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Frequency Control of an Islanded Microgrid Based on Type-2 Fuzzy Logic Controller

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I dedicate this modest work to:

The sake of Allah, my Creator to whom I belong.
My great teacher and messenger, Mohammed
(My Allah bless and grant him).
To my beloved father, may he rest in peace
beneath his grave, may Allah, the Most High,
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⋆⋆⋆

BARIK Ishak

Abstract

Microgrids offer a superior solution to traditional energy systems, especially in the quest to reduce pollution and enhance sustainability. This thesis explores the advanced control of frequency in islanded microgrids using Type 2 Fuzzy Logic Controllers. The research begins with an in-depth examination of microgrids, outlining their components, advantages, and the challenges they address.

It then details the modeling of various energy sources, including photovoltaic systems, wind turbines, diesel generators, and hybrid electric vehicles, as well as energy storage solutions.

The findings demonstrate that Type 2 Fuzzy Logic Controllers significantly enhance frequency stability, reduce response time, and minimize chattering, thereby paving the way for more resilient and efficient energy systems.

Keywords: Frequency control, Islanded microgrids, Renewable energy, Type 2 Fuzzy Logic Controller (FLC), Distributed energy resources (DERs), Energy storage systems (ESSs), Fuzzy logic, Simulation, System stability, Reliability, Controller performance, Comparative analysis.

ملخص

تقدم الشبكات المصغرة حلاً متفوقاً على الأنظمة الطاقية التقليدية، خصوصاً في سعينا للحد من التلوث وتعزيز الاستدامة. تستكشف هذه الأطروحة التحكم المتقدم في التردد في الشبكات المصغرة المعزولة باستخدام وحدات التحكم بالمنطق الضبابي من النوع الثاني. تبدأ الدراسة بفحص عميق للشبكات المصغرة، محددة مكوناتها ومزاياها، والتحديات التي تواجهها. ثم توضح تفصيلات نمذجة مصادر الطاقة المختلفة، بما في ذلك أنظمة الطاقة الشمسية الكهروضوئية، ومحطات توليد الطاقة عن طريق الرياح، ومولدات الديزل، والمركبات الكهربائية الهجينة، بالإضافة إلى حلول تخزين الطاقة. تظهر النتائج أن وحدات التحكم بالمنطق الضبابي من

النوع الثاني تعزز بشكل كبير استقرار التردد، وتقلل من زمن الاستجابة، وتقلل من الاهتزازات، مما يمهد الطريق لأنظمة طاقة أكثر مرونة وكفاءة.

الكلمات المفتاحية: التحكم في التردد, الشبكات الصغيرة المعزولة, الطاقة المتجددة, متحكم منطقي ضبابي من النوع 2 ,مصادر الطاقة الموزعة ,أنظمة تخزين الطاقة , المنطق الضبابي ,المحاكاة, استقرار النظام, الموثوقية , أداء المتحكم , تحليل مقارنة.

Résumé

Les microgrids offrent une solution supérieure aux systèmes énergétiques traditionnels, notamment dans notre quête de réduction de la pollution et de promotion de la durabilité. Cette mémoire explore le contrôle avancé de la fréquence dans les microgrids isolés en utilisant des contrôleurs logiques flous de type 2. L'étude commence par un examen approfondi des microgrids, définissant leurs composants et leurs avantages, ainsi que les défis auxquels ils sont confrontés. Ensuite, elle détaille la modélisation des différentes sources d'énergie, y compris les systèmes photovoltaïques, les éoliennes, les générateurs diesel, les véhicules électriques hybrides, ainsi que les solutions de stockage d'énergie. Les résultats de simulation obetenus montrent que les contrôleurs logiques flous de type 2 améliorent considérablement la stabilité de la fréquence, réduisent le temps de réponse et atténuent les oscillations, ouvrant la voie à des systèmes énergétiques plus flexibles et efficaces.

Les Mots clés: : Contrôle de la fréquence, Microgrids isolés, Énergie renouvelable, Contrôleur logique floue de type 2 (FLC), Ressources énergétiques distribuées (DERs), Systèmes de stockage d'énergie (ESSs), Logique floue, Simulation, Stabilité du système, Fiabilité, Performance du contrôleur, Analyse comparative**.**

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Notation & Abbreviation

General:

P_s: Total average power generation.

P_W: Mechanical power of wind turbines.

P_t: Net average power of WTGs or PV to the system.

K: Gain.

T: Time constant.

Δf: System frequency deviation.

V_W: Wind speed (m/s).

Φ: Solar irradiation (kW/m^2).

λ Derivative Order.

μ Differential Order.

w Inertia weight.

Abbreviation:

MG: Microgrid

CHP: Combined heat & power

USDOD: US Department of Defense

USDOE: US Department of Energy

CSP: Conversion-concentrated solar power

PVs: Photovoltaic system

UC: Ultra Capacitor

MCS: Microgrid control system

COE: Cost of energy

AC: Alternative current

DC: Direct current
DER: Distributed energy resources
EMS: Energy management system
WTs: Wind turbine system
BESS: Battery energy storage system
VSC: Voltage Source converter
TS: Ternal Storage
ES: Electrical Storage
RES: Renewable energy source
ESS: Energy Storage System
ACMG: Alternative current Microgrid
DCMG: Direct current Microgrid
HMG: Hybrid Microgrid
LV: Low Voltage
MV: Medium Voltage
HV: High Voltage
CO_2: Carbon Dioxide
SO_2: Sulfur Dioxide
CNG: Compressed Natural Gas
PEL: Power Electronics
DG: Distributed Generation
DEG: Diesel Engine Generator
CSI: Current Source Inverter
VSI: Voltage Source Inverter

LB: Low Bandwidth

HB: High Bandwidth

WTG: Wind Turbine Generator

SM: Synchronous machine

DGS: Dynamic Generator System

PHEV: Plug-In Hybrid Electric Vehicle

SOC: Stake of Charge

FESS: Flywheel Energy Storage System

FLC: Fuzzy Logic Controller

MF: Membership Function

FIS: Fuzzy Inference System

TCT: Total Cross Tied

BL: Bridge Link

STC: Standard Temperature Condition

D: Diode

NOCT: Nominal Operation Cell Temperature

Tc: Cell Temperature

$\mathbf{I}_r$: Solar irradiation

β: is the generator efficiency temperature

V_{OC}: Open Circuit Voltage

R_{Shunt}: Parallel Resistance

S_p: Series-Parallel

R_s: Serie Resistance

I_{SC}: Short-Circuit

General Introduction

Amid the rapid technological development and continuous search for clean and sustainable energy sources, microgrids have emerged as an ideal solution to meet energy needs in isolated areas and remote communities. Microgrids represent an integrated system consisting of a variety of renewable energy sources, such as solar panels and wind turbines, in addition to energy storage systems and load management. These grids are characterized by their ability to operate independently of the main grid, making them an efficient and reliable option in many applications. Microgrids offer numerous benefits, including improved energy security, reduced transmission losses, and enhanced integration of renewable energy sources. Furthermore, these grids reduce reliance on fossil fuels, contributing to a reduction in carbon emissions and environmental preservation. By decreasing environmental pollution, microgrids help improve quality of life and public health. However, operating microgrids requires effective solutions for energy management challenges, such as frequency and voltage control, and system stability amidst fluctuations in renewable energy sources. This thesis, titled "Frequency Control of an Islanded Microgrid Based on Type 2 Fuzzy Logic Controller," explores how to enhance the performance of microgrids using advanced control techniques.

