on and off at the proper frequency to get an output voltage and current waveforms. The application of high-frequency pulse width modulation (PWM) strategies reduces the harmonic distortion and gives good control of load voltage, because high harmonics can cause overheating for motor loads, because of some uneven magnetic fields as well as a high copper loss which can affect the operation of the system (Sumathi et al., 2015).

2.7.1.1Types of inverters based on the mode of operation

Depending on the types of operation, inverters are divided into two groups such as stand-alone inverters which are used for off-grid systems, and grid-connected inverters which are used for grid-connected systems.

2.7.1.1.1 Stand-alone inverters

The stand-alone inverters are the inverters used mostly for off-grid systems where there is no need to synchronize with the grid. However, their application differs from each other depending on the amount of power to be converted. Therefore, the stand-alone inverters are quite minor compared to the grid-connected inverters (Algaddafi et al., 2016). Nevertheless, there is still more research going on the increasing the application of such material in the industrial and power supply area (Daher et al., 2008). Figure 2.23 shows the stand-alone inverter topology.

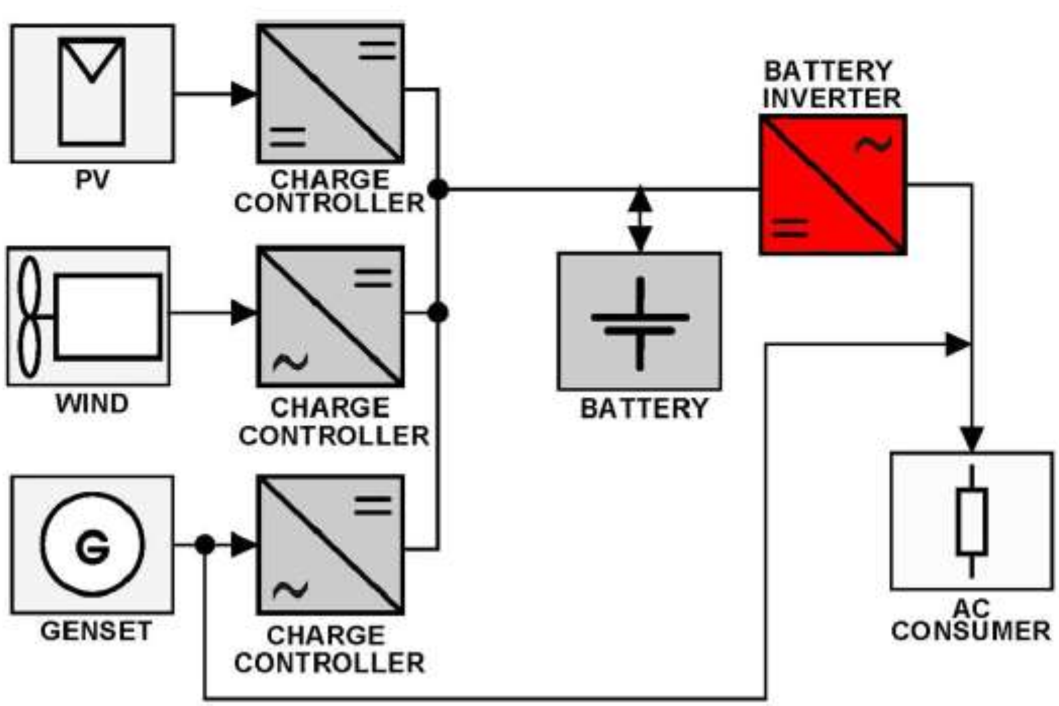

Figure 2. 23: Stand alone inverter topology (Daher, Schmid and Antunes, 2008)

2.7.1.1.2 Grid-connected inverters

The grid-connected inverters are the types of inverters that are used for such a grid-connected system. They play such a significant impact in the energy sector because they can perform from the system with low energy usage to the high-energy usage system up to 100 MW as seen in the following paragraph (Kjaer et al., 2005).

- Central inverters: from the range of a few KW to 100 MW
- String inverters: from the range of a hundred W to some few amounts of kW
- Multi-string inverters: the range between 1 KW to 10 kW
- Micro-inverters or Module inverters: between the range of 50 to 500 W.

Figure2.24 shows the structure of a grid-connected inverter system, central inverter, string inverter, multi-string inverters, module inverters (Adekola, 2015).

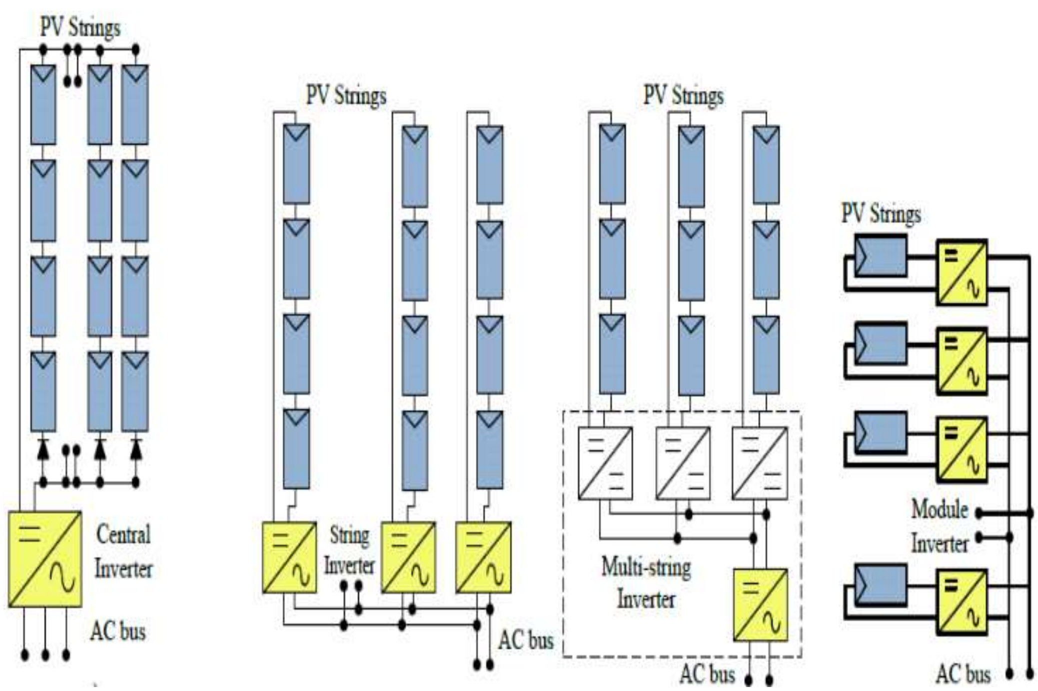

Figure 2. 24: Structure of the grid-connected inverter system (ADEKOLA, 2015).

2.7.2 The DC-DC power electronics converter

DC-DC converter has gained popularity due to its stability and efficiency. There are many types of converters such as boost converter, buck converter, and buck-boost converter (Massawe, 2013). Details of the converter are given below.

2.7.2.1 Boost Converter

A boost converter is a converter that is designed to increase the output voltage of a system; therefore, the converter is comprised of various components such as semiconductor switch, capacitor, inductor, rectifier diode, and load. All these components work together to be able to do the voltages increase mechanism in the circuit (Sira-Ramirez and Silva-Ortigoza, 2006). Therefore, the equivalence circuits diagram of the boost converter is presented in Figure 2.25 (a), while Figure 2.25(b), shows the circuit diagram of a boost converter with the switch on, and Figure 2.25(c), shows the circuit with a switch off. Therefore, in case the switch is on as shown, the input voltage is connected to the inductor, and the current passes through the inductor, which in turn accumulate the energy by generating a magnetic field and use it in case the source (input voltage) is not available. In case the switch is off the stored energy in the inductor is distributed to supply the load and capacitor.

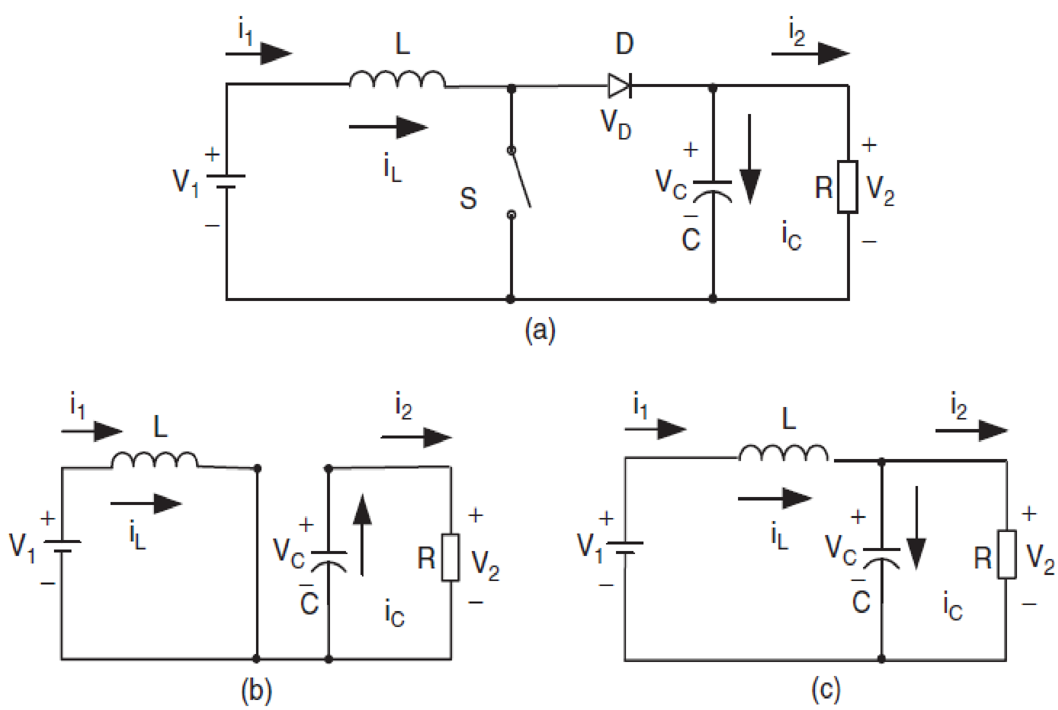

Figure 2. 25: Schematic design of a boost converter (Rashid., 2017, p. 269)

2.7.2.2 Buck-boost Converter

Figure 2.26 presents a buck-boost converter which is known as a chopper amplifier converter. However, as explained by the name buck-boost converter can either increase the output voltage or decrease the output voltage magnitude, it consists of an inductor, capacitor, semiconductor switches, and a rectifier diode (Rashid, 2011; Sira-Ramirez and Silva-Ortigoza, 2006). Therefore, in case the switch is on as shown in Figure 2.27 on-state, the input voltage is connected straight to the inductor which in turn accumulates the energy by creating a magnetic field and use it in case the input voltage or source is not available (Kazimierczuk, 2008). therefore, the load is supplied by a capacitor (Sira-Ramirez and Silva-Ortigoza, 2006). However, in case the switch is off the stored energy in the inductor is distributed to supply the load and capacitor as seen in Figure 2.27 off-state.

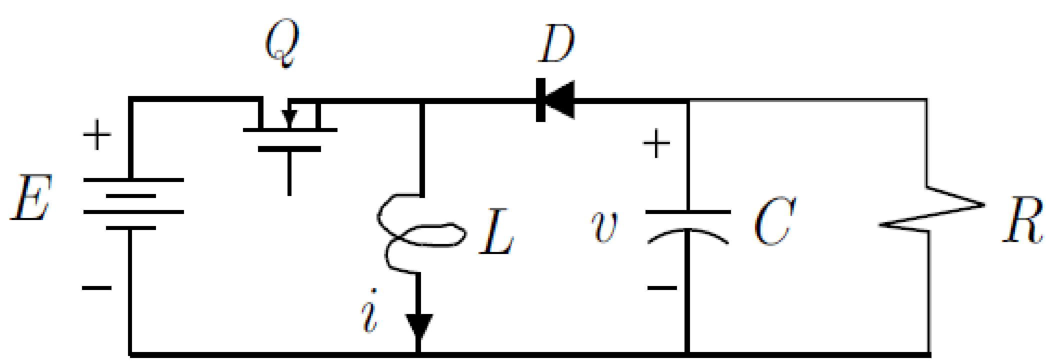

Figure 2. 26: Schematic design of a buck-boost converter (Sira-Ramirez and Silva-Ortigoza., 2006, p. 27)

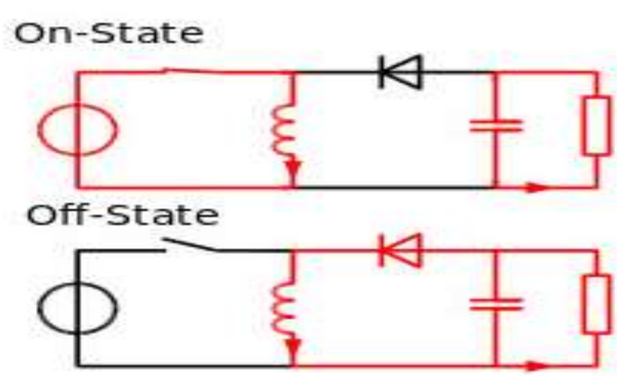

Figure 2. 27: On-state and Off-state circuit diagram of a buck-boost converter

2.7.2.3 Buck Converter

The buck converter is known as a step-down converter, it is comprised of various components such as source voltage, semiconductor switch, rectifier diode, inductor, capacitor, and load as shown in Figure 2.28 (a). However, these components work together to step down the voltage at the output side of the converter. Therefore, the switch is designed in a way it can be on and off depending on the time it is needed to do so (Kazimierczuk, 2008). Figure 2.28(b) shows the circuit diagram of a buck converter with the switch on, and Figure 2.28(c), shows the circuit diagram of a buck converter with the switch off. Therefore, in case the switch is on the input voltage is supplying the voltage to the inductor, which in turn accumulates the energy and to use it in case the source (input voltage) is not available. In case the switch is off the stored energy in the inductance is distributed to supply the load and capacitor (Lasnier, 2017).

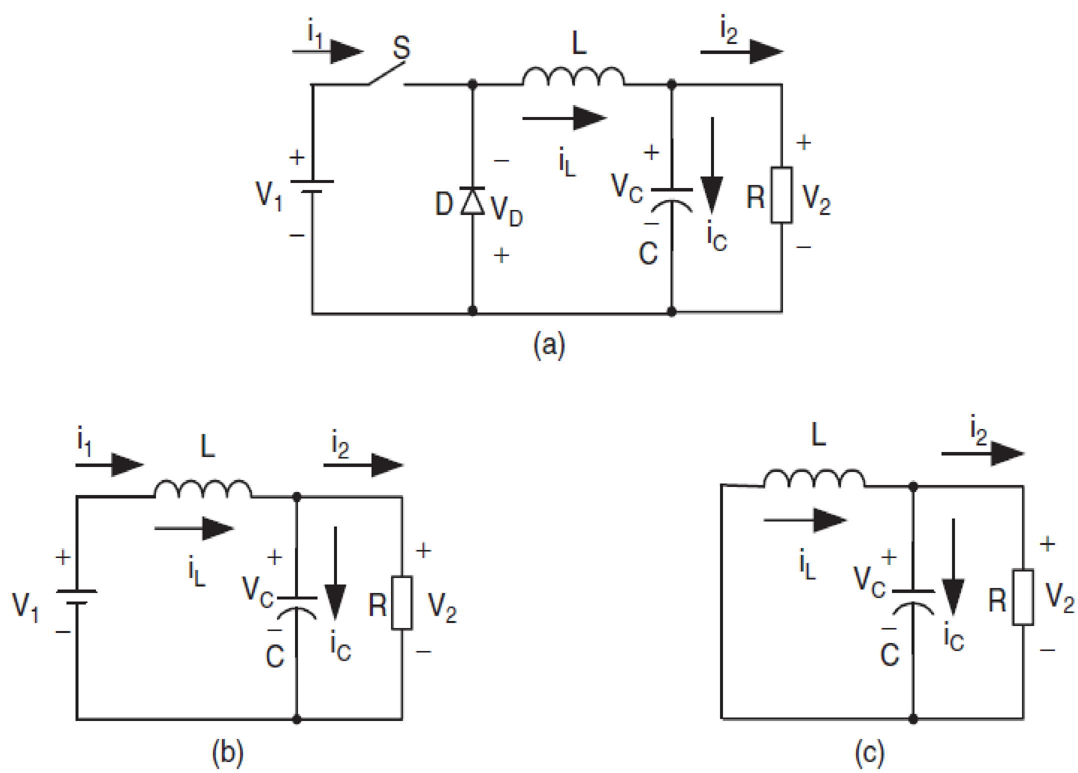

Figure 2. 28: Schematic design of buck converter (Rashid., 2017. p. 269)

2.7.2.4 DC-DC Bidirectional Converter

There are two types of the bidirectional converter; such as Isolated converter and non-isolated converter, their application is differing from each other (Agatep and Ung, 2011; TÃ¼may, 2015). Therefore, an isolated converter is divided into two parts, and all parts are separated by a transformer as illustrated in Figure 2.29. The system has a high quality of performance due to the implication of a transformer. The drawback is that the excessive cost of a transformer makes a system expensive and heavy. While a non-isolated bidirectional converter is classified as cuk converter, half-bridge converter, and SEPIC/Luo converter, whereas an interleaved half-bridge converter and cascade half-bridge converter is considered as derived topologies(Simões et al., 2015. p.4). Therefore, the most used and attractive converter is a half-bridge converter which can be able to operate in both a boost and buck model. As illustrated in Figure 2.30, different kinds of non-isolated converter designs are shown such as a half-bridge converter, Luo converter, cascade half-bridge converter, and interleaved half-bridge converter.

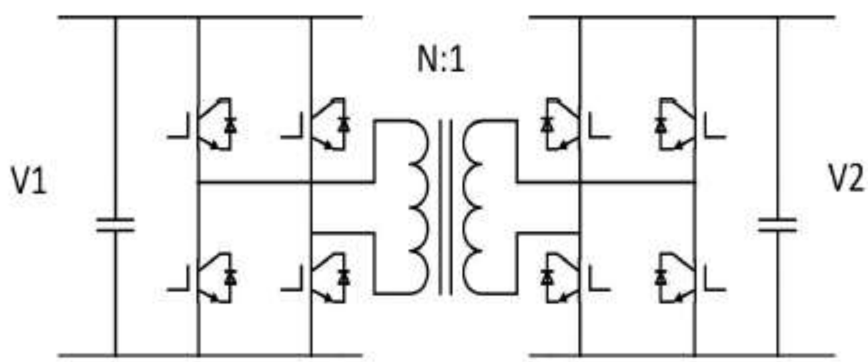

Figure 2. 29: Isolated bidirectional converter (Simões et al., 2015. p.4).