The thesis is divided into three main chapters, each providing an in-depth look at different aspects of microgrids. The first chapter, titled "General Information on the Microgrid," provides a solid foundation for understanding the basic concepts of microgrids. This chapter begins with a historical background outlining the gradual development of this technology and then details the different components of a microgrid, such as distributed energy resources, energy storage systems, and electrical loads. It also reviews microgrid control systems, including power management systems and the various types of microgrids, such as remote microgrids, grid-connected microgrids, and islanded microgrids. The chapter further compares different microgrid structures, whether operating on AC or DC, and reviews the types of energy sources used in these grids, both renewable and non-renewable. It concludes by discussing the main advantages of microgrids and the technical and economic challenges they face.

The second chapter, titled "Modeling of Microgrid System," focuses on the technical aspects of modeling and controlling microgrids. This chapter explains how to model renewable energy sources like solar panels and wind turbines, starting from modeling the solar cell to the mathematical models of PV generators and wind turbines. It also addresses the modeling of conventional sources such as diesel generators and fuel cells, as well as models for various energy storage systems, including lead-acid batteries, lithium-ion batteries, sodium-sulfur batteries, and flywheel energy storage systems. Additionally, the chapter covers the modeling of ultra-capacitors and the water electrolyzer, detailing the mathematical equations and models used to analyze and improve the performance of these systems.

The third chapter, titled "Improving the Performance of Microgrid Systems Using Fuzzy Logic Controller Classic and Type-2 Fuzzy Logic," explores advanced control techniques to enhance microgrid performance. This chapter begins with an introduction to the concept and functioning of islanded microgrids, followed by detailed modeling of each energy source in the microgrid, including PV models, wind models, PHEV models, diesel generator models, and graphic ΔL models. The chapter then discusses the applications of classical fuzzy logic controllers, presenting simulation results obtained using these controllers and comparing them to the results obtained using Type-2 fuzzy logic controllers. The advantages and benefits of Type-2 fuzzy logic, including improved system response and reduced oscillations, are highlighted.

In conclusion, this thesis represents a significant step towards understanding and improving frequency control within microgrids using advanced fuzzy logic techniques. The study highlights the potential of Type-2 fuzzy logic controllers to address the complex challenges faced by microgrids, opening new horizons for enhancing the efficiency and sustainability of future energy systems. We hope that the results of this research will inspire researchers and professionals to continue developing innovative and effective solutions to modern energy challenges, while simultaneously contributing to environmental pollution reduction and achieving greater sustainability for our communities.

Chapter 1

General Information on the Microgrid

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1.1 Introduction

In today's era of technological advancement, the world is seeking innovative solutions to efficiently meet energy needs sustainably. Innovations in the energy sector abound with new and advanced methods for generating and distributing electricity, among which microgrids stand out as one of the most promising and innovative technological models. In this first chapter, we will provide a comprehensive overview of microgrids, starting from the historical background that contributed to the evolution of this innovative technology, moving on to the key components of microgrids and their various types, and delving into the available energy sources in these grids and their manifold benefits. We will also shed light on the challenges and barriers facing microgrid adoption, along with practical applications benefiting from this advanced technology. Lastly, we'll take a brief look at the future of microgrids and their exciting prospects. This chapter will serve as a comprehensive and engaging tour into the world of microgrids, where we'll explore together their importance and impact on the future of energy and sustainable development.

1.2 Historical Background

Like many technologies in the energy industry, microgrids have been around in some form or other for many years but not with the name “microgrid”, or with the same level of technical sophistication we see today [1]. Campus type energy generation and distribution systems, often with multiple shared distributed energy resources (typically fossil fueled generators and CHP systems) and multiple loads have been around for years, many at such facilities as universities, military bases, and in industrial parks [2]. The term “microgrid” appears to have started being used in the late 1990’s when the US Department of Energy (USDOE), at the request of the US Congress, started programs to examine grid reliability and how to maximize the use of distributed generation resources to improve reliability and resiliency [3]. Multiple studies were completed by industry participants and especially the US Department of Defense (USDOD). More recently a number of factors boosted interest in microgrids including Superstorm Sandy in October 2012 [4]. While a large part of the Northeast US lost grid power as a result of the Superstorm, microgrid operators like Princeton University in New Jersey were able to keep the lights on and remain in uninterrupted operation. This opened industry, regulator, and politician’s eyes to the resiliency benefits of a microgrid that could continue to operate when isolated from the utility grid, and that could maximize the value and benefit of its distributed energy resources. Several states (e.g. New York, Connecticut, and California), as well as the USDOE and USDOD, funded studies on microgrid development, design and implementation [5]. As a result, according to recent studies, there are currently over 2,430 operational microgrids in the US and there was over 19,575 MW of operational or planned worldwide microgrid capacity at the end of 2018 [6]. Bridgestone Associates’ recent City of Binghamton Community Microgrid Feasibility Study provides a good example of a microgrid, how it is configured, and its community benefits [8]. This study was funded in major part by a grant from the New York State Energy Research and Development

Authority (NYSERDA) under New York's PRIZE Program. The planned microgrid will serve seven buildings in downtown Binghamton, New York, an area that is prone to severe flooding cutting off City Hall and its emergency services (fire, police and ambulance) and several low income and senior living facilities. The microgrid will link these buildings through underground electrical conduits and will include a 1,000 kW CHP plant, a 400-kW gas engine generator, a total of 600 kW solar PV, a 1,200-kW hydroelectric plant, and a few standby generators. The CHP plant will provide heat and cooling to several of the buildings which will be hardened to withstand flooding. There will be one point of common coupling with the local electric utility. A microgrid controller located at the CHP plant will control the microgrid during normal "blue sky" and abnormal, grid isolated "dark sky" times. This microgrid will allow the city and its emergency services to continue operations during a major flood event, and also avoid evacuation of over 450 often elderly residents.

1.3 Microgrid System Components

Being as intelligent and flexible as they are, the integration of micro-grids in power networks is currently getting great attention. Micro-grid system would comprise one or more of the following resources:

1.3.1 Distributed Energy Resources

a. Solar Energy

The sun is ultimately the source of all energy supplies, excluding nuclear energy generation. Solar-electric power can be produced by power plants using the sun's heat or direct electricity generation using photovoltaic technology, which is more practical for urban use. Solar energy resources are: [63]

- solar thermal conversion.
- low and medium temperature conversion.
- high temperature conversion-concentrated solar power (CSP).
- optical efficiency.
- combined optical and thermal efficiency; and
- solar electrical conversion (photovoltaic systems).

As a case study, Algeria, lies within the Sun Belt region, making it an ideal candidate for solar energy utilization. Here are some related data specific to Algeria:

- Algeria is located in the Sun Belt, receiving about 3,000 hours of sunshine annually.
- The country's solar energy potential is estimated at around 169,440 terawatt-hours (TWh) per year.
- Algeria has ambitious plans for solar energy, including the Algerian Renewable Energy and Energy Efficiency Program, which aims to install 22 GW of renewable energy capacity by 2030, with a significant portion from solar energy. Algeria's abundant solar resources present a significant opportunity for the development of solar energy projects across the country. Leveraging these resources can contribute to Algeria's energy independence, reduce reliance on fossil fuels, and mitigate carbon emissions, while also fostering economic growth and sustainable development. [28]

b. Wind Energy

Wind energy is a significant source of renewable energy, originating from the natural movement of air in the atmosphere due to differences in temperature and air pressure. Wind energy can be converted into electrical power using wind turbines, which harness the mechanical motion of the wind to turn blades and generate electricity. [27]

Electrical power from wind is produced through various means, including:

- These are power generation plants located on land in areas with strong and stable winds.
- These are built in seas and oceans where wind speeds are higher and more consistent than on land.
- These are used to generate electricity for residential, agricultural, or small commercial purposes.

Wind generation equipment is divided into three main categories:

- Utility-scale Turbines: Used in large wind farms, with capacities reaching several megawatts.
- Industrial-scale Turbines: Used for small to medium industrial applications, with capacities ranging from 50 to 250 kilowatts.
- Residential-scale Turbines: Used for residential and agricultural applications, with capacities ranging from 400 watts to 50 kilowatts. [27]

Wind energy resources include [27]:

- Coastal Areas: These areas benefit from high and steady wind speeds, making them ideal for wind farms.
- Mountainous Regions: These regions can exploit altitude differences to accelerate wind

speeds.

- Desert Areas: These areas offer vast open spaces and suitable wind speeds.

1.3.2 Energy storage

Storage systems are vital to any micro-grid since they allow the balancing of electrical fluctuation and support the load required by the user. In isolated micro-grids, batteries are the mostly used as they are still considered the most economic electric storage technology [23]. Although energy storage technology has developed extremely in the past years, it is still expected to continue developing. A tendency of reducing costs of battery technologies such as lithium-ion and flow battery suggests that these technologies will be more applied. There is a relationship between energy storage and emissions. Energy storage is not 100% efficient which may cause extra emissions [24]. Even though batteries exist longer than pumped storage, costs have generally been too expensive for utility scale applications. **Table 1** illustrates classification of energy storage technologies while **Table 2** presents benefits of energy storage system.

Table 1.1_ Classification of energy storage technologies [25].

Energy Storage				
Mechanical	**Electrical**	**Chemical**	**Thermal**	**Electrochemical**
• Pumped Hydro (PHS) • Compressed Air Energy Storage • Flywheel	• Capacitor • Superconductor	• Hydrogen • Methan	• Molten Salts • Chillers	• Conventional Batteries (Lead-Acid/ NiCd/ Li…) • High Temperature (NaS/ NaNiCl) • Flow Batteries (Redox flow/ Hybrid flow)

Table 1.2_ Benefits of Energy Storage. [27]

Reducing Peak Demand	- Provide additional power during high usage periods to alleviate grid stress. - Reduce the need for costly infrastructure upgrades.
Enhancing Grid	- Supply backup power during blackouts or grid failures. - Ensure critical services remain operational during emergencies.

Reliability	
Integrating Renewable Energy	- Store excess energy from renewable sources for use during low generation periods. - Maintain a consistent power supply and increase the share of renewables in the energy mix.
Mitigating Power Outages	- Provide localized backup power in areas prone to frequent outages or remote locations. - Improve quality of life and support essential services.

1.3.3 Electric load

Construction of micro-grid and sizing of their energy components depends principally on the required load pattern to be supplied. Load may be domestic industrial or commercial demand.

1.3.4 Microgrid control system (power management system)

Micro-grid control system (MCS) is the crucial component that enables the incorporation and optimization of energy to reduce the overall micro-grid energy cost [26]. The MCS provides an easy solution to combine conventional and renewable energy sources with energy storage to reach optimal operation minimizing the total cost and cost of energy (COE). Modern systems often merge software with control systems, such as smart meters, that can make the grid operation efficient and reliable.

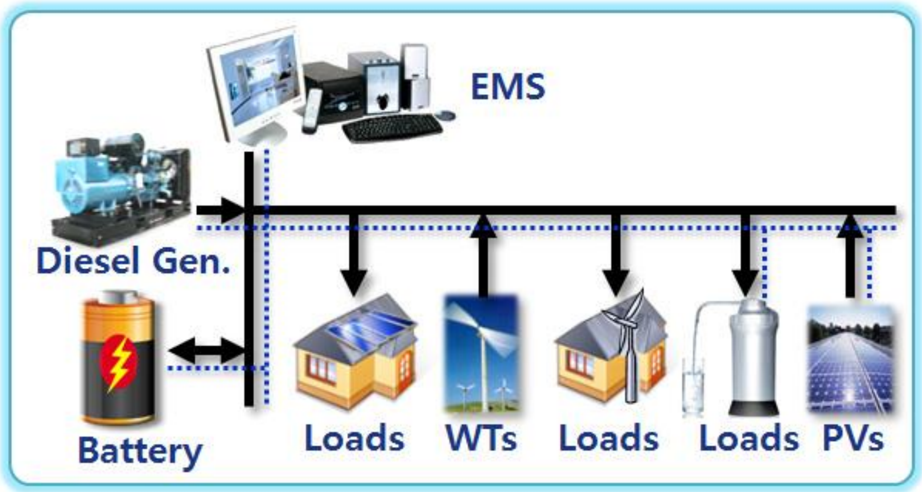
1.4 Types of Microgrid

Most users today get their power from the macro-grid commonly referred to as the utility the macro-grid receives its AC power input from large decentralized power stations, in a microgrid however is a group of interconnected loads in distributed energy resources or (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the microgrid, a microgrid has power generation independent of the macro-grid; there are four types of microgrid:

Remote Microgrid, Grid-Connected Microgrid, Islanded Microgrid, and Networked Microgrid. [29].