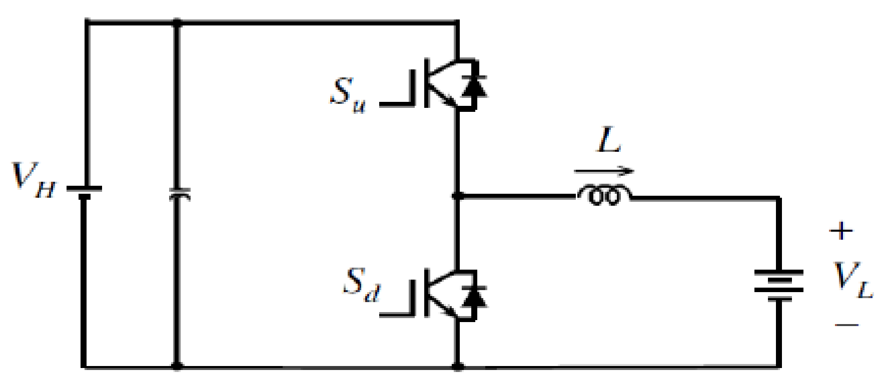

Figure 2. 30: Non-isolated bidirectional converter (Simões et al., 2015. p.4).

2.8 Related Work

Different studies have been done regarding the integration of renewable micro-grid systems either in a residential home, industrial, or for a large firm. The study made by Abo-Al-Ez et al., (2012) approached the integration of smart interconnection control for a hybrid micro-grid system such as wind turbines, and photovoltaic connected to the grid. A squirrel cage induction generator was chosen for a wind turbine. Therefore, the simpower toolbox system from Simulink/MATLAB was used to simulate the proposed model, and photovoltaic coupling voltage Source Inverter (VSI), was used as a smart control of micro-grid. The proposed model was able to supply both active and reactive power for the system, this enhances the power factor of the system. In Sarkar et al., (2018) the reactive power control system was investigated to manage the reactive power stability since the penetration of high renewable power affects reactive power. In Cabrera-Tobar et al., (2019) the control of both active and reactive power was investigated, the aimed of the research was to integrate the controller for both active and reactive power to be able to comply with the need to connect the photovoltaic farm on a transmission line, the different ambient conditions were taken into account and Dig Silent was used to model the photovoltaic system, and the results prove that the control can still monitor active and reactive power even under various temperature and solar radiation. Whereas (Zhu et al., 2013; Pr´ymek et al., 2013) addressed the implementation of an energy management system for a smart grid integrated with a micro-grid hybrid renewable energy system, an autonomous active distribution grid (AADG) was introduced for each bed. The author Al-Ali et al., (2011) presented an energy management system for a residential house integrated with photovoltaic and battery storage systems; that optimized energy flow and consumption through scheduling and arranging energy resources. It was controlled by a two-way communication protocol. The results revealed that the integration of renewable energy for a smart home saved 33% of the bill paid. Merei et al., (2013) proposed the integration of renewable energy sources such as wind and photovoltaic, battery storage, and diesel generator in a remote area at a minimum cost, the integration of three different batteries such as vanadium redox flow, lead-acid, and lithium-ion, was applied to enhance the efficiency of the system. The system was modeled and implemented in MATLAB Simulink using a genetic algorithm. A study revealed that the minimum cost was achieved by using a combination of three different batteries, whereas the use of redox flow only shows superiority in times of cost reduction of the system. Several researchers addressed the integration of PV and diesel generator hybrid on a residential building (Luu, 2015; Anayochukwu and Nnene, 2013; Tazvinga et al., 2013; Suryoatmojo, et al., 2014; Tsuanyo et al., 2015). Tazvinga et al., (2013) considered daily variation load for both summer and winter periods. The quadratic program in MATLAB was used to simulate the proposed model since fuel consumption cost was taken as a non-linear function. Energy flow, fuel cost, and diesel dispatch strategy were implemented. Hence, the result shows that the model achieved 80.5% and 82% fuel saving in the summer, and 73% and 77% in winter. While (Tazvinga et al.,2014; Kumaravel and Ashok, 2012; Samia and Ahmed, 2013; Ekren and Ekren, 2009), were approaching renewable micro-grid hybrid systems such as PV-wind and battery system with either generator and grid. (Ekren, and Ekren, 2009), considered unit cost and various load, the simulation was carried using the "opt Quest" tool in ARENA 12.0 software. A Study aims to size the integrated hybrid system such as wind and PV. Optimum results were found using autonomous analysis and LLP. (Samia and Ahmed, 2013), including the application of a tracking system to the system to capture the maximum possible wind speed and solar radiation, by orienting the rotor blade and photovoltaic panel system in an appropriate direction. Therefore, MATLAB Simulink was used to simulate the model, whereas (Kaabeche et al., (2011), considered the sub-model, deficiency of power supply probability, and Levelized cost of a unit. The Simulation conducted using the MATLAB software system.

As stated in Zhu et al.,(2013), the optimization of sharing energy in a smart micro-grid was presented. The study aimed to match the generated energy with the energy demand of a system at any time, and the losses occur during both transmission of energy and conversion of energy. Information from all homes were collected by the Cluster controller to allow the sharing of energy between homes, switches, and controllers used. However, the study found that the sharing method used can reduce the energy losses by 60% and can reduce losses that occur during transmission.

A study conducted by Saha et al., (2014) based on the designing of the Home Energy Management system (HEM) and the integration of micro-grid Renewable Energy. However, the Home Energy Management algorithm based on reducing power consumption of a residential home with an integration of renewable energy sources has developed. Therefore, a simulation was conducted by putting together photovoltaic (PV), battery storage and combined them with home energy management (HEM); the study considered only a big load and neglected the small loads such as lighting, TV, etc. The result shows that depending on the battery level, the peak hour will be reduced up to 0 kW. As pointed out in Tascikaraoglu et al., (2014) the integration of renewable energy by considering forecasting renewable energy resources. The system consisted of a smart home connected to a grid, with different Micro-grid renewable energy sources such as wind, solar photovoltaic (PV), and battery storage system to store unused energy. Energy Management System combined with two ways communication system, and advanced power forecasting models were used. The application of shifting the peak load to off-peak time and the time of use was considered. Therefore, the load was split into two ways such as shiftable and unshiftable load. A simulation was conducted using the demand-side management (DSM) control algorithm, and the result revealed that the cost reduced by 4.23% per two months, and 2.93% of the reduction was obtained per year. Whereas, in Mesaric and Krajcar, (2015). The shifting of consumption energy during the peak hour to off-peak was done by considering both the availability of energy generated by renewable energy (PV) and stored energy in a battery. The smart meter was applied. The study aimed to decentralize generation and control. Many hypotheses were made to model the problem, EVs was considered as a storage system, and load from the house was managed by (DSM) by shifting the peak load to the time where there was no load and also where energy generated by the renewable system such as (PV) was big enough to feed the load. Therefore, results showed that the use of mixed-integer linear programming (MILP) was successful in times of scheduling the load management of a household. However, using (EVs) as storage was also successful. Whereas a paper by Arora and Chanana, (2014) focused on the energy management of a smart home with PV, and a battery hybrid system connected to the grid. The load was divided into two groups such as (HVAC) known as heating ventilation and air conditioning Load and non-HVAC Load. However, to reduce the cost related to the energy consumption of a smart home, an optimal scheduling mechanism was applied to manage the energy from solar photovoltaic panels, the charging and discharge of the battery, and air conditioning operation. Therefore, the maximum saving was obtained by using Mixer integer programming system.

The study by Sarker and Nagasaka, (2012) presented a model that enabled the integration of a micro-grid renewable energy into a grid, by proposing a web-based platform for dynamic demand response. However, Integration of different utility devices such as transformer, switch gears, sensors were introduced between the smart grid and smart home. Smart meter and sensors were used to convert a grid into a smart grid by changing unidirectional to bi-directional power flow. Therefore, a PLC network was applied to simulate the model, the result showed that PLC can bring some change to the national grid, and the use of smart meter revealed that the connection between smart home to a grid was giving hope for the future Bangladesh network. Research presented by Et-tolba et al., (2013) presented an energy management system for a home, the main aims of the study was to create a balance between supply and load demand based on real-time, and the environmental concern which pushed to choose Demand Side Management to enhance the integration of renewable energy sources that improved the energy efficiency of the systems, satisfy customer need and minimize CO_2 emission. Therefore, the classification of loads was based on operation time such as loads which operates for a long time as a regular load and loads which operate for a moment (limited time) as Burst load. Hence the proposed model meets the objectives proposed.

Angenendt et al., (2016) approached the operating strategies which intend to increase the life cycle of the battery, by applying intelligent operating strategies, such as PV-BESS, without changing load consumption. Simulation was done using real data measurement, as input, and DC-coupled PV-BESS model. Minimization of energy stored has been established to enhance the lifetime of a battery, by simply store the energy use for the next night. Approaching that method, they perceive that the beginning of the night residual load is negatives, while at the end of the night, the residual load becomes positives. However, an evaluation of persistence forecast and perfect forecast has been done. Therefore, results showed that the approach can enhance the lifetime of a battery system, but slightly affect self-consumption. Hence immense potential has been found, due to the operating strategies applied.

As addressed in Jayasekara et al., (2016) proposed the integration of distributed storage to improve the hosting ability between load and distributed generation. The two primary factors were taken as a necessary day ahead of operation strategy and optimal capacity with the cost of the distribution system, and the cost of battery cycling was taken as two primary factors. Simulation was conducted using MATLAB software, and both low voltage and medium voltage were considered. The results showed that the implementation of a distributed storage system improved the stability of both the network and load. Ogunjuyigbe et al., (2016), the study aimed to minimize the lifecycle cost of the system, dumping energy and emission of CO_2, while maximizing the usage of a renewable energy microgrid system for a residential building. Certain rules relating to the operating of diesel generators have been applied, depending on the availability of renewable energy distributed resources such as wind, solar radiation, and the State of charge of a battery. Hence, a small split generator has been chosen instead of a single big diesel generator. However, a genetic algorithm has been applied to implement the three objectives mode designed in MATLAB software. Different five scenarios have been considered such as (Wind/Battery, PV/Battery, aggregable 3-split Diesel generator, single big diesel generator, and PV/Wind/Split-diesel/ and Battery), typical load, and resources such as wind speed and solar radiation were the same for all five scenarios. Therefore, results showed that the last scenario was quite attractive compared to the other scenarios, within a low life cycle cost of $11,273, cost of the energy of 0.13 ($/KWh), net CO_2 of 13,273 kg, and net energy dump of 3 MWh. It shows savings of 46% for Life-cycle cost (LCC), 28% of the cost of the energy (COE), 82% for Dioxide Carbon (CO_2), and 94% for Dump energy. Dufo-López, et al., (2016), approached a multi-objective evolutionary algorithm (MOEA) to minimize both net present cost, and emissions, rather, maximizing both job creation (JC), and human development index (HDI). The study coped with the integration of micro-grid renewable energy such as wind, photovoltaic (PV), and battery system for a remote area. However, optimal Pareto was implemented to obtain the best control. A study by (Baneshi and Hadianfard, 2016) focused on the techno-economical parameters of a micro-grid hybrid system, such as Photovoltaic (PV), wind turbine, diesel generator, and battery storage system for a non-residential building located in the southern region of Iran. The study aimed to meet the non-residential load with high electricity consumption. A simulation was conducted by Homer software, both economic and environmental aspect was investigated, and both off-grid and grid-connected system also were investigated. Results showed that the off-grid system achieved 9.3-12.6 ₵/KWh of the cost of energy (COE), and 0-43.9% of a fraction; While grid-connected system without considering battery, system achieved 5.7-8.4 ₵/KWh of a cost of energy (COE), and 0-53% of renewable fraction, respectively. A study conducted by (Kolhe et al., (2013) took place in Sri Lanka, the study area was full of potential in terms of solar radiation, and wind resources. A combination of micro-grid hybrid systems such as photovoltaic (PV), wind turbine, diesel generator, and battery storage system has been implemented and the study aimed to power the remote area, and to found the best combination of a hybrid system, with a minimum cost of the implemented system. Both sizing and simulation of the proposed system has been done with homer software. Both Sensitivity and optimization results have been presented and the results revealed that a combination of 20KW-PV, 40 KW of wind, 20 KW of a diesel generator, and battery storage system was considered as the best optimal results based on homer sensitivity and optimization results. While the study by Al-falahi et al., (2016) was conducted in a standalone area (Australia), equipped with a microgrid hybrid system such as photovoltaic (PV), wind turbine, and battery storage. The study aimed to find out the optimal size of micro-grid components that could power and sustain the yearly variable load of a remote area. Homer was used to simulate the proposed model. Optimal results showed that the system was able to sustain the load demand of a remote area. While Alalwani (2015) aimed to find the optimal size, within a minimum cost, the study used typical meteorological data, four houses have considered for a case study. Ziad and Islam, (2016) proposed an active management model for a hybrid system, the study aimed to develop a control system model for a voltage of hybrid system comprised of both, diesel generator and wind turbine. Mathematical model was developed for both a diesel generator and a wind turbine to evaluate the performance of the system. MATLAB Sim-Power system was used to simulate the proposed model, and the phasor explanation process was used to simulate the distribution structure. Results found reveals that both OLTC and wind turbine are suitable for the system proposed, and shows 4-6% increasing of network voltage, and power loss. Whereas, in Al-falahi et al. (2016), incorporated the lack of access to the grid of various remote area, by incorporating a micro-grid hybrid system as the answer to the appropriate problem. Homer software was used to size the system comprised of distributed generation such as photovoltaic-wind-micro-turbine and distributed storage such as fuel cell and battery. Therefore, the economic aspect and environmental concern were considered. The proposed model showed its effectiveness in terms of management and sizing of the proposed system.

Studies made by (Jayasekara et al., 2016; Qiang et al., 2016), proposed the integration of distributed storage to improve the hosting ability between load and distributed generation. Day-ahead operation strategy and optimal capacity were presented by Jayasekara et al., (2016), with the cost of the distribution system, and cost of battery cycling taken as two primary factors, considered as a multi-objective function. However different services such as loss reduction, voltage regulation, and peak reduction have been conducted regarding the benefit and trade-offs of battery energy storage system (BESS) installation. The comparison was made between multi-services simultaneously and one services option, MATLAB interior-point algorithm was used to approach the proposed model, low voltage and medium voltage was considered for the simulation, results figure out that the cost-benefit and maximum operation can be achieved by the integration of BESSs, whereas elevating the load and DG hosting capability of the network. While Qiang et al., (2016) considered distributed generation (DG), battery energy storage system, smart home, micro-grid, changing and exchanging station. Therefore, the concept of reliability sensitivity and net loss sensitivity were introduced. However, results showed that the smart distribution and utilization system (SDUS) used in this paper has benefits and reliability compared to the previous method. While, a study by (Hossain et al., 2017) took place in Malaysia, the study aimed to reduce the dependency on fossil fuel used by a diesel generator, the study approached the integration of a multi-combination of a hybrid system for the rural area. Daily load and average peak of the selected area were recorded as 1185 KW and 13,048 KW.

A study developed by Ehsani et al., (2018) was dramatically based on the control of a grid-connected inverter with LCL filters, however, the proposed dual closed-loop control was based on the grid current feedback. Therefore, the proposed model has shown high accuracy in terms of control. Whereas a study conducted by Dondapati et al., (2017) was based on the integration of super-capacitor energy storage for a grid-connected system to reduce load fluctuation which is the response of lightning fault currents, and non-uniform load distribution. The integration of superconducting magnetic energy storage

(SMEs) with a superconducting fault current limiter (SFCL) was incorporated to prevent fault currents. A study made by Miller (2018) was based on the integration of supercapacitors to store energy due to their high life cycle, high efficiency, and reliability in terms of operation. Whereas a paper by Chan et al., (2018) developed multifunctional energy storage systems to reduce the dependence on fossil fuel energy. The structural electric double-layer capacitors (EDLC) and structural dielectric capacitors were introduced. Therefore, both overall performance and the experimental results related to the improvement of the electrical and mechanical properties of structural dielectric capacitors (EDLC) were given. Results showed that under a mechanical load the capacitive function of a structure dielectric capacitors was maintain.

A study by Bouharchouchel et al., (2013) was based on the implementation of a control system to allow the safe and secure energy flow from micro-grid renewable energy such as double-feed induction generator for wind turbine, solar photovoltaic (PV), battery storage, the AC load and grid. However, the work aimed to satisfy the energy requirement from the residential houses and to manage generation energy for various sources as mentioned above. MATLAB software was used to examine the proposed model; a different operating model has been settled in MATLAB/Simulink to illustrate the performance of the proposed control model. While a study by Mtshali, T.R. et al., (2011) was also based on the design of a micro-grid system comprised of PV-Wind and Battery storage systems. However, the system was designed for off-grid purposes and the controller system was applied to make sure the power flow between intermittent sources was ensured. Thus, the consideration of temperature and weather conditions has been involved. Therefore, Homer software was used for technical and economic analysis of the proposed system. Finally, the results showed that the system proposed might be applicable to any tourist area with the same climate condition.

Even though micro-grid renewable energy has been addressed in either rural or urban area, there are still many problems that still needed to be addressed such as: how distributed energy resources can be integrated and managed to sustain a residential household located in a rural area, where there is no access to the grid, how good management of distributed energy resources can help the rural areas and; which combination of distributed energy resources is suited for a rural area in South Africa, especially Cape Town, what is the interest of combining both AC and DC load for the efficiency of the renewable energy system (RES). This study approaches the above-mentioned questions, by proposing a method that will be able to answer the stated above questions. The proposed model will take a storage battery as a backup system, which is used to store energy from sources, then in a case where energy from renewable energy (RE) is not enough to sustain the load, power will be drawn from a battery, to compensate the shortage of power. MATLAB will conduct the performance analysis of the system and energy management between load and sources.

2.9 Summary

This chapter conducts a literature review from various authors for both the implementation of microgrids and their energy management. The literature review is split into two categories, the first category is related to the explanation in details of various components used in this project by giving accurate and updated information regarding those components. The second category is based on the review of research made by various authors regarding the proposed field of study. Therefore, more, and deep review has been conducted regarding this topic in this literature part to fully clarify the study area.

CHAPTER THREE
MATHEMATICAL MODELLING

3.1 Introduction

This chapter introduces the mathematical modeling of the systems proposed in the microgrid under study. Details regarding the mathematical modeling of a solar photovoltaic system, wind turbine, and battery system is developed. Therefore, the mathematical modeling of each component is illustrated in this chapter.

3.2 Solar photovoltaic system mathematical model

The following is the single solar cell diagram comprising of the current source (I), diode current (I_d), shunt resistance (R_{sh}), series resistance (Rs). The system is connected in parallel and each one consists of a string connected in series. The solar cell model is shown in Figure 3.1.