1. Remote Microgrid

also referred to as off-grid, microgrids are physically remote and isolated from the macro grid and said to be operating in Island mode. advantage of remote microgrids over the microgrid include no infrastructure Coast to erect transmission lines to remote macro-grid power station, in many cases renewable such as wind and solar and less expensive Solutions, they meet in environmentally sustainable distributed energy requirements [29], and they have a greater reliability then aging macro-grid Network.



Figur1.1_ Example of a remote microgrid.

2. Grid-connected Microgrid

are the second type of microgrid system where there is the ability to switch the macro-grid either to take energy from or input to when the microgrid is connected to both the extra high voltage and high voltage section of the macro-grid, connection of the two grids is via switching mechanism at the point of common coupling enabling the microgrid to be switched from Island mode to Grid connected mode, having the ability to connect the macro-grid addresses issues such as capacity power quality where is switching to Island mode can isolate connected loads from voltage and frequency issues occurring on the macro-grid when serving relatively small geographic area grid-connected microgrid demonstrated economic viability from educational Campuses medical complexes Public Safety bases military buses agricultural Farms commercial buildings and Industrial facilities[29]

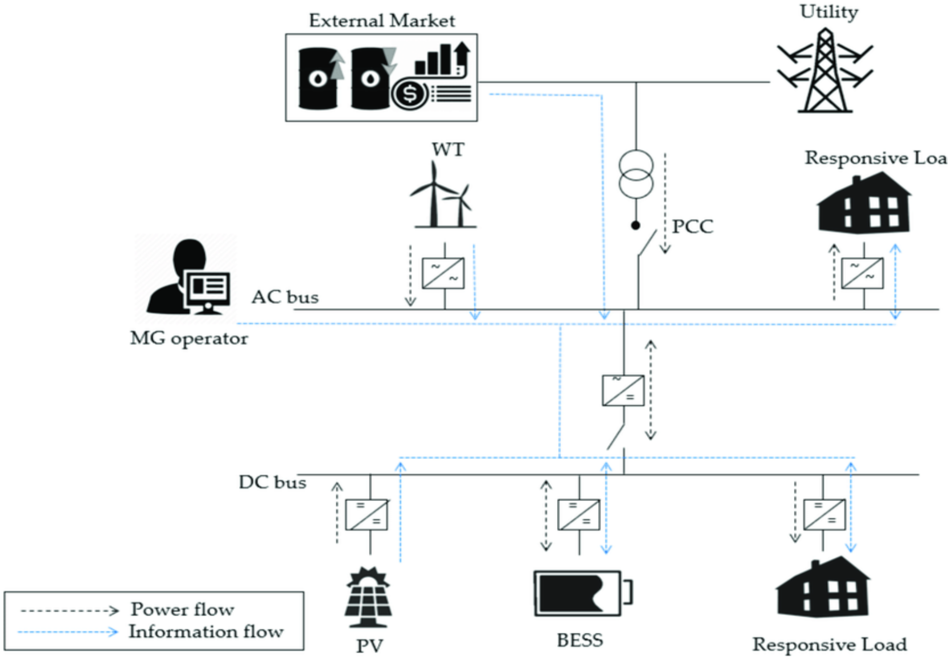


Figure 1.2_ Structure of Grid-Connected Microgrid

3. Islanded Microgrid

An islanded microgrid is a flexible and advanced power system designed to operate autonomously, providing electricity to a specific area without relying on the main grid. It utilizes diverse local generation sources such as solar panels, wind turbines, diesel generators, and combined heat and power (CHP) systems, along with emerging technologies like fuel cells and microturbines. Energy storage systems, including batteries and thermal storage, ensure a balance between supply and demand. Managed by advanced control systems like the Energy Management System (EMS) and a microgrid controller, the microgrid maintains stability and balance. It features a tailored distribution infrastructure, including cables, transformers, and interfaces with the main grid for seamless transitions between grid-connected and islanded modes. Operating in both grid-connected and island modes, it ensures a stable and reliable power supply, improves energy efficiency, and reduces carbon footprint. Islanded microgrids enhance reliability, sustainability, economic efficiency, and energy independence, making them highly advantageous during emergencies and for integrating renewable energy sources [29].

Figure 1.3_ An illustration of islanded microgrid scheme.

4. Networked Microgrid

The fourth type of microgrid is network grid also known as nested grid and employs several microgrid system.

Nested microgrids, connected to the macro-grid can supply power to a wider geographic area, for example, a residential microgrid system could be linked to smart city system, supervisory controls operate the network of microgrid within the system.

Another microgrid could be supplying an industrial area. And another microgrid could be powering a data centre. The nest of microgrids would also be concerns and more security than the macro-grid can provide [29].

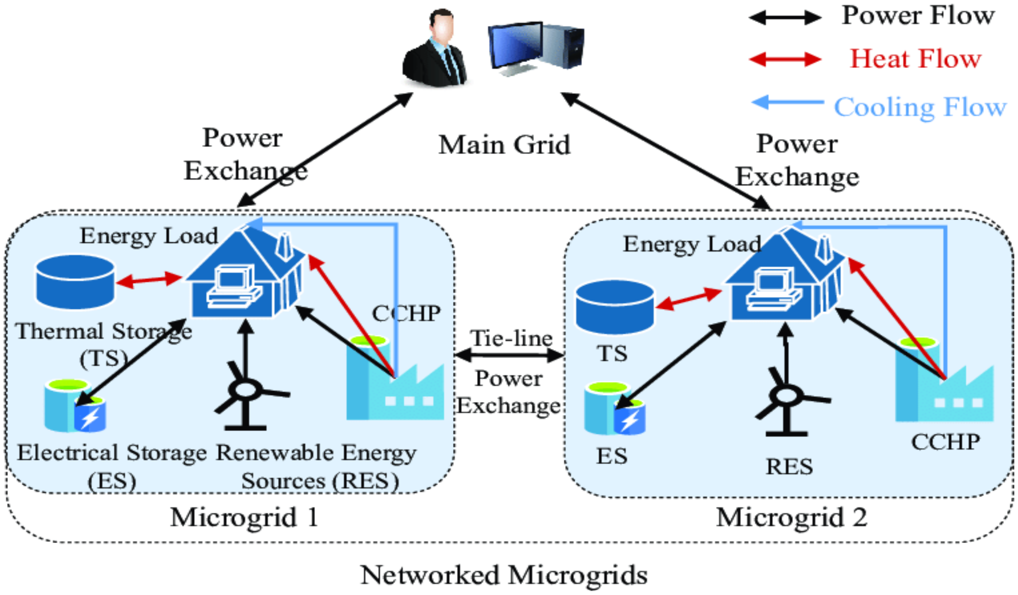


Figure 1.4_The networked microgrids with major components.

1.5 Different MG Structures

Based on the type of their current and the way of the connection of their buses, Microgrids can be categorized in several ways. However, according to their current type (Direct and Alternative), Microgrids are Classified into three major groups:

AC Microgrid, DC Microgrid, Hybrid Microgrid [30], Which are respectively shown in **Figures 1.5-1.7** in **Table 1.3**, the main characteristics of each Type of Microgrid are briefly listed.