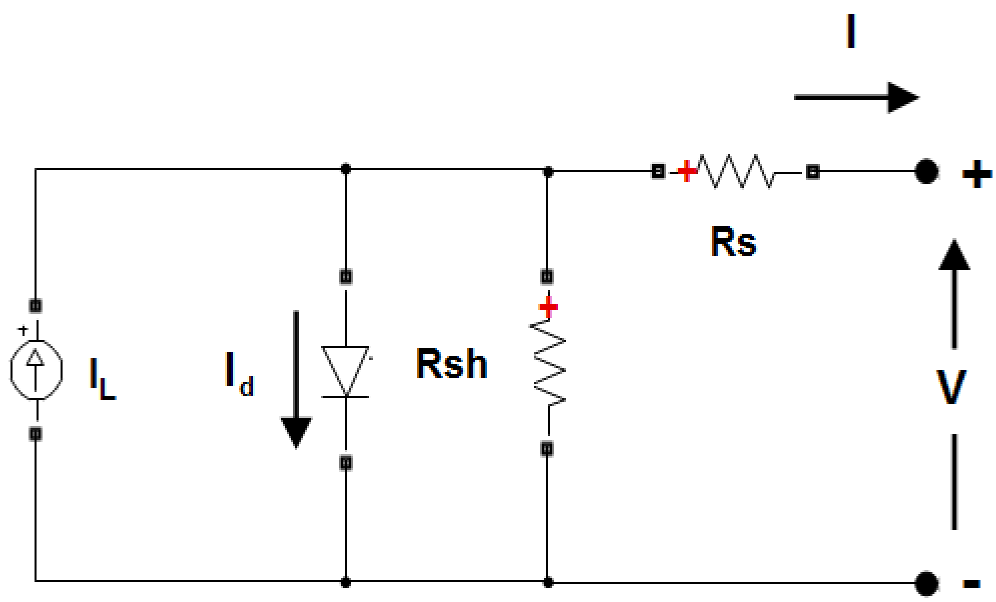

Figure 3. 1: Equivalent circuit of a photovoltaic model with a single diode (Sumathi, Kumar and Surekha, 2015)

The power generated by the solar photovoltaic panel is the product of three components such as photovoltaic efficiency $\mathrm{n}_{\boldsymbol{pv}}$, the area $\boldsymbol{A_{pv}}(m^2)$, and solar irradiance $\boldsymbol{I_\tau}$(W/m^2) (Sawle et al., 2016).

$$\boldsymbol{P(t)} = \mathrm{n}_{\boldsymbol{pv}}\, \boldsymbol{A_{pv}}\, \boldsymbol{I_\tau} \qquad (3.1)$$

with

$$n_{pv} = n_R\left[1 - 0.9\beta\left(\frac{I_{pv}}{I_{pv,NT}}\right)\left(T_{c,NT} - T_{A,NT}\right) - \beta\left(T_A - T_R\right)\right] \qquad (3.2)$$

Where n_{pv} is the efficiency of the photovoltaic panel, n_R is the measured efficiency under standard test condition ($25°\mathrm{C}$), T_R (ºC) is reference cell temperature. $\beta$is the temperature coefficient for cell efficiency {$0.004 - 0.005/°\mathrm{C}$} $T_{c,NT}$ is the cell temperature at NT test conditions ($45°\mathrm{C}$), while $T_{A,NT}$ are ambient temperatures at NT test conditions ($20°\mathrm{C}$). $I_{pv,NT}$ is incidence hourly solar irradiation at NT (0.8 KWh/m^2); (Tazvinga et al., 2013:p 7).

Whereas load current is calculated as follows.

$$I_{pv} = I_L - I_d = I_L - I_0\left[exp\left(\frac{U_{pv}+I_{pv}R_s}{\alpha}\right) - 1\right] \qquad (3.3)$$

Whereas I_{pv} (A) is the photovoltaic current, I_L (A) is the load current, I_d (A) is the diode current, I_0 (A) is the saturation current, U_{pv} (V) is the terminal voltage (output voltage), α (V) is the thermal saturation factor, R_s (Ω) is the series resistance. Whereas

$$I_d = I_0 \left[exp \langle \frac{V_d}{V_T} \rangle - 1 \right] \quad (3.4)$$

$$V_T = \frac{KT}{q} * nl * Ncell \quad (3.5)$$

Where, V_d (V) is the diode voltage, V_T (V) is the thermal voltage, nl is the diode ideality factor which is close to 1.0, **k** is the Boltzmann constant (1.3806e-23 JK-1), q is an electron charge (1.6022e-19C), N_{cell} is the number of cells in a module which are connected in series, T is a cell temperature (ºC) (Al-falahi et al., 2016; Bouharchouchel et al., 2013)

3.2.1 Sizing of the PV System

Because the energy generated by the PV system is not constant at any time of the day, it is necessary to size the PV system to meet the load demand, the eq. (3.6) described the area needed to meet the estimated energy demand.

$$A_{pv} = \frac{E_l}{H_{t(av)} \ x \ \eta_{pv} \ x \ \eta_{batt} \ x \ \eta_{inv} \ x \ A_{Tcf}} \quad (3.6)$$

Where E_l (Wh) is a demanding energy which is estimated in a day, η_{pv} is the efficiency of a photovoltaic module, η_{batt} is the efficiency of a battery storage, η_{inv} is the efficiency of an inverter, A_{Tcf} is a temperature correction factor, $H_{t(av)}$ (W/m^2) is the average solar irradiation collected on the study area. Therefore, the no of PV module needed to generate the needed amount of energy is expressed in (3.7) (Ogunjuyigbe et al., 2016)

$$\mathbf{N_{pv-modules}} = \frac{\mathbf{P_{(t)}}}{\mathbf{S_{peak-power}}} \quad (3.7)$$

Where, $S_{peak-power}$ (W) is the rated maximum power of the chosen PV module.

3.3 Wind Power

The wind model used in this study is a permanent magnet synchronous generator (PMSG) with 230V, 6kW, and 50Hz as frequency. Therefore, the equation (3.8) expresses wind turbine power (Bouharchouchel et al., 2013):

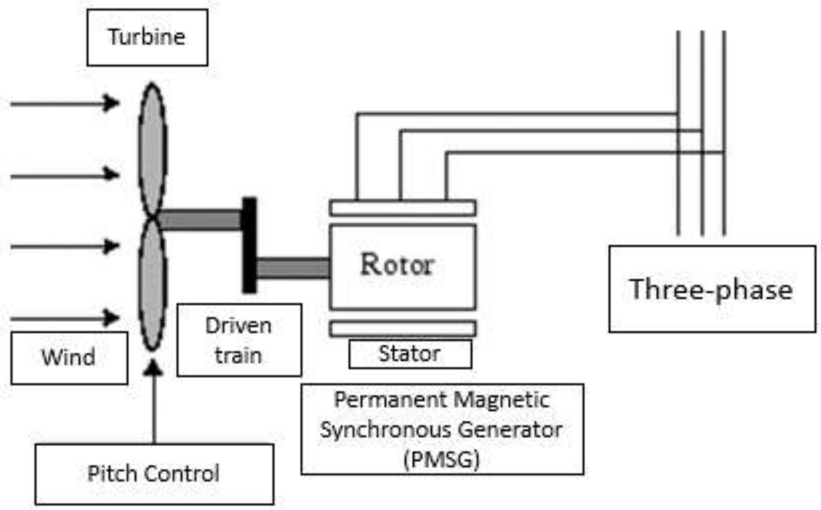

Figure 3. 2: Permanent Magnetic Synchronous Generator (PMSG) driven by wind turbine

The output power of the wind is dependent on the following parameters such as wind turbine efficiency, speed of the wind, pitch angle, and height of the tower (Bouharchouchel et al., 2013). Therefore, power produced by a wind turbine is expressed by equation (3.9)

$$P_w = \frac{1}{2}\eta_{wt}C_p(\lambda,\beta)\rho A v^3 \tag{3.8}$$

Where,

v is the velocity of the wind hitting the turbine blades, A (m^2) is the area of the turbine, $C_{p(\lambda,\beta)}$ power coefficient of the wind turbine, and is a function of (ß -blade pitch angle and λ -tip speed ratio), and ρ (kg/m^3) is the air density at the height of the turbine hub, and η_{wt} (%) is the efficiency of the turbine, β is the pitch angle of the blade, and λ is the tip speed ratio of the rotor blade tip speed to wind speed (Bouharchouchel et al., 2013).

The average power in terms of the average wind speed V_{avg} (m/s) is expressed as (Masters, 2013).

$$P_{wt} = \frac{6}{\pi}\cdot\frac{1}{2}\eta_{wt}\rho_{air}C_p A v_{avg}^3 \tag{3.9}$$

The wind speed at the hub of the tower is expressed as:

$$v_{hub} = v_{ref}\left(\frac{H_{hub}}{H_{ref}}\right)^{\beta} \qquad (3.10)$$

β is used to reflect the effects of the land, v_{ref} (m/s), v_{hub} (m/s) are the wind speed at the reference and the hub, respectively. H_{hub}(m) , H_{ref} (m) are the hub and reference measured heights respectively (Masters, 2013).

The power coefficient of the wind turbine is calculated as:

$$C_p = \frac{1}{2}[(1-\lambda)(1-\lambda^2)] \qquad (3.11)$$

Where: $\lambda$is the wind speed ratio. To maximize the rotor efficiency tip speed ratio must be $\lambda = \frac{1}{3}$(Letcher., 2017). Also, the power coefficient can be calculated as in (Luta, 2014, p.24).

$$C_p(\lambda, a) = \frac{P_t}{P_w} = \frac{Power\ of\ the\ wind\ turbine}{Power\ of\ the\ wind}$$

$$C_p(\lambda, a) = 0.5\left(\frac{116}{\lambda_i} - 0.4a - 5\right)e^{\frac{-21}{\lambda_i}} \qquad (3.12)$$

Where α is a rotor pitch angle.

With

$$\lambda_i = \left(\frac{1}{\lambda+0.08a} - \frac{0.035}{a^3+1}\right)^{-1} \qquad (3.13)$$

The number of wind turbines desired to meet a certain amount of load is expressed in the following equation (Ogunjuyigbe et al., 2016).

$$N_{turbines} = \frac{P_L x SF}{P_w} \qquad (3.14)$$

Where, obviously SF is about 120% and is known as a safety factor (Ogunjuyigbe, Ayodele and Akinola, 2016).

3.4 Energy Storage Equation

Distributed energy storage is playing a vital role in the energy generation industry due to its capability to store energy. There are many types of batteries and each one differs from the other depending on the characteristics of each battery. A battery can charge and discharge at a given time, and a control system is needed to ensure the safety of a battery. A maximum and minimum charge condition of a battery is needed to avoid overcharge or over-discharge which reduces the life cycle of a battery. Figure 3.3 shows a schematic diagram of a battery.

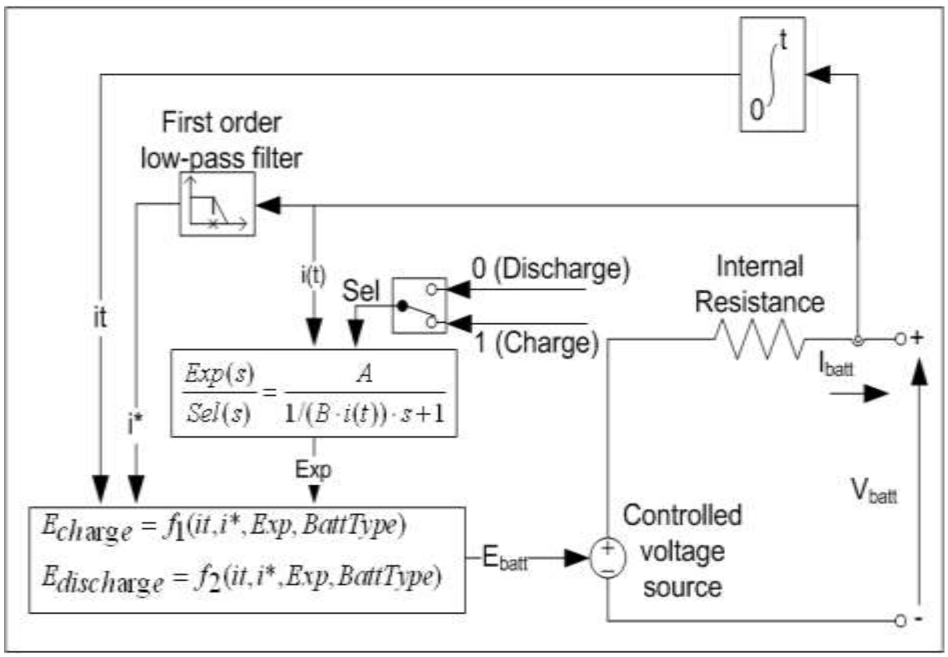

Figure 3. 3: Schematic design of a battery model (Sumathi, Kumar and Surekha, 2015)

The following equation shows the mathematical model for charging and discharging of a battery state model (Mirbagheri, Mirbagheri and Mokhlis, 2014).

$$SOC(t+1) = SOC(t) + \eta_{ch} P_{ch} - \eta_{disch} P_{disch} \quad (3.15)$$

$$SOC(t+1) = SOC(t) + \eta_{batt} \left(\frac{P_b(t)}{V_{bus}}\right) \Delta t, \quad (3.16$$

Where SOC is the battery current state of charging, $\eta_{bat}$is the battery efficiency during the charging and discharging process, $P_b(t)$ (W) is battery power, Δt is the time step which is 20 second, while V_{bus} (V) is the voltage at DC bus.

The availability of battery capacity banks must be between the minimum and the maximum capacity and is expressed in equation (3.17) (Ogunjuyigbe et al., 2016). Therefore, the minimum limit of a battery to discharge is set to be 40% and the maximum state of charge of a battery is set to be 90%, to prolong the life cycle of a battery (Mirbagheri et al., 2014).

$$SOC_{min} \leq SOC(t) \leq SOC_{max}, \tag{3.17}$$

$$SOC_{min} = (1 - DOD)SOC_{max} \tag{3.18}$$

Where DOD is the depth of discharge and $SOC_{max}$the maximum state of charge of a battery.

The battery capacity needed in Ah is given by the following equation (Ogunjuyigbe et al., 2016).

$$\mathrm{M_{bat}} = \frac{\mathrm{A_d\ E_L}}{\eta_{bat}\ \eta_{inv}\ \mathrm{DoD\ V_s}} \tag{3.19}$$

Where **Ad (s)** is the maximum time the battery can operate without any other support from any other sources, E_L (Wh) is energy …, **Vs (V)** s the voltage of a system, and **DoD** is depth of discharge.

The batteries are connected in series to give the desired nominal DC operating voltage and are connected in parallel to yield a desired Ah system storage capacity. The number of batteries needed for the system is calculated as:

$$\mathbf{N_{bat}} = \frac{\mathbf{M_{bat}}}{\mathbf{M_{sin}}} \tag{3.20}$$

Where, M_{sin} is the capacity of a battery which is measured in Ah.

Number of batter needed in series $\boldsymbol{(N_{bs})} = \frac{\boldsymbol{V_{bus}}}{\boldsymbol{V_b}}$ (3.21)

Where $\boldsymbol{V_{bus}}$ is a bus voltage, $\boldsymbol{V_b}$ is battery voltage

Number of batter needed in parallel $\boldsymbol{(N_{bll})} = \frac{\boldsymbol{I_T}}{\boldsymbol{I_{batt}}}$ (3.22)

Where $\boldsymbol{I_T}$is a total current, and $\boldsymbol{I_{batt}}$ is a battery current.

3.5 Boost Converter Parameter Calculation

The boost converter parameters are calculated using the following equation:

$$D = 1 - \frac{V_{in} * n}{V_{out}} \quad (3.23)$$

$$d_i = I_{ripple} * I_{out} \frac{V_{out}}{V_{in}} \quad (3.24)$$

Where I_{ripple} (A) is the inductor ripple current which is estimated to be between 20 and 40% of the output current, I_{out} (A) is the output current, V_{out} (V) is the output voltage, V_{in} (V) is the input voltage, and **n** is the efficiency and di is the input ripple current (Massawe, 2013).

$$I_{out} = \frac{P_{out}}{V_{out}} \quad (3.25)$$

The Inductance is calculated as illustrated by equation (3.24)

$$L = \frac{V_{in} * (V_{out} - V_{in})}{di * fs * V_{out}} \quad (3.26)$$

$$dv = \frac{V_{out}}{100} \quad (3.27)$$

Where dv is the output voltage ripple

Where **L (H)** is an inductance, and **fs (hz)** is the resonant frequency

$$C = \frac{I_{out} * D}{fs * dv} \quad (3.26)$$

$$R = \frac{V_{out}}{I} \quad (3.27)$$

3.6 Summary

This chapter is based on the mathematical modeling of the case study microgrid, which helps us to understand the performance parameters of each component of the microgrid. Modeling of each component has been done to determine the required value of each component and the description of each component in detail concerning a study field.

CHAPTER FOUR

COMPUTER MODELING AND THE STATE MACHINE ALGORITHM

4.1 Introduction

In this chapter, the following methods are used to achieve the settled aims. A proposed microgrid model comprised of wind conversion system, photovoltaic (PV), and battery storage is modeled and simulated in MATLAB/Simulink. The energy management system is proposed to fairly share the energy generated by the microgrid system for a residential building. The proposed energy management strategy controls different renewable energy systems and battery storage, to coordinate their operation for supplying the residential load. which can be suitable for a stand-alone system or off-grid system. State machine modeling in MATLAB is used to design the energy management system to control the sharing of energy between different intermittent sources. Different parameters, calculations, and block diagrams are used to implement the modeling and simulation of the proposed system.

4.2 Methodology

The following MATLAB models present the performance of a photovoltaic (PV) system, a wind energy conversion system, and battery storage for the proposed microgrid system. Simulation is done using sim-power toolbox, and state flow algorithm to model and evaluate the performance of the proposed energy management system of the microgrid

4.2.1 Photovoltaic Model in Simulink/ MATLAB

The PV model used in this study is a 1soltech 1STH-345-WH PV model with the 4-string module connected in series and 4-string module connected in parallel, the PV Arrays formed a total power of 3660 W, a total current of 30.5 A and 120V as output voltage required of a PV array based on the input of DC/DC converter system. The characteristic of the chosen photovoltaic model is given in Table 4.1. The MATLAB/Simulink block of a generic PV system is presented in Figure 4.1 It shows that the photovoltaic model is connected to a DC-DC boost converter to raise the voltage at the desired level and is driven by a Maximum Power Point Tracking (MPPT) system using perturb and observe (P&O) algorithm to extract the maximum possible power from photovoltaic (PV) system. Figure 4.2 illustrates the V-I and P-V characteristic curves from the PV Array system MATLAB model at 1000 W/m^2 undera nominal standard condition 25^0C as a temperature.

Table 4. 1: PV systems parameters in MATLAB

Module Data	Unity
Module: 1Soltech 1STH-230-P	
Minimum Power (W)	228.735
Open circuit voltage V_{oc} (v)	37.1
Voltage at maximum power point V_{mp} (V)	29.9
Temperature coefficient of V_{oc}	−0.361
Cells per module (Ncell)	60
Short-circuit current Isc (A)	8.18
Current at maximum power point Imp (A)	7.65
Temperature coefficient of I_{sc}	0.102

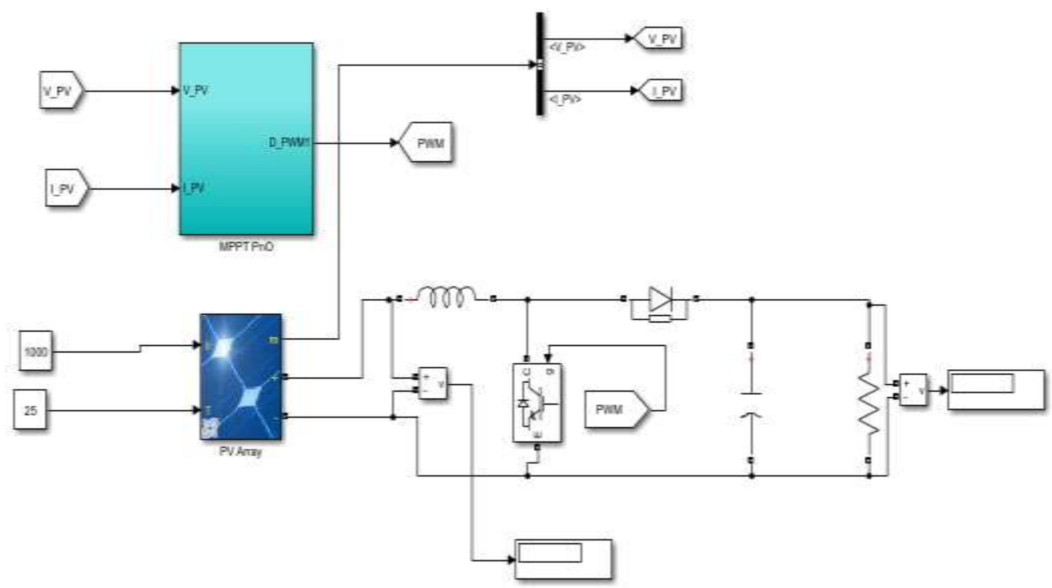

Figure 4. 1: Block diagram of a photovoltaic system connected to a boost converter.

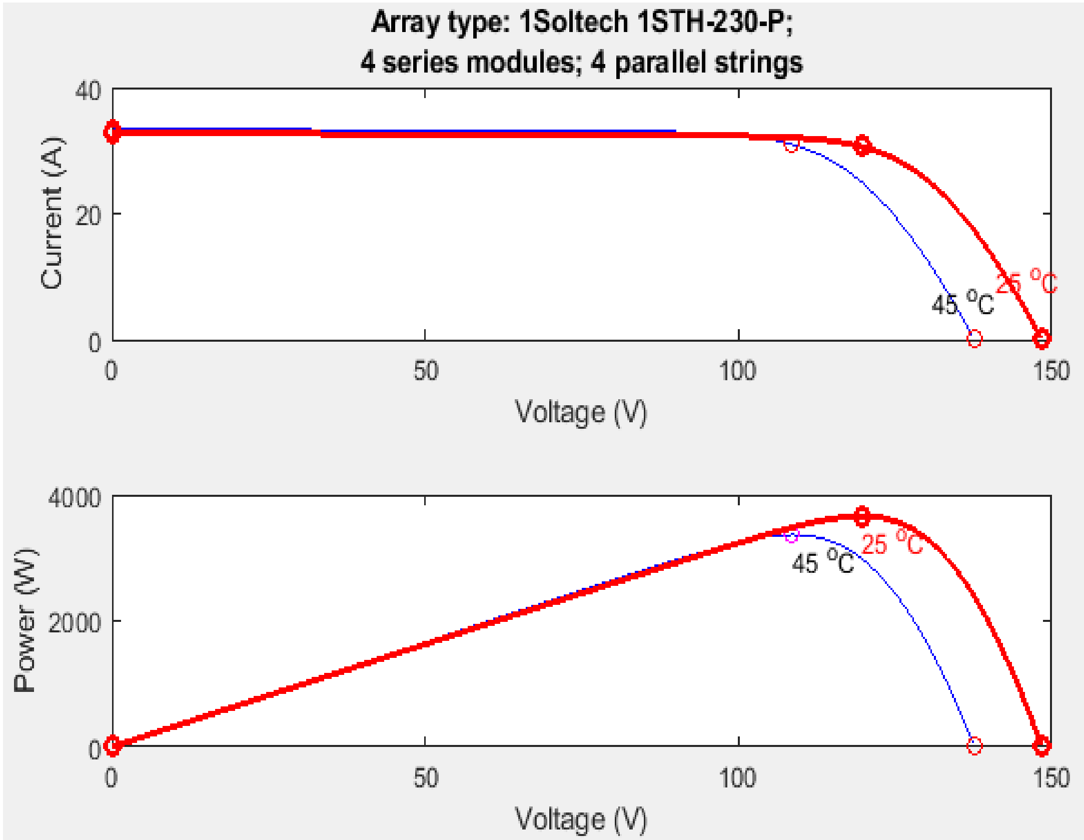

Figure 4. 2: V-I and P-V characteristic curves of the PV array at 1000 W/m^2

4.2.1.1 Input Parameter of PV system

Number of panels needed in series (V_{ps}) $=\frac{120}{29.9} \cong 4$

$V_{new} = 4 * 29.9 = 120\ V_{dc}$

The current is calculated from the following formula,

$P = VI$

The total current is calculated as follows

$I_T = \frac{P}{V} = \frac{3660}{120} = 30.5\ A$

Number of panels in parallel

$$(N_{pp}) = \frac{I_T}{Imp} = \frac{30.5}{7.65} = 3.9 \cong 4$$

$$\text{Actual Power} = (N_{pp} * I_{mp} * N_{ps} * V_{mp}) = (4 * 7.65 * 4 * 29.9) = 3659.7\ W$$

Therefore, by connecting 16 PV panels, 4 in series and other 4 in parallel, the overall power from photovoltaic (PV) is expressed by the number of all panels

(N_p) times the power of each panel (P_p)

-= 16 x 228.735 = 3659.76 W

4.2.1.2 Maximum Power Point Tracking System

MPPT algorithm is used to extract the maximum output power from the photovoltaic system, there are several MPPT methods to extract the maximum power from PV such as fuzzy logic, perturb and observe (P&O), Incremental Conductance, Fractional short circuit voltage, neural network, (Sumathi et al., 2015). There are several methods presented in the literature review regarding the MPPT algorithm. Therefore, for this study, the chosen MPPT algorithm is a perturb and observe (P&O) algorithm due to its efficiency and simplicity in terms of application (Bouharchouchel et al., 2013). Figure 4.3 shows the MATLAB block of the P&O algorithm. Figure 4.4 shows a flow chart of the P&O algorithm.

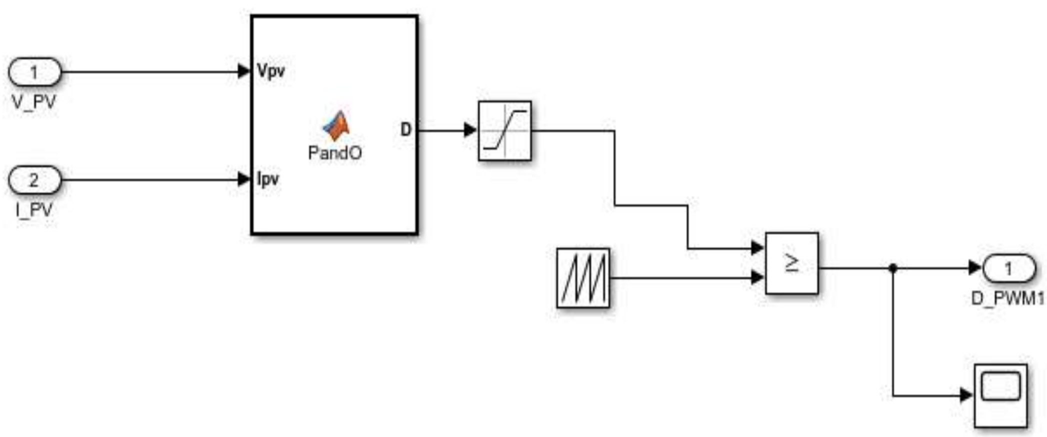

Figure 4. 3: MATLAB Function for the implementation of a Maximum Power Point Tracking System

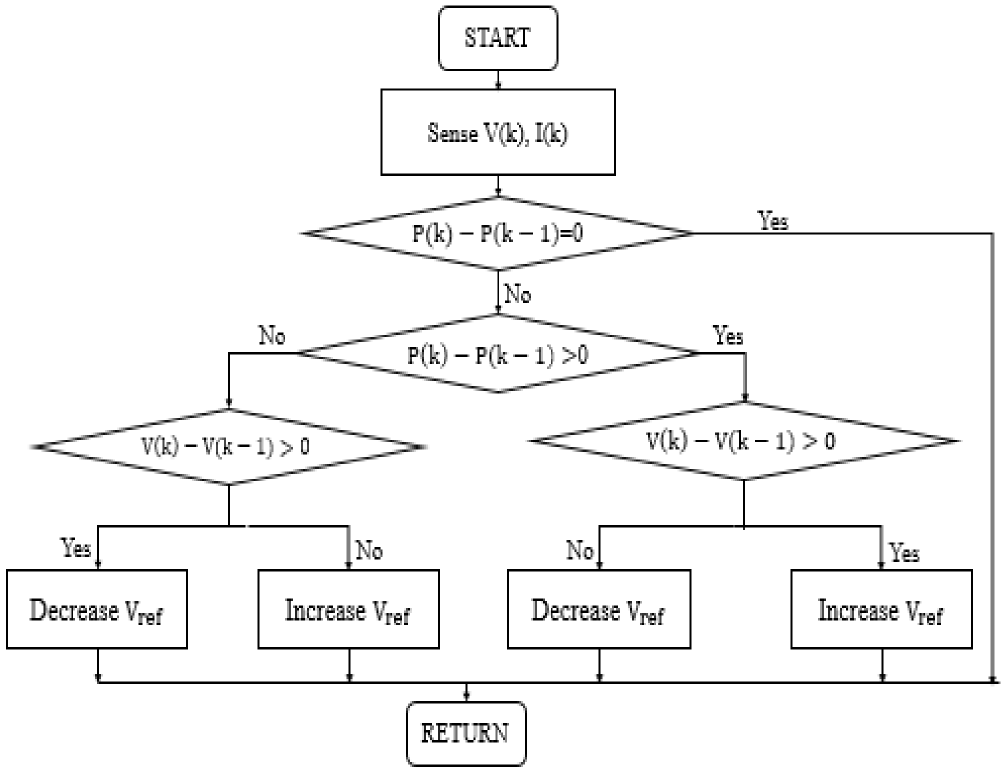

Figure 4. 4: Flowchart of P&O Algorithm

4.2.2 Boost Converter Model for PV

The boost converter is modeled using MATLAB/Simulink to raise the 120 V of PV to 230 V voltages driven by the MPPT system. Calculations were made to determine the capacitance, inductance, and load resistance to get the desired output voltage from the converter. The boost converter diagram with all parameters is presented in Figure. 4.5 and Table 4.2, the duty cycle is driven by the MPPT controller was used to control the system to have the desired output voltage. From the calculations L=2.3 e^{-4} H, C =1.8 e^{-4} F, and R = 14.5 Ω. Boost converter parameters were calculated using the formula stated in the equations 3.21 – 3.27. Therefore, Figure 4.6 shows the power output of a converter, while Figures 4.7 and 4.8 show the simulation results of a converter, where Input current and voltage are almost close to its calculated value, and the output voltage and current of the inverter are the same as calculated values.

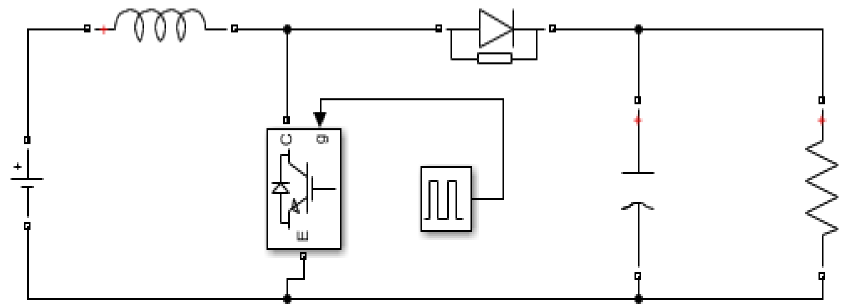

Figure 4. 5: Boost Converter diagram

$$D = 1 - \frac{V_{in}*0.9}{V_{out}} = 1 - \frac{120*0.9}{230} = 0.53$$

Sample time is T_s = 1/20000

$$I_{out} = \frac{P}{V_{out}} = \frac{3660}{230} = 15.9\ A$$

I_{ripple} is estimated to be between 20% to 40% of output current

$$d_i = I_{ripple} * I_{out} * \frac{V_{out}}{V_{in}} = 0.4 * 15.9 * \frac{230}{120} \cong 12.2A$$

$$L = \frac{V_{in}(V_{out} - V_{in})}{d_i * f_s * V_{out}} = \frac{120(230-120)}{12.2 * 20000 * 230} = \frac{13200}{56120000} = 2.3\ 10^{-4}H$$

where ΔVis 1 percent of V

$$\Delta V = 1 * \frac{230}{100} = 2.3\ V$$

$$R = \frac{V_{out}}{I} = \frac{230}{15.9} = 14.5\ \cap$$

$$C = \frac{I * D}{f_S * \Delta V} = \frac{15.9 * 0.53}{20000 * 2.3} = \frac{8.4}{46000} = 1.8\ 10^{-4}F$$

Table 4. 2: Input parameters of a boost converter

Input parameter of boost converter system	
Nominal Power (W)	3660
Inductance (H)	2.3 e-4
Capacitor (F)	1.8 e-4
Load Resistance (Ω)	14.5
Input Voltage (V)	120
Output Voltage (V)	230
Converter Efficiency	0.9