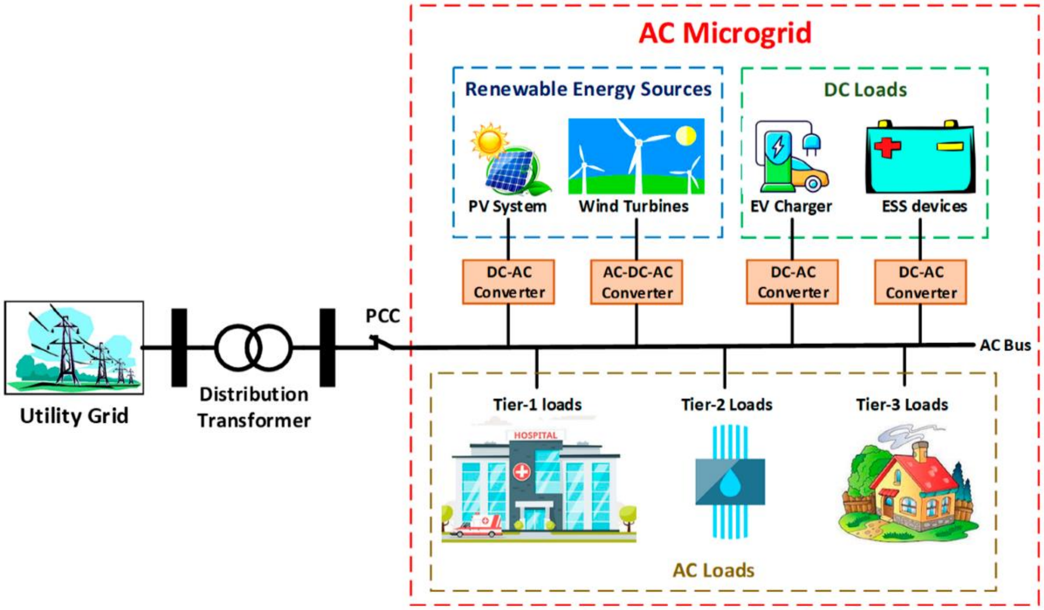


Figure 1.5_Simple diagram of a typical ACMG.

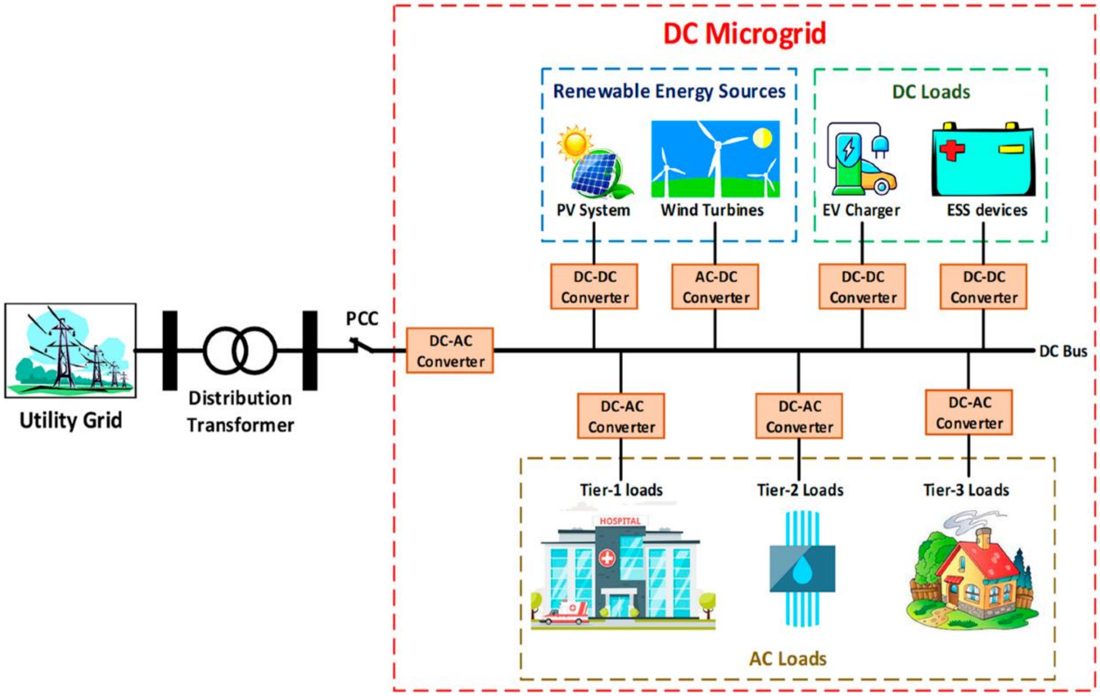


Figure 1.6_ Simple diagram of a typical DCMG.

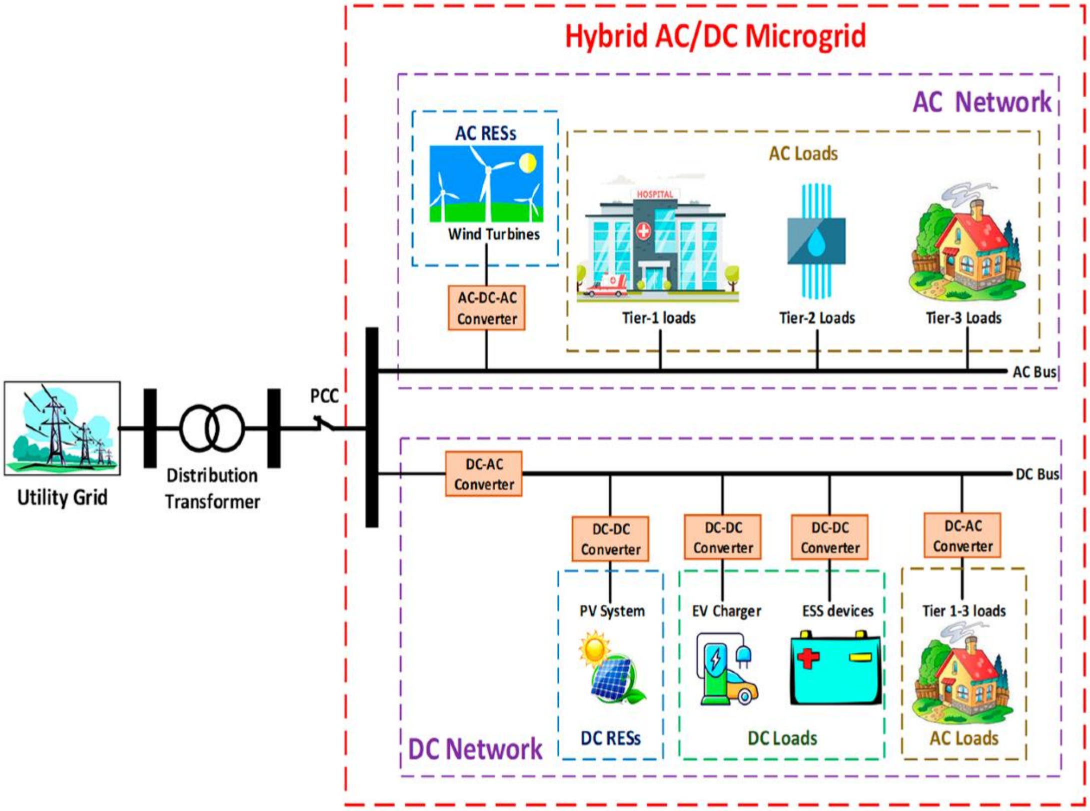


Figure 1.7_ Simple diagram of a typical HMG.

Table 1.3_ Main characteristics of different types of MG.

Type	**Features**
ACMGs	- Usually, a common AC bus exists, connecting its different components. - They can be easily integrated into conventional AC power systems, providing more controllability and flexibility for them compared to other kinds of MGs. - DC/AC converters must be used as an interface between DC components and the AC common bus, decreasing the total efficiency dramatically [31,32,33].
DCMGs	- Generally, a common DC bus exists, connecting its different components. - They are connected to the main grid through a DC/AC power converter. - In terms of operation principles, DC and AC MGs are similar. - Compared to ACMGs, DCMGs provide reduced power conversion losses since fewer power conversion stages are needed, resulting in a higher efficiency, lower cost, and smaller size. - They provide better stability than AC ones since no reactive power exists in DCMGs [31,34,35,36]. - They are better options for DER integration [67,70,71,72]. - Their most popular structures are the bipolar, monopolar, and homopolar structures [32,37].
HMGs	- They are obtained by combining both ACMGs and DCMGs in the same distribution system. - Both AC and DC components can be directly integrated into them. - They benefit from all the advantages of ACMGs and DCMGs, such as the least number of interface devices, facilitated DR integration, fewer conversion stages, decreased power losses, lower overall costs, and higher reliability. - In HMGs, AC and DC components can be respectively connected to AC and DC parts. Hence, no synchronization is required for generation and storage units [38,39,40].

In terms of the DERs connection way, MGs can be categorized into three main types: parallel, cascaded (series), and hybrid cascaded–parallel MGs [41,42,43,44]. These MG structures are respectively shown in **Figure 8a–c** [45]. The hybrid cascaded-parallel MG is among the most recent structures that can support high-power operation and be employed for integrating LV sources such as cascaded solar panels and battery cells [45]. Besides the aforementioned classifications, it is noteworthy that MGs also can be classified into LV, MV, and HV systems in terms of their voltage level.

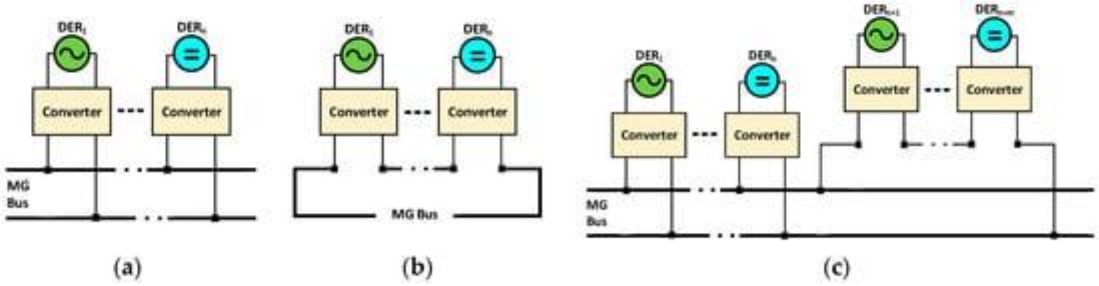


Figure 1.8_ Simple diagrams of different MG structures in terms of DERs connection types: (a) Parallel structure; (b) Cascaded structure; (c) Hybrid parallel–cascaded structure.

1.6 Comparison between AC and DC Microgrid

As a comparison between AC and DC configuration of microgrid, AC systems have more advantages than DC systems in the following points or aspects: The first point, the AC systems line impedance is much higher than DC systems. Meanwhile, an AC element, such as transformer, can withstand more overloading (Asan example, a 30/40MVA, 138/13.8kV transformer can withstand 160% overload for 30 minutes and 170% during 15 minutes according to transformer factory test.

In addition to this, the DC system for which slight overloading for milliseconds over-power electronic device rating could permanently damage the power converter. In case of fault such as short circuit, the AC can be limited and also it rises slowly because of relatively high AC impedance; thus, the overloading ability provide enough time for protection devices to operate but in DC system, the low DC "impedance" induces high rising rate in the fault current, resulting in more challenges for the design of a fast response DC circuit breaker. In the second point, the AC circuit breaker is much mature than DC. Forced by AC voltage, AC has nature zero-crossing features, but DC is always persisting. Breaking the DC circuit is much more difficult than breaking AC especially in high current rating. AC voltage can be economically and so easily transformed to another level (increasing or decreasing) by electromagnetic transformers without control strategy, but DC transformation requires power electronic devices with complex control and measuring. Semiconductor applications can be found everywhere, from industrial variable speed motor drive to building lighting, not to mention ubiquitous information technology devices this with technical development. Appliances based on semiconductors require always the use of DC power. Conversion from AC to DC generally loses 10-25% of energy, depending on various devices and/or their rated power addition, DC systems do not experience skin influence, so the thinner cable can be used with ameliorate material efficiency. In DC microgrid, AC sources, like diesel generators, wind turbine and MT are integrated to the DC bus through converters. As no reactive power is present in the DC bus, connected AC sources could run with only active power, which increases the power transfer ability and the power efficiency. Coupling AC microgrid element with AC grid and AC bus obliged all conversion stages to work at the same frequency, while the amplitude and harmonic must also be as consistent as possible to avoid undesired loop current. The DC microgrid, as zero frequency system, only the voltage amplitude should be regulated and there is no need for synchronization when connecting DC bus or DC local grid. Coupling DC bus to AC. [22]

1.7 Types of Energy Sources in Microgrid

Microgrids are innovative energy systems that rely on a variety of energy sources to meet local energy needs. With the advancement of technology and the increasing demand for sustainable and reliable energy solutions, microgrids have become a significant focus in the energy sector. The efficiency and effectiveness of microgrids largely depend on the quality and diversity of the energy sources used within them. In this context, different energy sources—whether renewable or non-renewable—play a crucial role in determining the performance and sustainability of these grids. We will explore the various energy sources that can be utilized in microgrids.