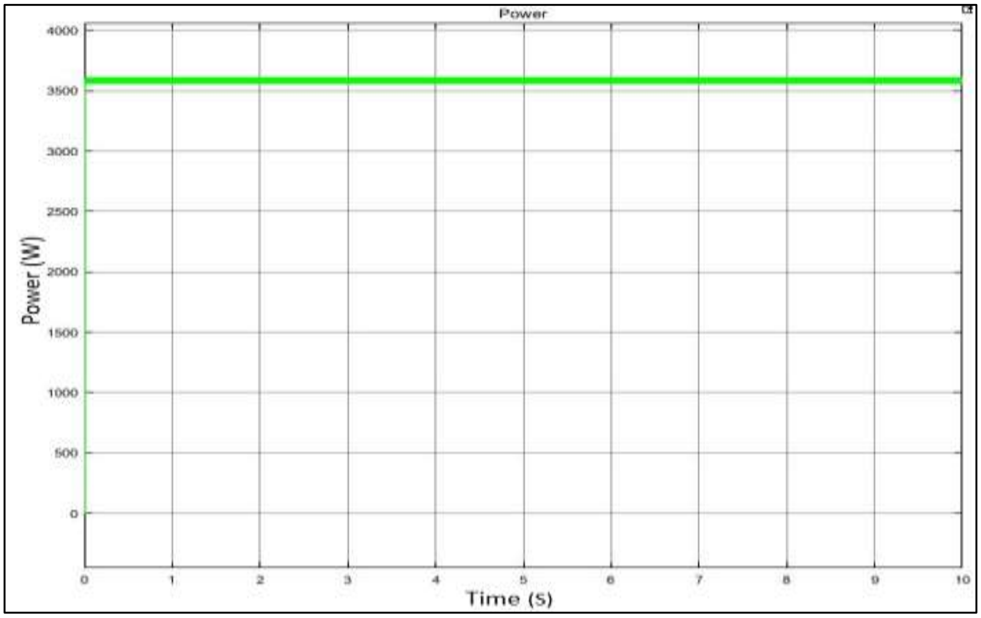

Figure 4. 6: Output power of a converter

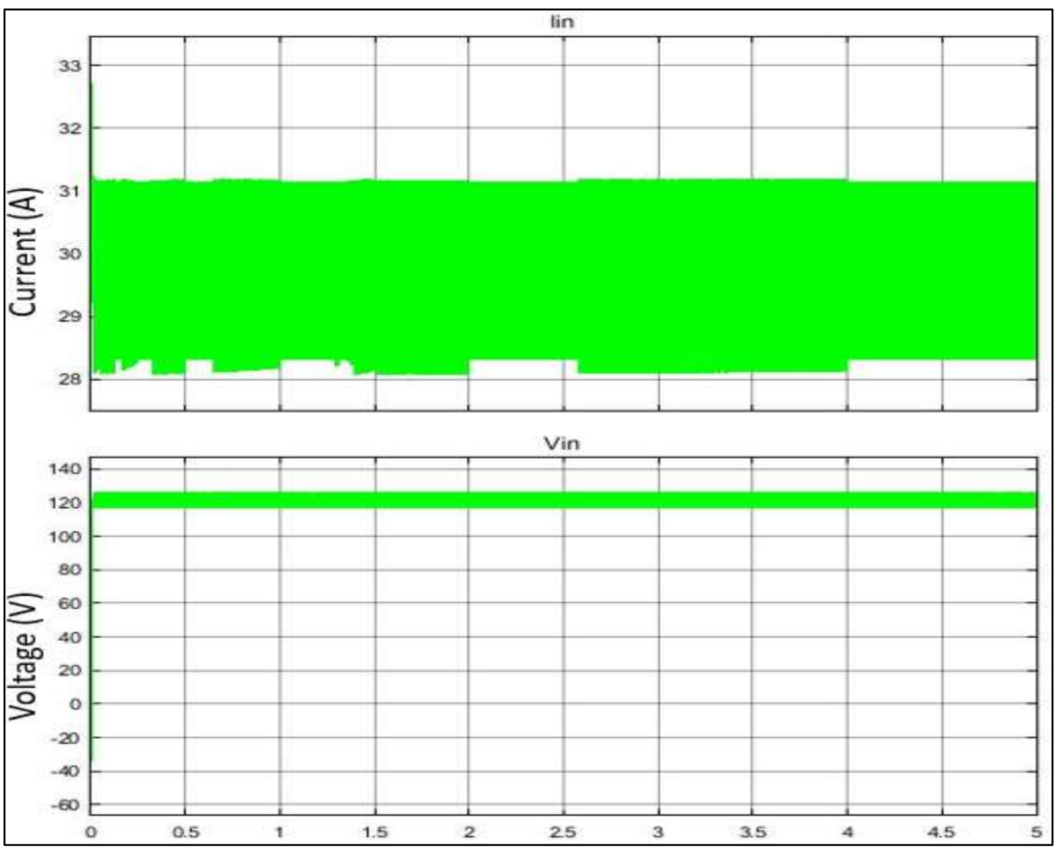

Figure 4. 7: Input voltage & Current of a converter

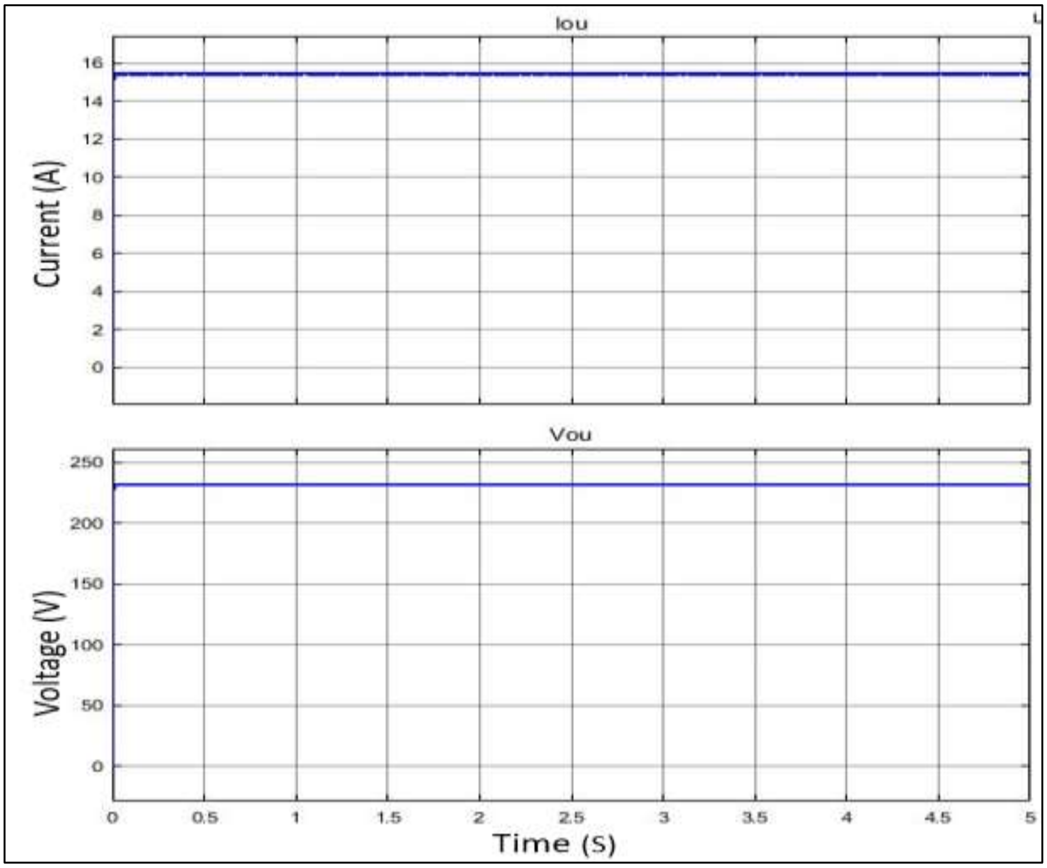

Figure 4. 8 Output voltage& Current of a converter

4.2.3 Wind Turbine Power

The wind turbine model considered in this study is a wind turbine connected directly to the rotor of a Permanent Magnetic Synchronous Generator (PMSG). The reason behind choosing the permanent magnet synchronous generator is the fact that they are cheaper in manufacturing because their motor does not need field winding which in turn decreases the prices. (PMSG) rotates at a fixed speed. Figure 4.9 shows the wind model in Simulink/MATLAB. Table 4.3 indicates the parameters of the PMSG. Wind turbine characteristics are developed using MATLAB as shown in Figure 4.10.

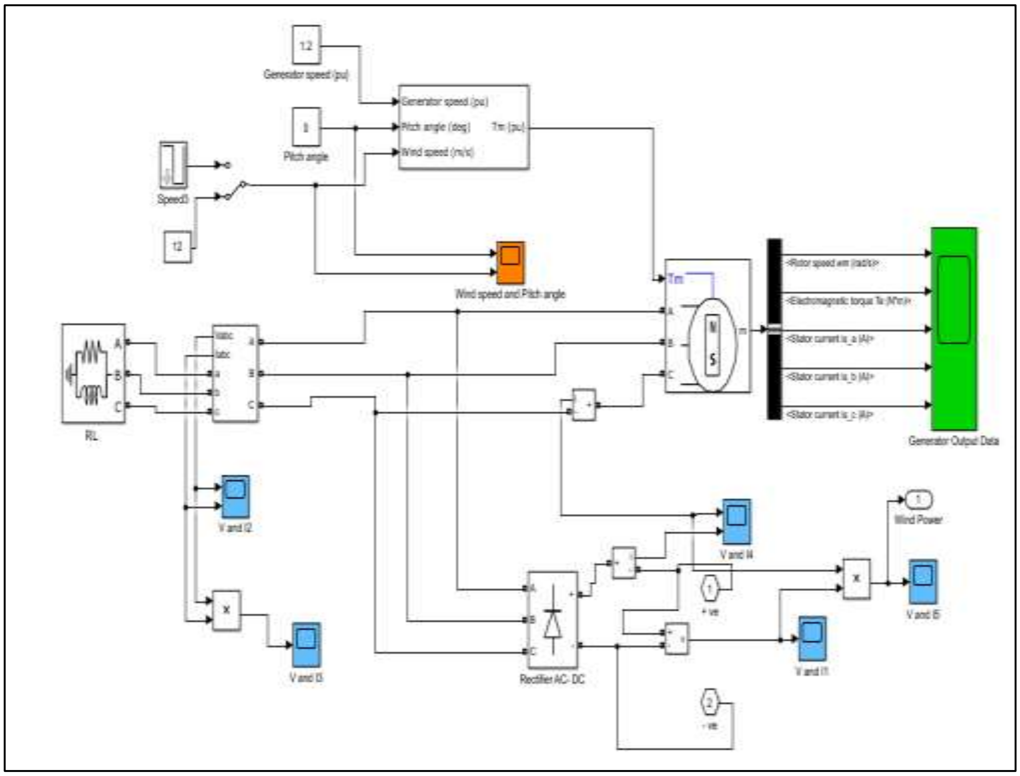

Figure 4. 9: Wind model in Simulink/MATLAB

Table 4. 3:Input parameters of (PMSG) model

Wind Turbine Parameters	Values
Rated output Power (kW)	6
Cut-in Speed (m/s)	2.5
Rated Speed (m/s)	12
Cut-out Speed (m/s)	13
Rotor-diameter (m)	2.5
Air Density (kg/m3)	1.225
Total Capital Cost (R)	3200
Annual Maintenance Cost (R)	100

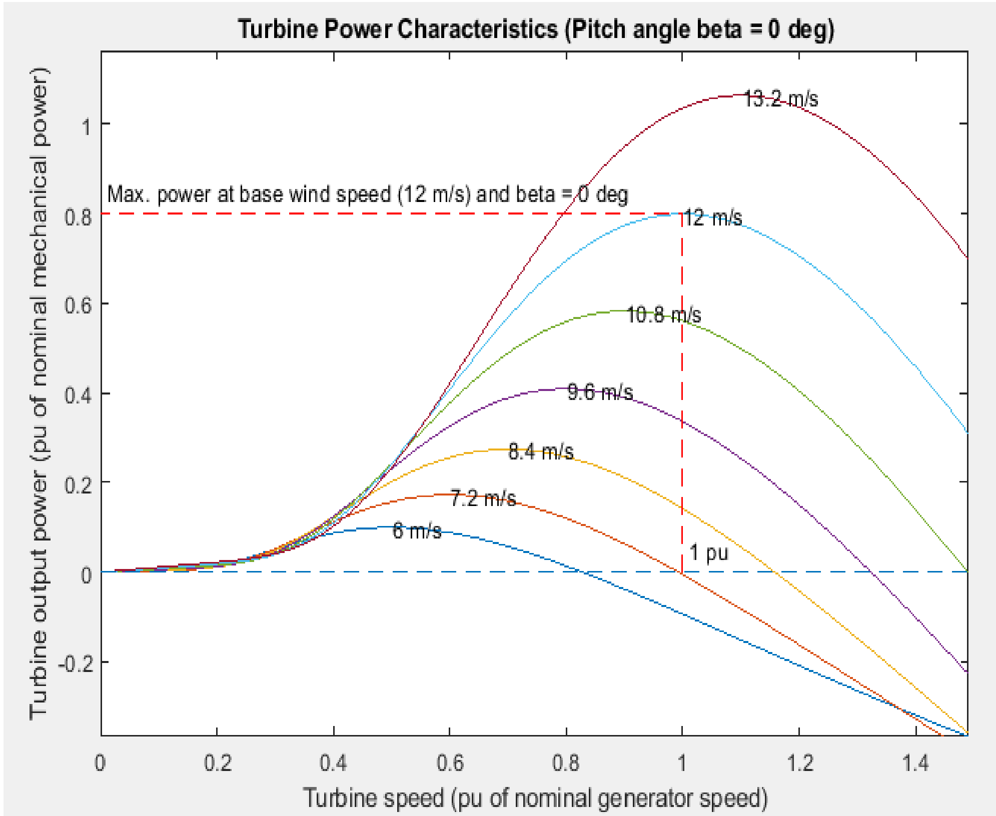

Figure 4. 10: Wind turbine characteristic curves for different wind speed

4.2.4 Battery

The battery is being used to store the energy and used it in case there is an energy shortage. There are many types of batteries with distinctive characteristics as explained in chapter two. The battery can be charged and discharged depending on the availability of power. However, a lead-acid battery is being used in this project for a micro-grid system due to its efficiency and durability both in terms of resisting load variation, and the charging and discharging process (Hadjipaschalis et al., 2009). The battery is connected to the DC bus bar via switches to be able to allow the charging and discharging, the switches are controlled by the state flow algorithm to decide if the battery should start charging or discharging or do neither both by closing and opening the switches. The battery bank of 230V and 40 Ah which makes 9200Wh as a total nominal capacity was chosen, the selection of a battery capacity was based on the cost because the battery can be used only as a backup in case the renewable energy is not enough, therefore, this size is perfect in terms of saving money since is not too small in terms of capacity and is not too expensive for the designed system. However, to increase the life cycle of a battery system and safe operation, the minimum and maximum rate of a battery discharge and charge are set to be 40% as a minimum and 90% as a maximum. Figure 4.11 shows the battery model in Simulink, while Figure 4.12 shows the battery discharge curves developed by MATLAB. Table 4.4 shows the input parameter of the chosen battery model.

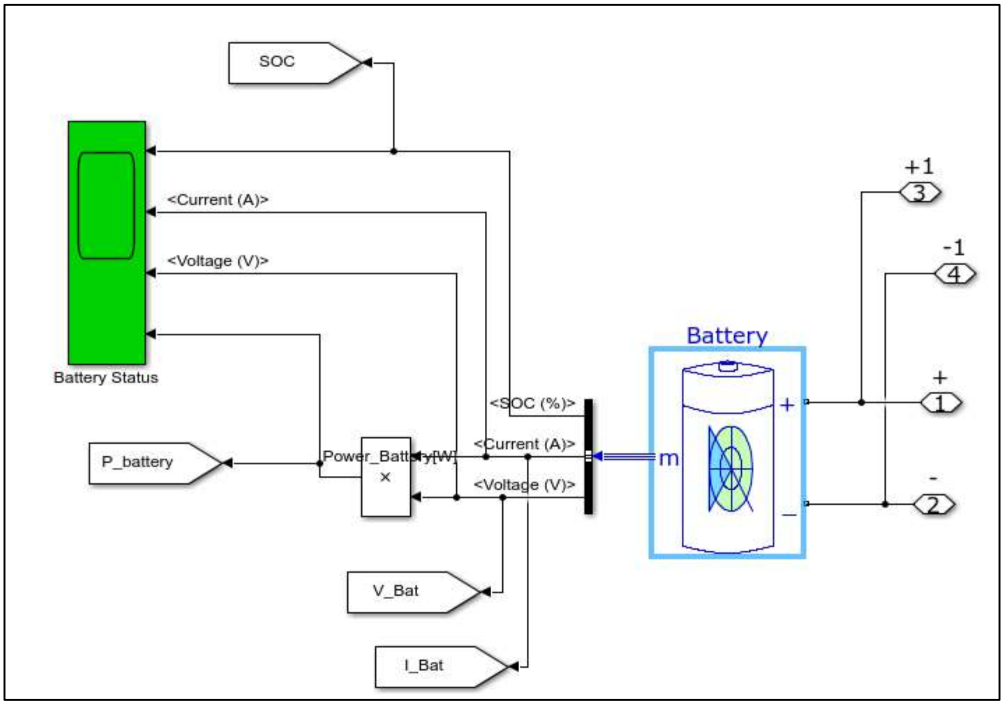

Figure 4. 11: Battery model in Simulink/MATLAB

Figure 4.12 presents the battery discharge curves developed by MATLAB respectively from the input parameter from Table 4.4. Note that the battery discharge performance depends on the size of the load applied, if the load is big the battery can be discharged quicker than the normal load. The discharge curve of a 230 V nominal battery voltage, 40Ah of capacity, is presented, and the voltage side is comprised of three states such as an exponential drop from full charge as the battery begins to discharge, a linear section where the battery is typically operated at a normal voltage and a nonlinear section where the battery close to its final discharge state, therefore, the amount of current the battery can deliver remain less constant for a quite a while and then drop off rapidly as the limit of its capacity is attained.

Table 4. 4: Input parameter of battery model

Battery Model Input parameter	
Nominal voltage (V)	230
Rated Capacity (Ah)	40
Maximum Capacity (Ah)	40
Fully Charged Voltage (V)	267
Nominal Discharge Current (A)	17.3913
Internal Resistance (ohms)	0.0575
Capacity (Ah)@Nominal Voltage	36.1739
Exponential Zone [Voltage (V), Capacity (Ah)	[48.48 1.96]
Battery Voltage Response time (sec)	0.1

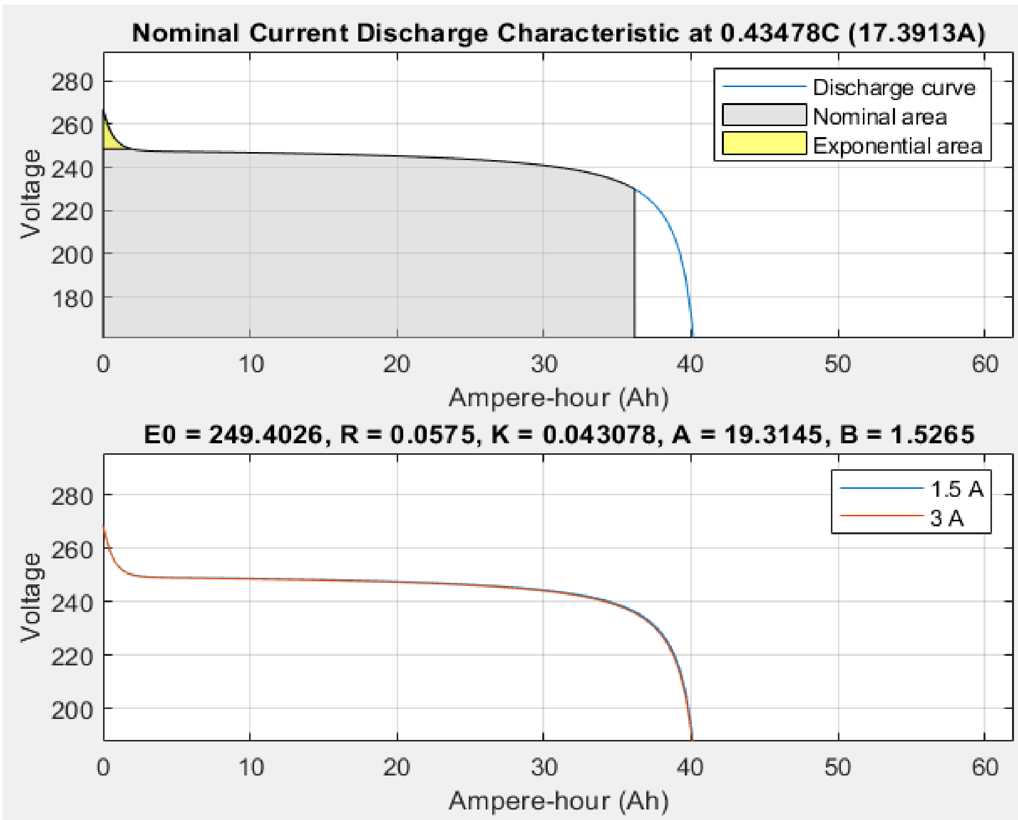

Figure 4. 12: Battery Nominal current Discharge Curves Characteristic

4.2.5 Energy management algorithm

The energy management system increases the reliability of micro-grid which could be affected due to the intermittency of renewable energy resources, which could lead to a mismatch between the load and the supply (Choi and Lim, 2018; Bouharchouchel, Berkouk and Ghennam, 2013). Many types of energy management systems can be used to guaranty the equitable sharing of energy between different sources such as fuzzy logic, state machine, and PID controller (Motapon et al., 2014). The state machine control system has been chosen due to its efficiency, where nine states have been implemented to fully control the flow of energy between our sources and load.

Energy generated by Photovoltaic and wind turbine will be used to supply the residential load (AC and DC) in the islanded microgrid. Note that the residential house has no other sources than that renewable energy only, and the DC load (Load 1) is comprised of three loads that are switched on and off with switches at a different time and are all connected in parallel and AC load (Load 2) is comprised with two loads connected in parallel, and controlled by a switch and turned on and off at a different time. Therefore, in case the power from renewable energy systems exceed the residential load demand, the excess will be used to charge the battery, if the battery state of charge becomes more than 90% then the battery will automatically disconnect and stop charging from the renewable energy systems. Note that the battery will be used only in case there is a shortage of power (PV and Wind Turbine). However, in case power generated from renewable sources (PV and Wind Turbine) is more than the load demand and the state of charge of a battery is at the highest level (90%), the dump load will be connected to accumulate the excess power as the battery is full.

In case that the generated renewable power is less than the needed load power, the state machine energy management system will check the state of charge of the battery. If the state of charge of the battery is at its normal or higher charged capacity level, the battery will automatically connect to the load to supply the deficit in the load demand. In case the state of charge of the battery is less than its minimum level, the battery will be disconnected to prevent damage.

4.2.5.1 Conditions of the state machine energy management system

The following conditions were designed and implemented in the State machine flowchart to conduct the proposed energy management system, whereP_{ren} is power renewable, P_{Load} is a power load, SOC is a state of charge of a battery D_{Load} is a dump load.

- If $P_{ren} \geq P_{Load}$&& SOC < 40%

Charging = 1; Discharging= 0; Load1On= 1; Load2On= 1; D_{Load}=0.

The power from renewable energy systems (PV and Wind) in this case will be used to supply the load and the excess will be used to charge the battery, in case the state of charge of a battery gets to its maximum (90%) the algorithm will disconnect the battery to prevent overcharge so that the life cycle of a battery storage will be boosted.

- If $P_{ren} \geq P_{Load}$&& SOC > 40%: && SOC < 90%

Charging = 1; Discharging= 0; Load1On= 1; Load2On= 1; $\mathrm{D}_{\mathbf{Load}}$ = 0.

In this case, as the battery state is at the normal state where it can be able to charge or discharge at any time, the excess power from renewable will be used to charge the battery. Dump load will not be necessary to be connected since the power will be used for both supplying the load and charging the battery in case there is excess power.

- If $P_{ren} \geq P_{Load}$&& SOC > 90%

Charging = 0; Discharging= 0; Load1On= 1; Load2On= 1; $\mathrm{D}_{\mathbf{Load}}$=1.

In this case, as the state of charge of the battery is at its highest level of charging, the excess power from renewable energy sources will connect to the dump load to avoid overpower.

- If else $P_{ren} < P_{Load}$&& 40 < SOC < 90%

Charging=0; Discharging= 1; Load1On=1; Load2On= 1; $\mathrm{D}_{\mathbf{Load}}$=0.

In case, the renewable energy is not able to supply the load demand, the algorithm will check the battery state of charge. In case the battery state of charge is at its normal level between (40%< SOC <90%), the power will be drawn from the battery to supply the load deficit. The load will be connected but the dump load will not be connected.

- If else $P_{ren} < P_{Load}$&& SOC >90%

Charging=0; Discharging= 1; Load1On=1; Load2On= 1; $\mathrm{D}_{\mathbf{Load}}$=0.

In case, renewable energy is not enough to supply the load, the algorithm will check the state of charge of a battery in case the state of charge of the battery is at the highest level (90%), the load deficit will be compensated by the battery.

- If else $P_{ren} < P_{Load}$&& SOC < 40%

First condition

- $P_{ren} \geq P_{L1}$

Charge = 1; Discharge =0; Load1On=1; Load2On= 0; $\mathrm{D}_{\mathbf{Load}}$=0.

Second Condition

- $P_{ren} \geq P_{L2}$

Charge = 1; Discharge =0; Load1On=0; Load2On= 1; $\mathrm{D}_{\mathbf{Load}}$=0.

Otherwise

Charge = 1; Discharge =0; Load1On=0; Load2On= 0; $\mathrm{D}_{\mathbf{Load}}$=0.

In case the power from renewable energy is not able to supply the load, and the SOC of the battery is less than its minimum, the algorithm will check the available power from renewable sources and compare to the load one in case renewable power is equal or higher than load one, the algorithm will disconnect load two, in case renewable power is less than load one, the algorithm will check load two, if found that renewable power is higher or equal than load two, load one will be disconnected and connect both load two and the battery, and if renewable power is less than load two, both loads will be disconnected.

Figure 4.13 presents the state machine control block subsystem in Simulink, the system intends to monitor and control the flow of energy between these intermittent energies and, it is clear that the system has three input such as P_{load}, Renewable Energy, and State of Charge of a battery, while the output is comprised with five components such as Load 1, Load 2, Dump Load, charging and discharging. This means that the system is controlling output based on the comparison of input to decide which output is for the next decision. Figure 4.14 shows the state machine algorithm presented by state flow in MATLAB, and Figure 4.15 shows the state machine logic control appearance when is in running mode, it is shown by the boundary that is turning to blue color, therefore, it is quite clear that the same condition designed above is implemented in state flow in MATLAB to fairly share the generated energy. The left side presents the state of a battery comprised of three state such as the default, charging, and discharging of a battery, where default describes the state where the battery is not either charging or discharging (charging =0; discharging=0), the other state in the battery state is charging(charging=1; discharging=0), means that the battery is at the charging mode and the last state is discharging (charging=0; discharging=1), means that the battery is at discharging state. The right side describes the load state comprised of three different loads (Load 1 known as a DC load, Load 2 known as AC load, and Dump Load), each one comprised of On and Off state. The arrow describes which state is chosen based on the available power and SOC of a battery.

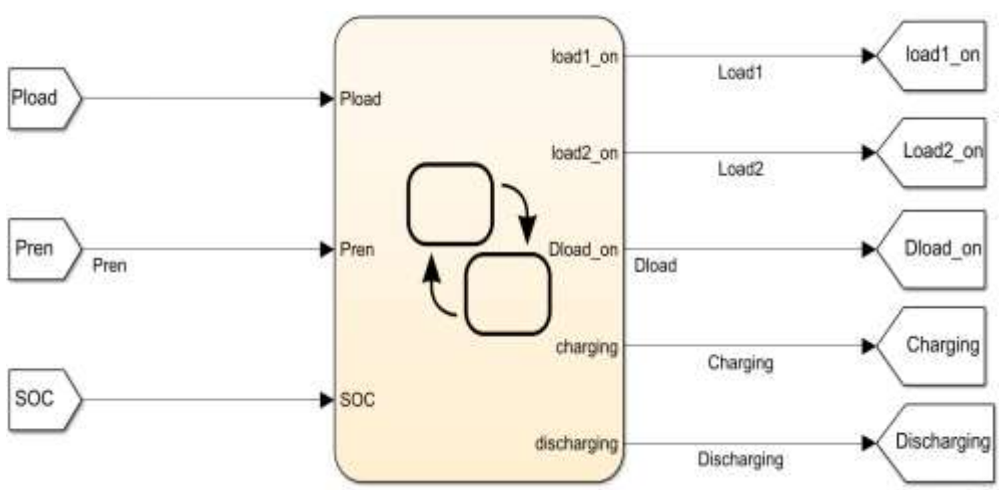

Figure 4. 13: State machine control block subsystem in Simulink

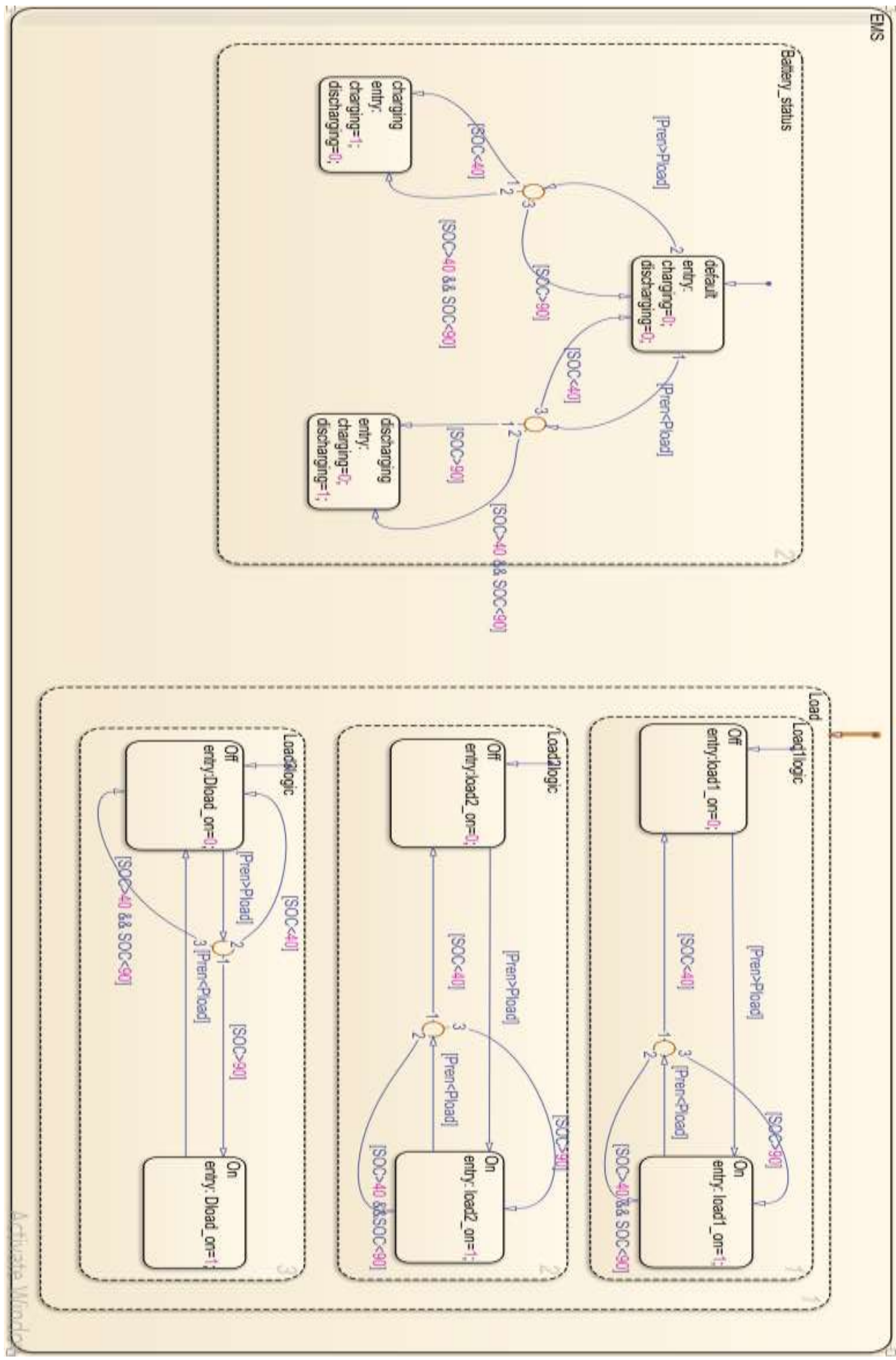

Figure 4. 14: State Machine diagram

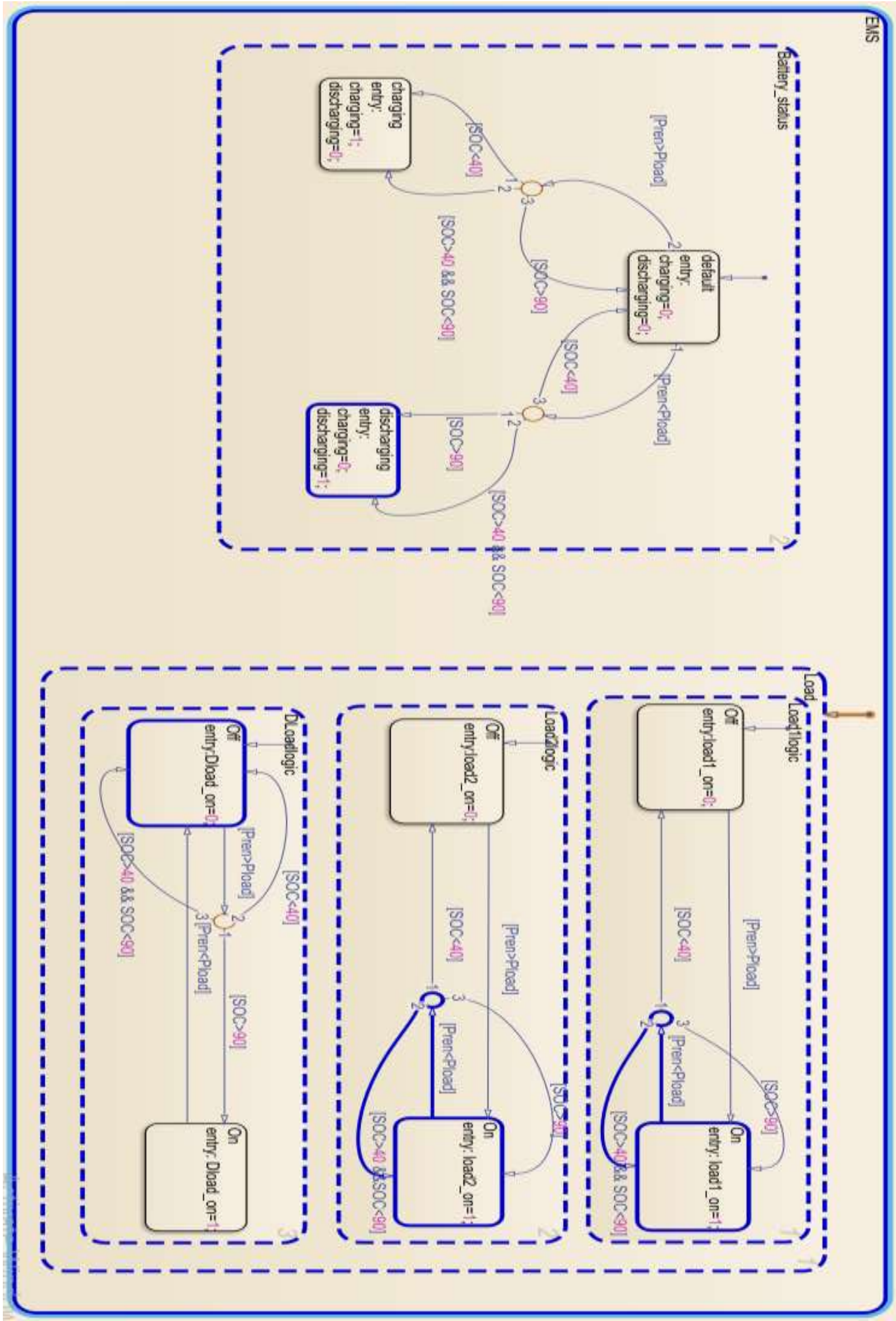

Figure 4. 15: State machine in running mode

4.2.5.2 State machine algorithm

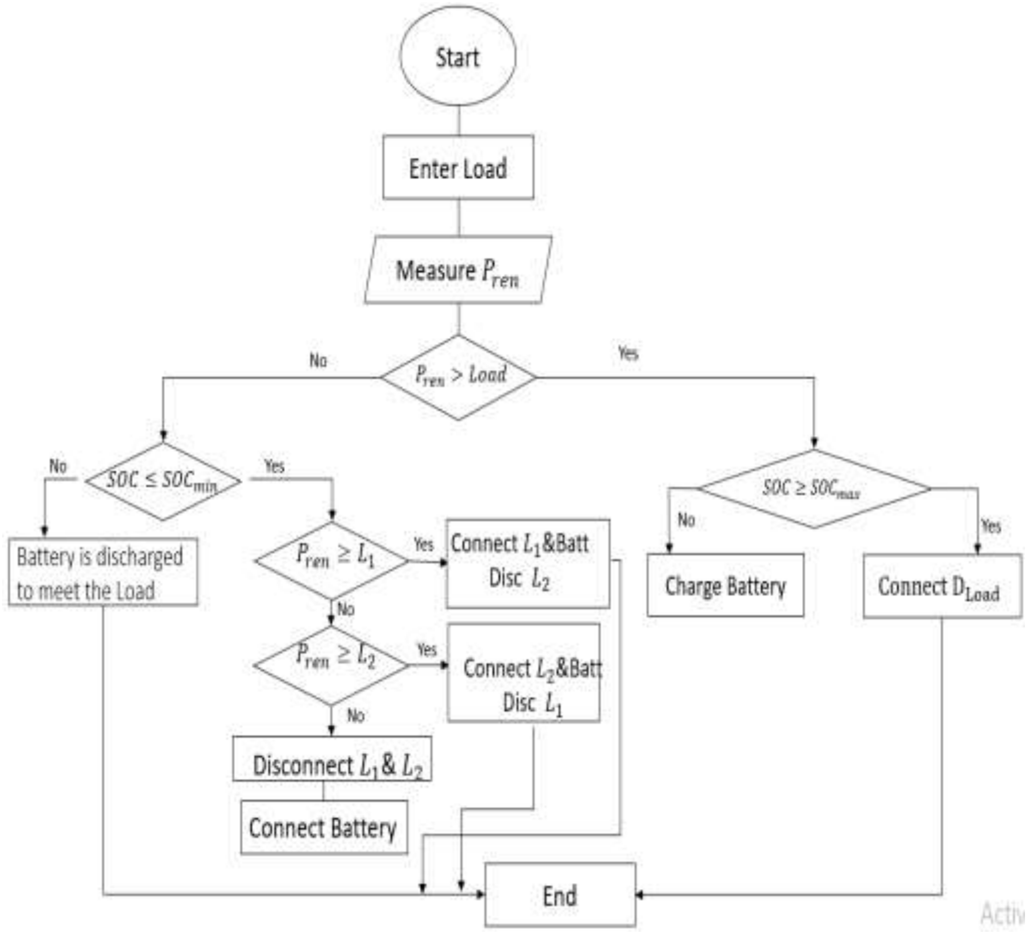

Figure 4. 16: Flow chart diagram of state machine energy management system

4.3 Summary

In this chapter, the modeling and implementation of all mathematical model which help us to establish the implementation of each device have been done and processed in detail to give accurate results for our system. Mathematic Modelling of each component particularly has been done separately to determine the required value of each component such as input voltage, output voltage, output power, and input power, etc. However, the modeling of each component has been conducted and implemented in Simulink/MATLAB.

CHAPTER FIVE
RESEARCH RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents simulation scenarios and results from applying the proposed state machine energy management system in the microgrid comprised of photovoltaic (PV), wind turbine, and battery storage systems in MATLAB/Simulink. Different scenarios are implemented to verify the accuracy of the energy management system in the proposed case study.

5.2 Simulation scenarios

The case study of the proposed microgrid is build using MATLAB/Simulink as shown in Figure 5.1, while Figure 5.2 shows PV connected to the boost converter to match the wind system voltage and Wind Turbine connected straight to the rectifier to convert its AC output to DC to match the PV voltage types. Simulink results from different scenarios are presented in Figure 5.3, 5.4, 5.5, 5.6, 5.7, and 5.8. The energy management system is designed using a state machine algorithm to execute the load sharing between different renewable energy sources (PV and Wind Turbine) which are combined as a DC Power and supply both the load and the battery system. The 6kW wind turbine with 230V relates to a PV system of 3.6 kW with 120V connected to a dc/dc boost converter driven by MPPT and change it to 230 dc voltage as seen in Figure 5.2. The battery model is set to be at 230V and the initial state of charge is 69% for the first scenario, 49% for the second scenario, and 89% for the 3rd scenario, connected to both DC and AC load at the same time. The load is comprised of both DC load (Load 1) and AC load (Load 2) that are controlled by switches so that they can be switched On and off at different times. Therefore, the first load is a DC load comprised of three different loads controlled by switches to be able to be turned on and off at different times, and connected in parallel with the overall power consumption of 4 KW, whereas the second load is an AC load comprised of two loads controlled by switched to be able to be on and off at different times connected in parallel as seen in Figure 5.1, both with the overall power consumption of 4 kW, note that AC load is connected via an inverter that change DC to AC power, Appendix 1 and 2 respectively show details about a block diagram of an inverter using a universal bridge and its PWM generator block, therefore both AC and DC load are 8kW.