1.7.1 Renewable Energy

1. Solar Energy

Solar Energy has the greatest potential for providing clean, safe, and reliable power. The solar energy falling on the Earths continents is more than 200 times the total annual commercial energy currently being used by humans [11]. The government started solar power adoption with subsidies. A consumer who installs a solar panel array on a house can sell surplus energy to the local utilities. The solar panel cost, reduced to 50%, which would make solar Powered Electricity cost comparable with other types of fuel, is possible within the next decade [12]. Solar Energy can be classified as two types 1. Passive solar and 2. Active solar. Passive solar energy is making direct and indirect use of thermal energies from the sun. Indirect use of Energy is possible only in building (or) structures. The southern exposure of a building guarantees the maximum exposure of the sun's rays. Special metal leaves covering over windows and roofs can block out the sun during the summer months. Special thermal solar collectors can circulate water through the collection unit that collect the sun's thermal energy for the purpose of heating the water for use [13]. Active Solar Energy is the use of the sun's Electromagnetic radiation in generating Electrical Energy. Generally, semiconductor silicon Boron solar chips are used for this. The problem of these chips one that they have low Efficiency ratio and can only be used in supplying Energy needs of small devices (i.e. calculators, watches, radio etc.)

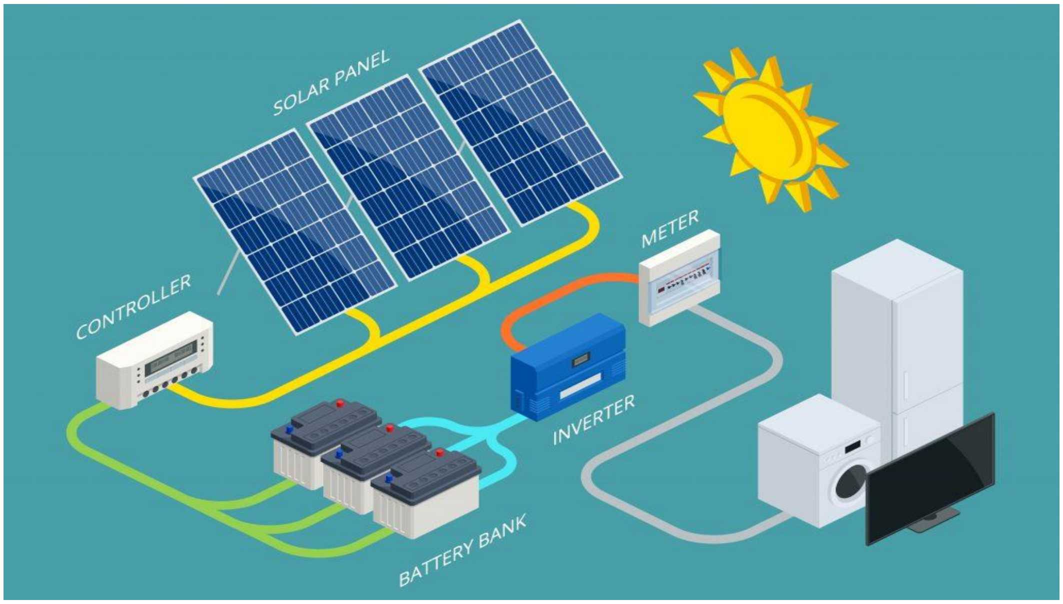


Figure 1.9_Solar Energy.

Advantages:

- Solar energy is a virtually unlimited resource, especially in sunny regions.
- Once installed, solar panels have low maintenance and operation costs.
- Solar power reduces greenhouse gas emissions and dependence on fossil fuels.
- Can be used for a variety of applications, from small-scale residential to large-scale commercial installations.
- Reduces reliance on imported energy sources.

Disadvantages:

- Solar energy production is weather-dependent and varies with daylight hours.
- The installation of solar panels and associated equipment can be expensive.
- Large solar farms require significant land areas.
- Efficient storage solutions are needed to supply energy during non-sunny periods.
- Manufacturing solar panels involves hazardous materials and energy-intensive processes.

2. Wind Energy

Wind, ultimately driven by atmospheric air, is just another way of collecting Energy. Sun also heats the atmosphere, which produces wind. It works on cloudy days and Rainy season also [14]. The location of wind turbines is a very important factor, which influences the performance of the machine. The windmills are generally located at the top of a tower to heights approximately 30 m. To avoid turbulence from one turbine affecting the wind flow at others it is located at 5-15 times blades diameter [15]. Windmills are working both in horizontal axis and vertical axis. The basic mechanics of the two systems are similar. Wind passing over the blades is converted into mechanical power, which is fed through transmission to an electrical generator [15]. Wind turbines will not work in winds below 13 km an hour. They work best where the wind speed averages 22 km an hour [14]. Most of wind turbines produced at the present time are horizontal axis turbine with three blades, 15-30 m diameter, producing 50-350 Kw of Electricity [15]. Wind energy produces no air or water pollution, involves no toxic or hazardous substances, and poses no threat to public safety [16].

Figure 1.10_ Wind Energy

Advantages:

- Wind energy produces no emissions and is a sustainable energy source.
- After the initial investment, maintenance and operating costs are relatively low.
- Wind farms create jobs in manufacturing, installation, and maintenance.
- Land used for wind farms can often still be used for agriculture or other purposes.

Disadvantages:

- Wind energy production is variable and depends on wind conditions.
- The cost of building wind turbines and associated infrastructure can be high.
- Wind turbines can be considered unsightly and noisy by nearby residents.
- Wind farms can pose threats to birds and bats.
- Suitable locations for wind farms are limited to areas with sufficient wind speeds.

3. Biomass Energy

Biomass is the most important source for energy production supplied by agriculture. Effective harnessing of bio-energy can energize entire rural milieu in a country like India where nature offers various types of biomasses. This energy is also available in the form of biodegradable waste, which is the rejected component of available biomass [17]. Biomass energy refers to fuels made from plants and animal wastes. The Biomass resource is organic matter in which the energy of sunlight is stored in chemical bonds. When the bonds between carbon, hydrogen and oxygen molecules are broken by digestion, combustion (or) decomposition these substances release stored energy. Biomass energy is generated when organic matter is converted to Energy. [18], Biomass is considered a renewable energy because the items used as fuel can be grown again. This type of fuel is not considered clean energy though, because it does release pollution into the air. In Washington, a state known for growing timber, there are six biomass plants that use logging and mill residue. The closest plant to Vancouver is in Longview.