The third load is a dump load, which can be connected only in case the energy generated by renewable sources is higher than the load demand and the state of a battery is at the maximum level. However, the loads are constants but are controlled in the way they can be switched on and off at different times as seen in each scenario.

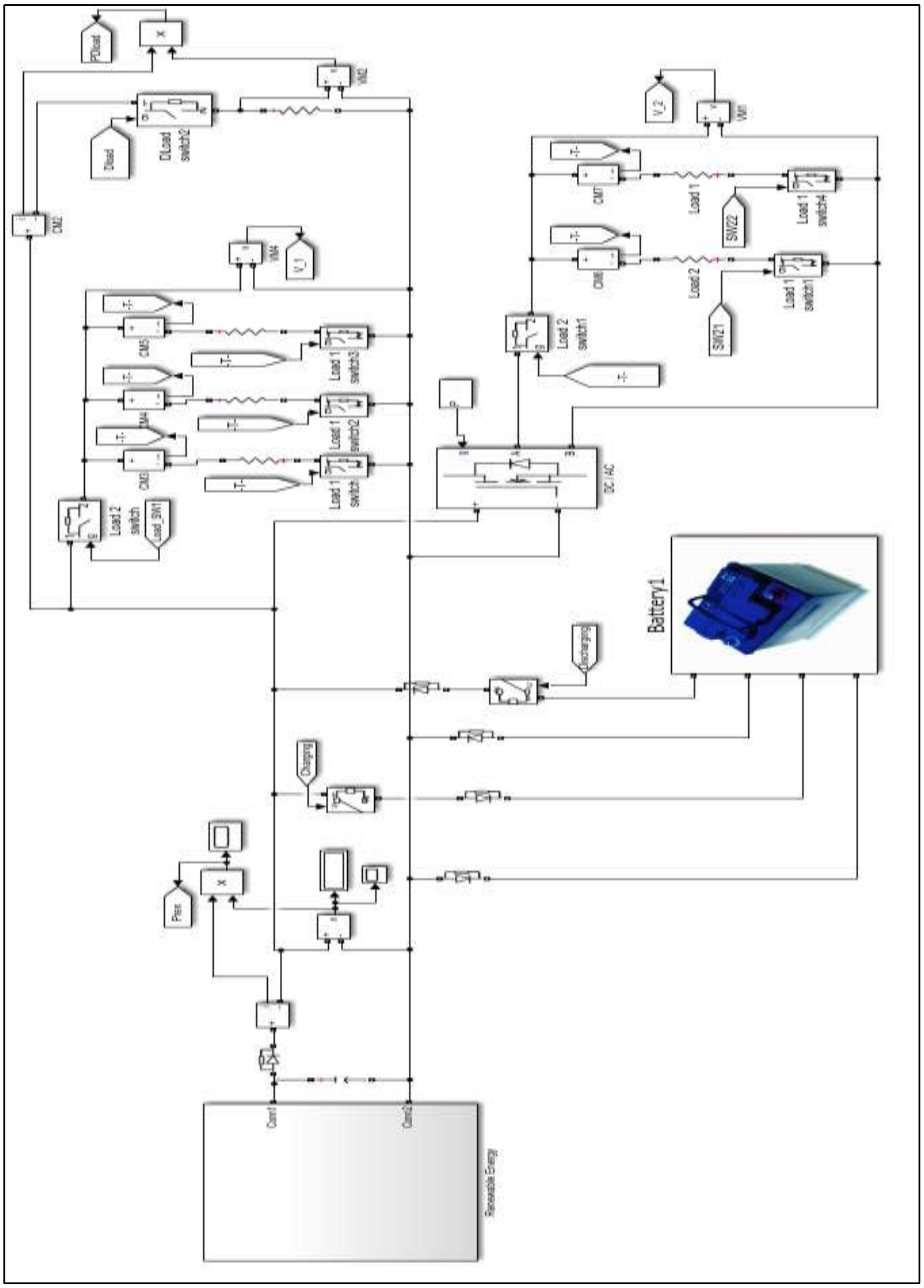

Figure 5. 1: Microgrid case study build in MATLAB/Simulink

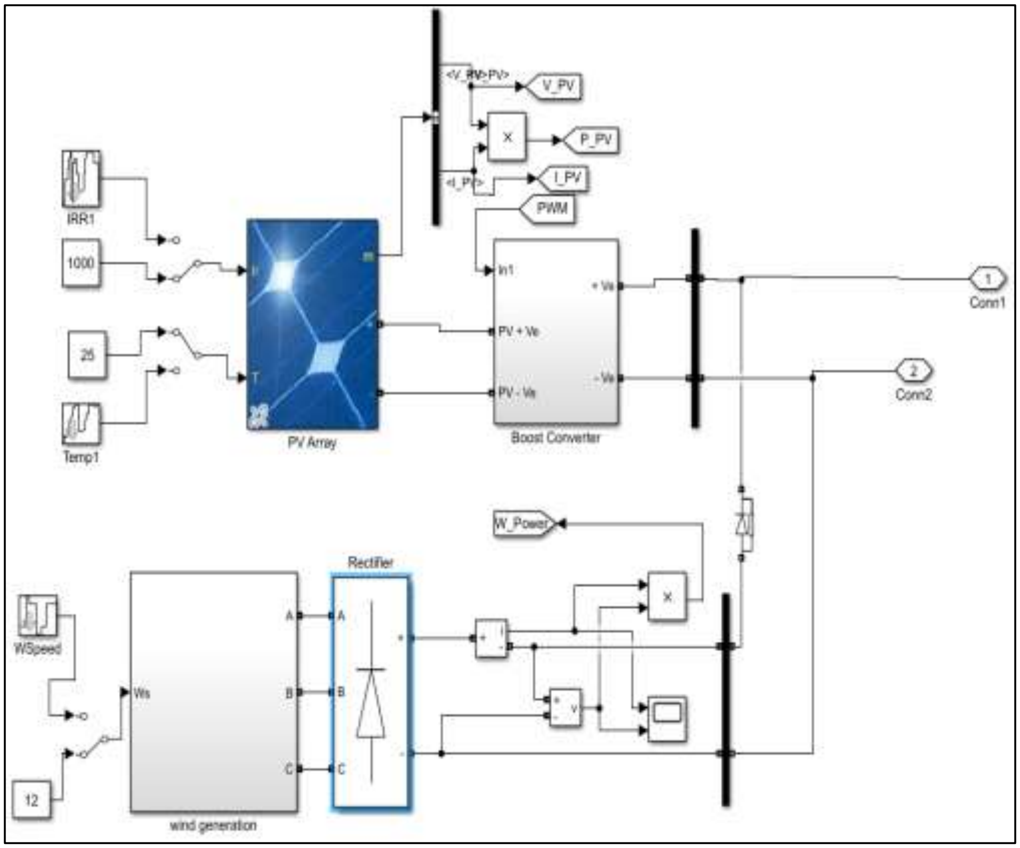

Figure 5. 2: PV and Wind Turbine combined power build in MATLAB/Simulink

1ST SCENARIO

In this scenario, the system is comprised of renewable energy sources such as PV and Wind turbine connected via a bus bar to combine their output power and are also connected straight to the load and a battery, note that the residential house has no other sources of energy than that one. Renewable energy generated by Photovoltaic and wind turbine is used to supply the residential load (AC and DC) in the islanded microgrid where load 1 is a DC load and is comprised of three sub loads that are switched on and off with switches at a different time and are all connected in parallel, and the second load which is an AC load comprised with two sub loads all connected in parallel, and controlled by switches and turned on and off at a different time. Therefore, the initial state of a battery is considered as 89% to be able to discharge or charge the battery at any time. And both wind speed and solar radiation are slightly variable, while loads are comprised of different loads that can be switched on and off at different times.

Figure 5.3 shows the load power, SOC of a battery, power generated by a wind turbine, and power generated by the photovoltaic system. Therefore, as seen on the first row the load profile varies depending on the time, the lowest load recorded is 2000W, and the highest load is 8000W. The second row presents the state of charge of a battery (SOC) which is varying also, it is clear that from 0seconds to 40 seconds the SOC is increasing since generated power is higher than load while from 40 seconds to 120 seconds the SOC is constant because there is no excess energy to charge the battery as the generated power matches exactly the load demand. The 3rd row presents the power from a wind turbine which is not constant due to the wind speed variation input, and the initial output wind power is 0, the power from the wind turbine reaches its normal condition after 10seconds and goes up to 60seconds, then decreased a little bit from 60seconds to 80secondsdue to the reason mentioned above, the lowest wind power is about 2000W while the highest is about 5000W. The 4th row presents the power from PV with the lowest power of 3000W and the highest of 3600W. Therefore, based on the following results, the proposed algorithm can track the movements of the load, therefore, the power generated by renewable energy sources (PV and Wind) is able to sustain the load during the full process, and the battery is able to be charged by excess power.

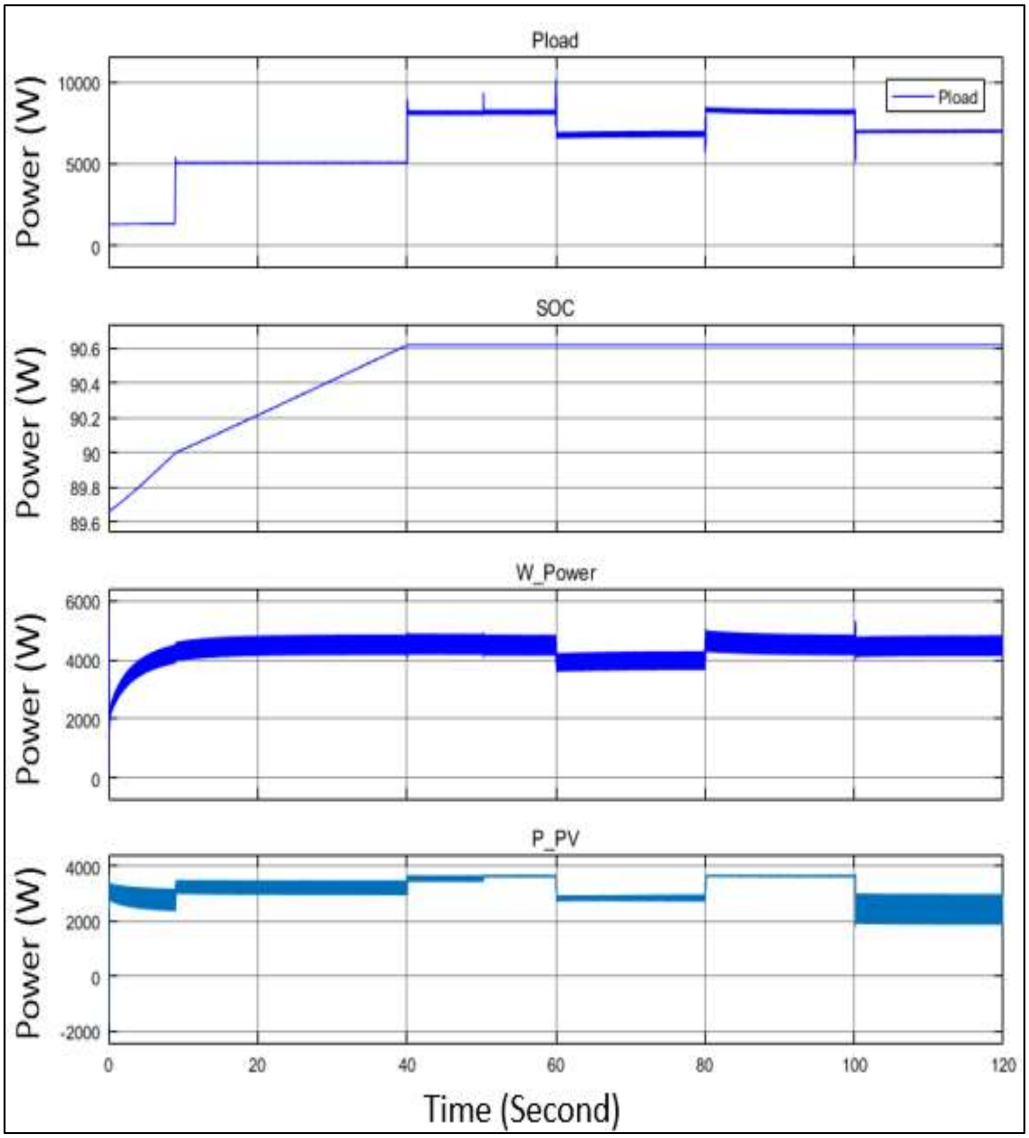

Figure 5. 3: Power Load, SOC of Battery, Wind Power, and Photovoltaic Power

Figure 5.4 presents the amount of power drawn from a battery or power accumulated by a battery, and the power generated by renewable energy (wind turbine and PV). The 1st row presents the power from renewable energy (wind turbine and PV) with the lowest of 5000W and the highest of 9000W. and the 2nd row presents the battery drained or accumulated power. It is clear that from 0 seconds to 10 seconds the battery is accumulating up to 6500W power from renewable energy while from 10 seconds to 20 seconds the battery still accumulating power but up to 4000W, then from 40 seconds to 120 seconds the battery is neither accumulating or releasing power since the load and generated power is the same. Table 5.1 presents the Results Summary of the first Scenario.

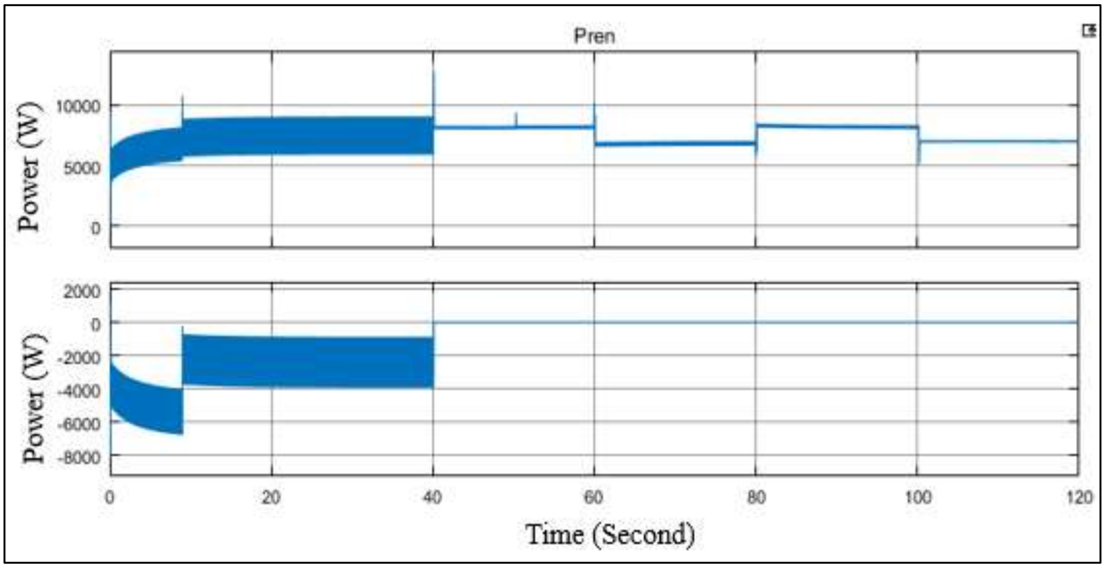

Figure 5. 4:Power Generated by Renewable Energy, Power Load, and Battery Power.

Table 5. 1: Results Summary of Third Scenario

Name	Value
Load	Size: 8000 W Highest Load = 8000 W Lowest Load = 2000 W
Battery	Initial SOC: 89% SOC_{min} = 40% SOC_{max} = 90% Battery Power: 6900 W
PV + Wind Turbine	Maximum Power: 9000 W Minimum Power = 5000 W Voltage: 230 V

2ND SCENARIO

For the second scenario, the load profile is completely changed for this scenario and the initial state of charge of a battery is decreased to 48% while wind speed remains the same and solar radiation is slightly changed to test the ability of the designed energy management to adopt on the change of a system. The system slightly changes, and the system can still react to the change. Then the following results occurred during the simulation for the second scenario.

Figure 5. 5 shows Load demand, State of charge of a battery (SOC), power from a wind turbine, and power from the photovoltaic system (PV). Therefore, as presented by the first row the load demand is varying depending on the time, this is because switches are programmed in a way they can be on and off at different times, the lowest load occurred is about 2000W and the highest is about 8000W. The second row presents the state of charge of a battery which is varying also, from 0 seconds to 120 seconds the SOC is increasing, which means that the battery is being charged by excess power. The 3rd row presents the power from a wind turbine which is not constant, the wind power gets at the normal level after 5seconds and just has a slight change between the 60seconds and 80seconds due to the wind speed change. the 4th row presents the power from PV which varies between 3000W and 3600W. Therefore, based on the following results it is clear that the proposed management system can react instantly to the system change both the load side and renewable sources side, as it can be seen that the power generated by renewable (PV and Wind Turbine) was able to sustain the load during the whole process, as well as charging the battery in case there is excess power, this shows that the proposed system designed can be able to fulfill the assigned duty.

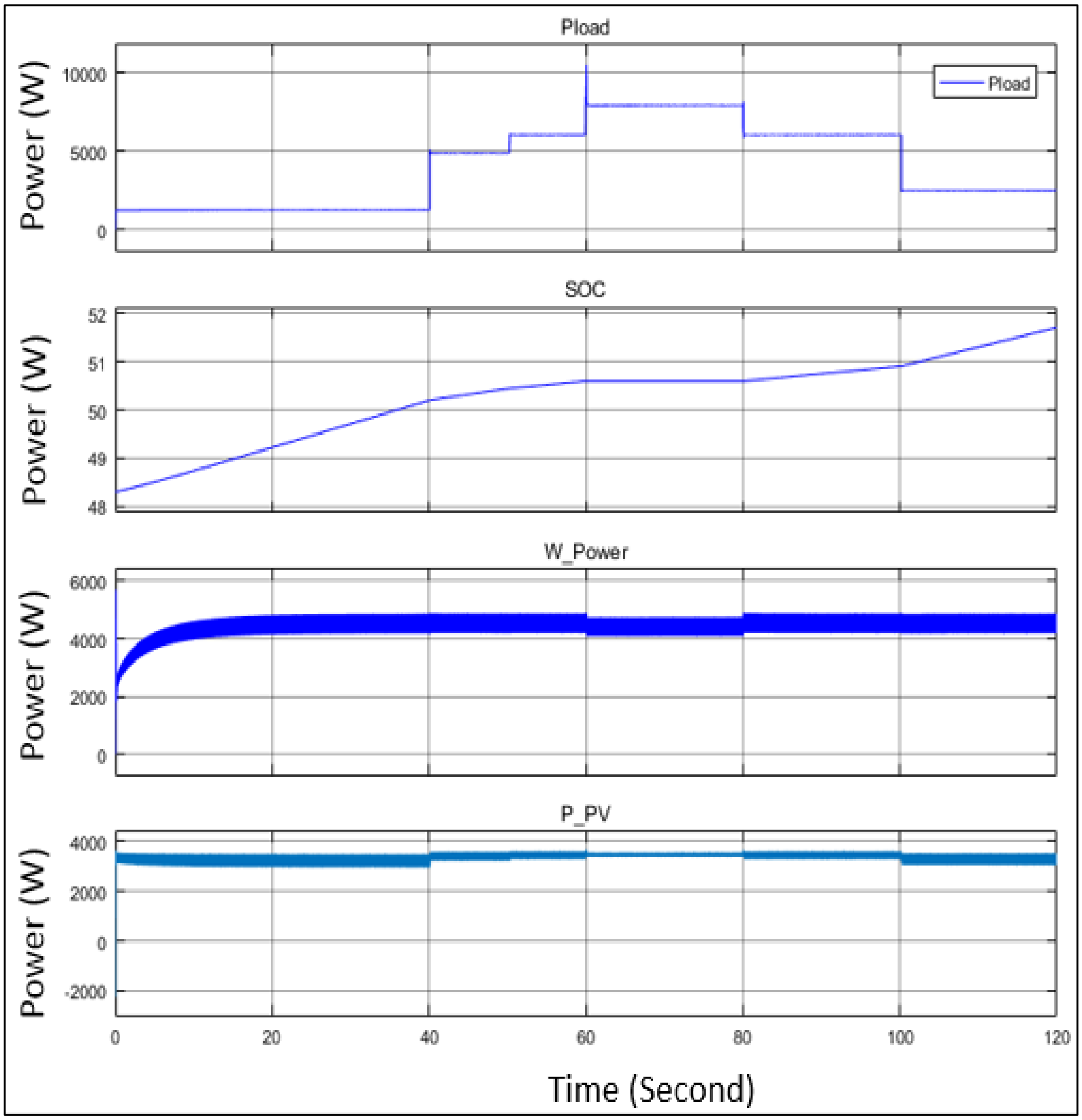

Figure 5. 5:Power Load, SOC of Battery, Wind Power, and Photovoltaic.

Figure 5.6 present the power from renewable energy sources (wind and PV), and the power consumed or drained from a battery (Battery Power). Therefore, the power from renewable energy sources (PV and Wind turbines) has slightly changed with a peak of 8500W. The second row shows the power accumulated by the battery or drained from the battery to meet the load demand for 120 seconds. The power from the battery is only brought in when generated power from renewable sources (PV and Wind Turbine) is not sufficient to meet the load demand. The power brought from the battery is to supplement the renewable power (PV and Wind Turbine) to meet the load demand. Therefore, as seen on the second row of Figure 5.6, from 0seconds to 40seconds the battery was getting almost 6000W because the power generated is higher than the load, from 40 seconds to 60secondspower drawn by the battery decreases from 3000W to 2000W, from the 60seconds to 80seconds as the load demand increases the battery stops charging since the generated power from renewable sources (PV and Wind Turbine) is the same as load power. From 80seconds to 100seconds the battery was getting 2000W, from 100seconds to 120seconds the battery was getting 5000W since the load power has decreased. Table 5.2 presents the Results Summary of the Second Scenario.

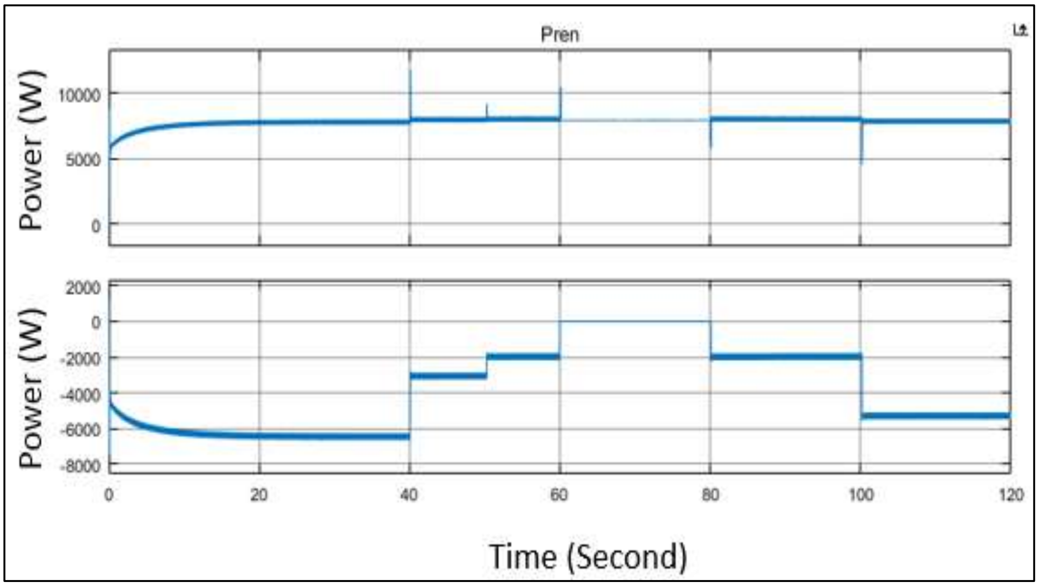

Figure 5. 6: Power Generated by Renewable Energy, and Operational State of battery

Table 5. 2: Results Summary of Second Scenario

Name	Value
Load	Size: 8000 W Highest Load = 8000 W Lowest Load = 2000 W
Battery	Initial SOC: 48% $SOC_{min} = 40\%$ $SOC_{max} = 90\%$ Battery Power: 6900 W
PV + Wind Turbine	Maximum Power: 8500 W Minimum Power = 3000 W Voltage: 230 V

3RD SCENARIO

In this scenario, the initial state of charge of a battery is 89%, and the load profile is completely changed, and also both wind speed and solar radiation are deeply changed, the load also is switched on and off at different times. Despite the variation of the results due to the change in wind speed, solar radiation, and load, the energy management system can still react to the system change.

Figure 5.7 shows the load power, SOC of a battery, power generated by the wind turbine, and power generated by the photovoltaic system. Therefore, the 1st row shows that the load power is varies depending on the time, the lowest load occurred is about 3500W and the highest is about 12000W. The second row presents the state of charge of a battery which is varying also, it is clear that from 0 seconds to 15 seconds the SOC is increasing while from 15 seconds to 55 seconds the SOC is constant, from 55 seconds up to 80 seconds the SOC is decreased since the load was increased, from 80 seconds to 100 seconds the SOC is constant, then from 100 seconds up to 120 seconds, the SOC is slightly increased. The 3rd row presents the power from a wind turbine which is not constant, the lowest wind power is about 0W while the highest is about 5000W. the 4th row presents the power from PV with the which is varying between 2000W up to 3600W. Therefore, based on the following results it is clear that the proposed management system can react to the variation of the load as you can see that the power generated by renewable was able to sustain the load during the whole process, and the battery was able to be charged by excess power and also to discharged in case the power generated by renewable energy was not able to sustain the load.

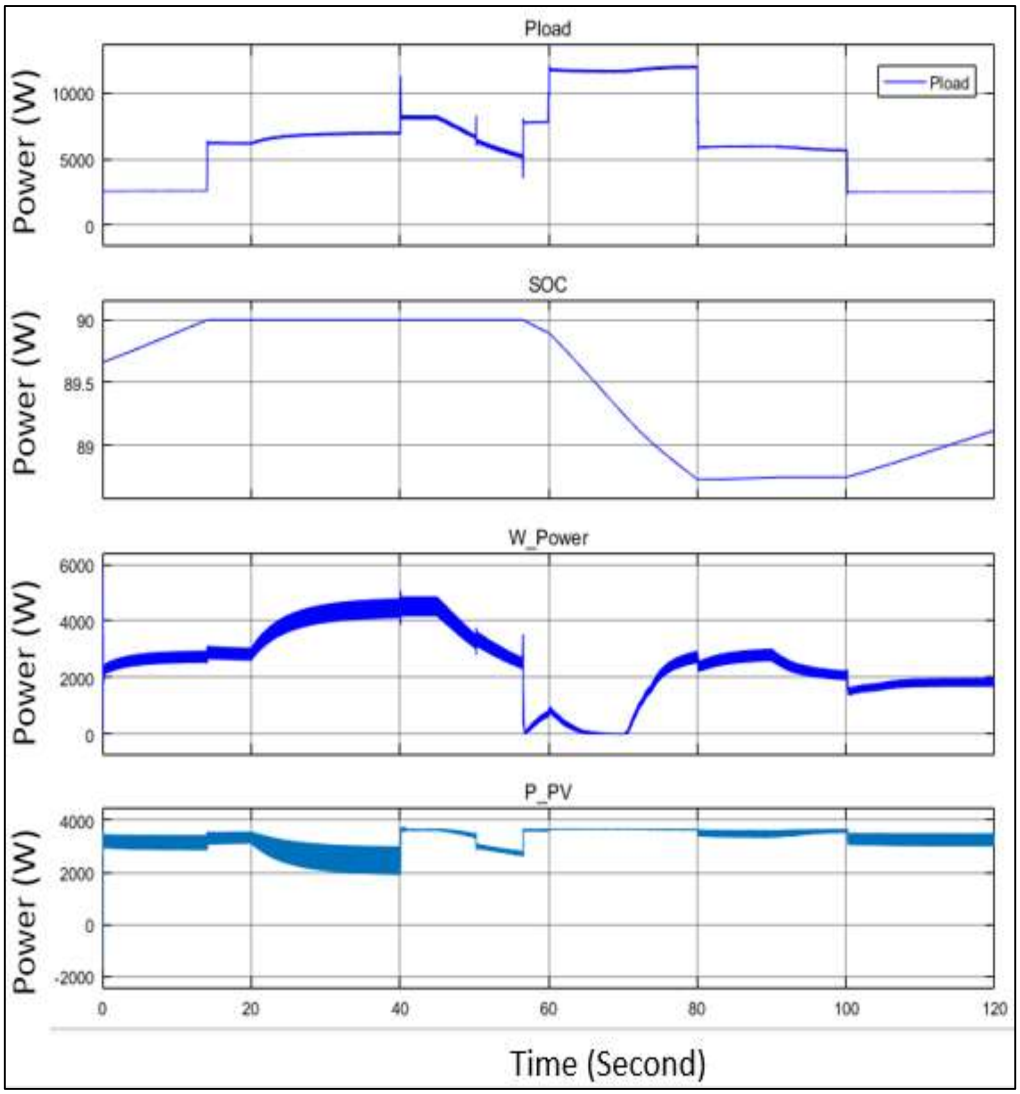

Figure 5. 7: Power Load, SOC of Battery, Wind Power, and Photovoltaic Power.

Figure 5.8 presents the renewable power (wind turbine and PV), and battery power. Therefore, the 1st row presents the power from renewable energy which is varying between 3000W and 8000W. The 2nd row presents the power accumulated by the battery or drained from the battery, it is clear that from 0 Seconds to 15 seconds the battery is accumulating almost 3000W power from renewable energy, this is due to the reason that there was excess power, while from 15 seconds to 55 seconds the battery is not either getting or releasing power because the power generated by renewable energy is the same as load power. Then from 55 seconds to 80 seconds almost 9000W of power is drained from the battery to supply the load, since the amount of the energy produced by the wind system is close to zero at this time, and the PV power is very low compared to the demand, from 80 to 100 Second the battery is not getting or releasing power, from 100 Seconds to 120 seconds the battery is accumulating almost 3000W from renewable energy as the generated power becomes higher than load. Table 5.3 presents a summary of the results obtained for the third scenario.

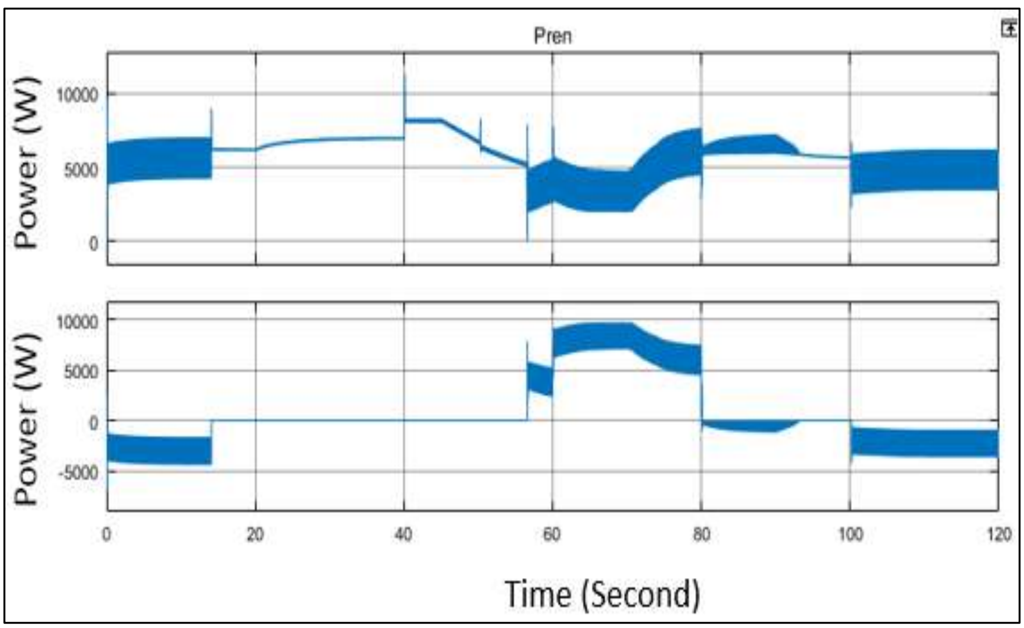

Figure 5. 8: Power Generated by Renewable Energy, and Battery Power

Table 5. 3: Results Summary of Third Scenario

Name	Value
Load	Size: 12000 W Highest Load = 12000 W Lowest Load = 3500 W
Battery	Initial SOC: 89% $SOC_{min} = 40\%$ $SOC_{max} = 90\%$ Battery Power: 9000 W
PV + Wind Turbine	Maximum Power: 8000 W Minimum Power = 3000 W Voltage: 230 V

5.3 Summary

This chapter presents and discusses simulations conducted to assess the performance of the proposed energy management system under various conditions. Therefore, the results generated by Simulink/ MATLAB on the performance of the overall system and Energy management for a system comprised of photovoltaic, wind turbine, and battery system is presented and discussed in detail in this chapter. However, to test the energy management system, different scenarios are considered based on the variable solar radiation, temperature, and wind speed. Therefore, results revealed that the proposed energy management system can carry any variation of load at any time of the day without any disturbance.

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

This study has focused on the design of an energy management system for the integrated hybrid micro-grid comprised of photovoltaic (PV), Wind turbine, and battery energy storage systems for off-grid systems. However, the energy management and energy flow between the intermittent sources have been presented in this study using the State Machine control strategy in Simulink/MATLAB. Hence, the proposed model aimed to minimize the energy loss through adequate allocation of energy resources to the loads for a residence building, while meeting the energy demand of a residential household located in a rural area by implementing 100% micro-grid renewable energy. Simulation results using a Sim-power toolbox from MATLAB for the performance of the proposed energy management model was presented.

Therefore, results showed that the proposed model has the potential to share the available energy at any time of a day without any disturbance, and the availability of a battery played an important role in this proposed model since the battery was able to supply the remaining energy in case PV and wind were not able to meet the load demand at any time. The drawback of the proposed model is that the surplus energy generated from renewable energy can only be sent to the dump load to avoid excess generated energy, or another solution is to increase the number of the storage battery to be able to store all surplus generated energy which in turns will be the barrier due to the increase of the prices of the system. Therefore, we recommend that the next research will introduce the grid to the system to be able to sell the surplus power to the grid so that there will be a generation of extra money.

Future Work

This work was based on the design of an energy management system for a residential house located in a remote area, it means where a grid system is absent. Therefore, the future work will incorporate the grid system so that the excess energy will be sold to the grid to gain more money, and the grid will be able to operate as a backup so that it can feed the load in case the system is not able to provide the required energy.

Publication

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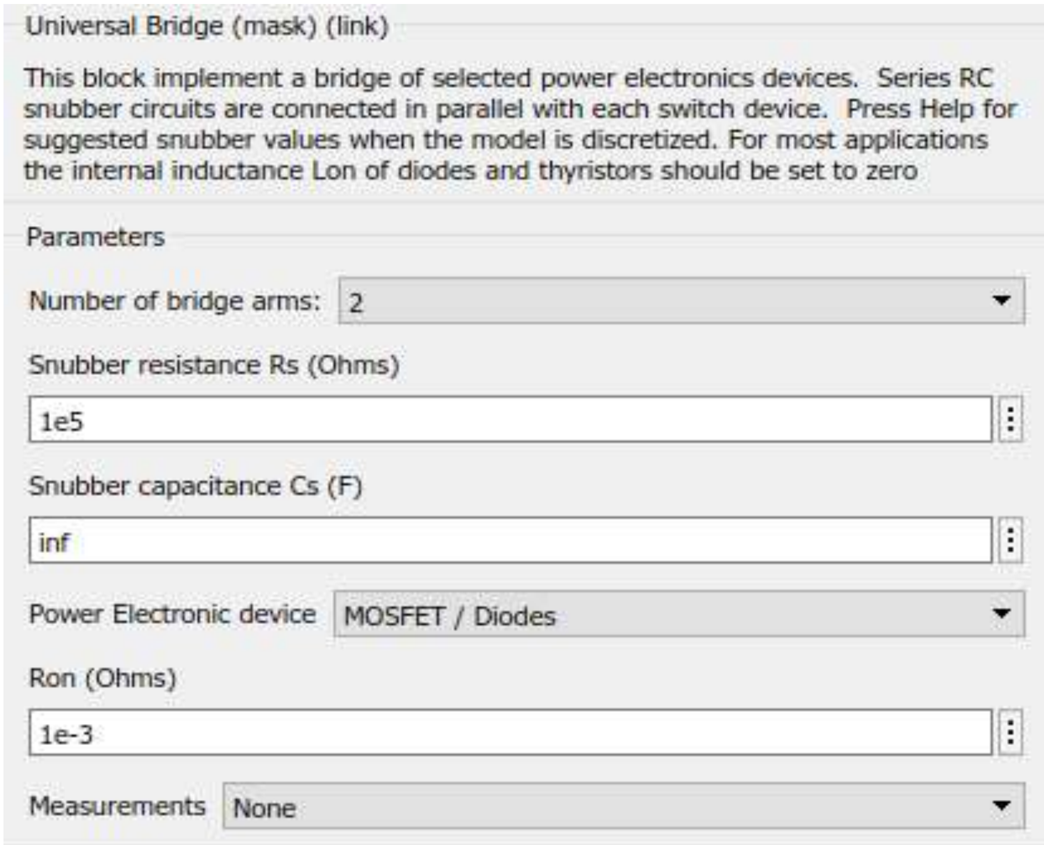
APPENDICES

Appendix 1 Block Parameters: Universal bridge used for DC to AC inverter



Appendix 2 Block Parameters: PWM Generator (2-Level)