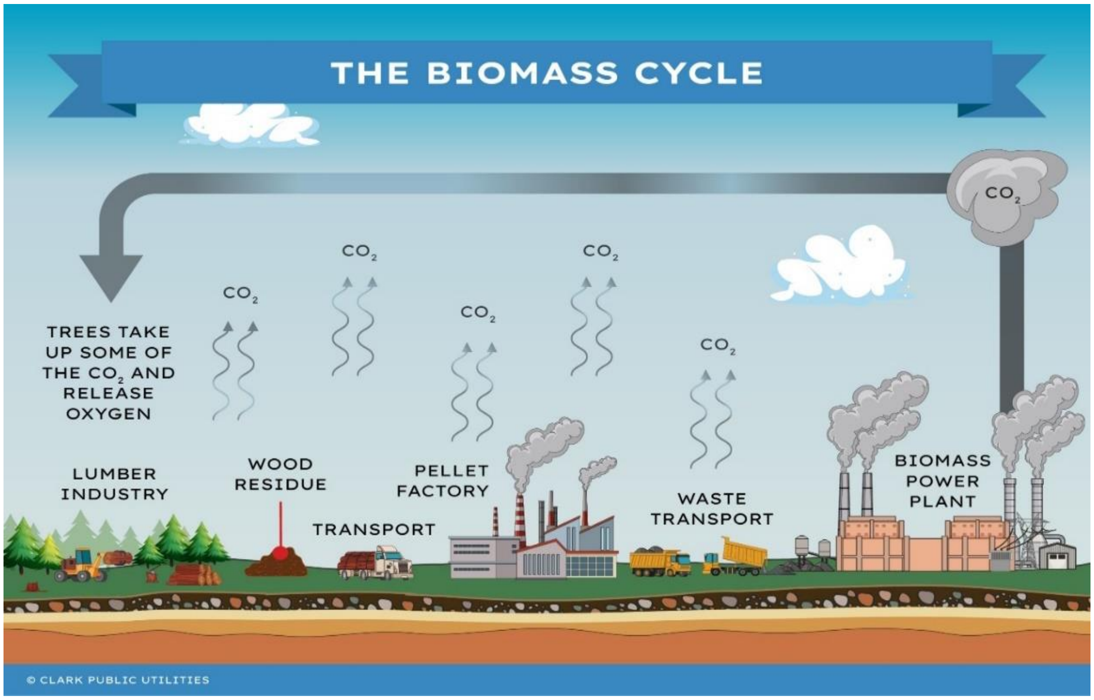


Figure 1.11_Biomass Energy.

Advantages:

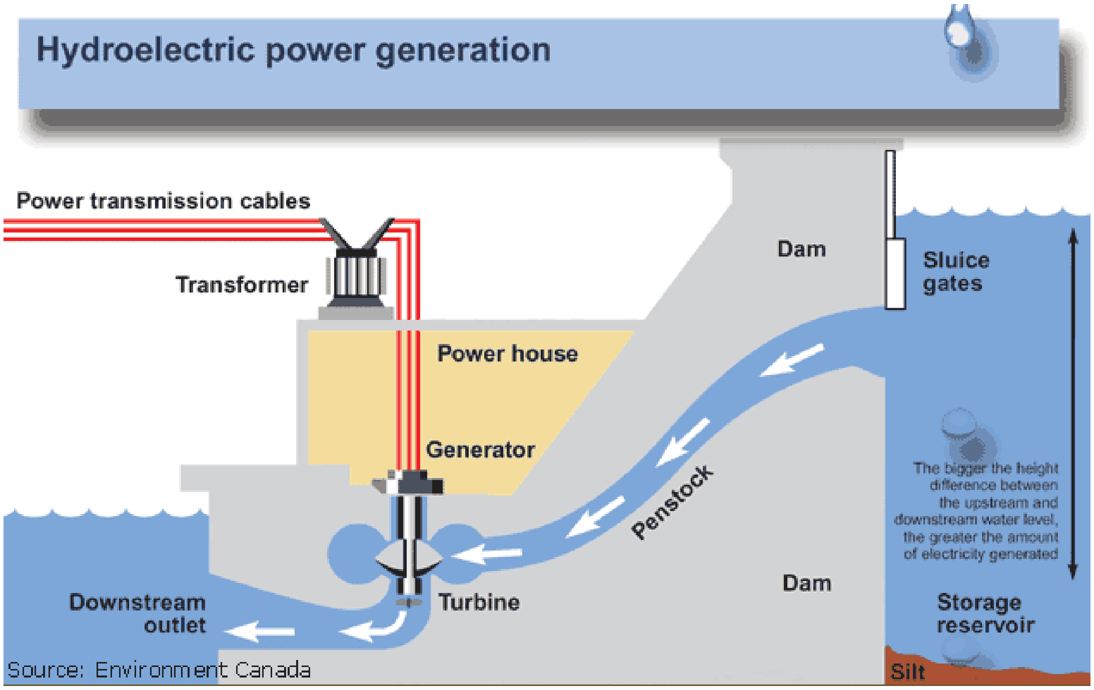
- Biomass is derived from organic materials and is renewable as long as it is sourced sustainably.
- Utilizes agricultural, forestry, and urban waste products, reducing landfill use.
- Biomass energy can be considered carbon-neutral if the CO2 released is offset by the CO2 absorbed by the plants used as biomass.
- Can be used to produce electricity, heat, and biofuels.

Disadvantages:

- Large-scale biomass production can compete with food production and natural habitats.
- Combustion of biomass can produce pollutants, although less than fossil fuels.
- Growing, harvesting, and processing biomass can be resource-intensive and require significant water and energy.
- The energy content of biomass can vary, affecting efficiency and output.

4. Hydroelectric power

Hydropower, or hydroelectric power, is a renewable source of energy that generates power by using a dam or diversion structure to alter the natural flow of a river or other body of water. Hydropower relies on the endless, constantly recharging system of the water cycle to produce electricity, using a fuel—water that is not reduced or eliminated in the process. [19] The principle consists of using the mechanical energy of water to rotate turbine and an alternator to produce electricity. This form of energy is mainly produced below dams' hydraulics and sometimes through artificial watercourses and canals using micropower plants. The power produced depends on the height of the water fall and the flow rate. the water. There are also other electricity generation processes around the world through the exploitation of water such as the use of the movements of sea waves and tides, or underwater currents and other new sea energy techniques such as the thermal energy of the seas and the osmotic energy of the seas. [20]



Source: Environment Canada

Figure 1.12_ Hydroelectric Power Generation.

Advantages:

- Hydropower is a consistent and reliable renewable energy source.
- Produces very low greenhouse gas emissions compared to fossil fuels.
- Hydropower plants have high efficiency levels compared to other renewable sources.
- Reservoirs can store water for future energy production, providing flexibility in energy supply.

Disadvantages:

- Large dams and reservoirs can disrupt ecosystems and displace communities.
- Building hydroelectric plants and dams requires substantial investment.
- Suitable sites for large-scale hydropower are limited to areas with sufficient water flow.
- Water availability can be affected by droughts and climate change, impacting energy production.

5. Geothermal Energy

Geothermal energy is a type of renewable energy derived from the Earth’s core. It originates from heat generated during the planet's formation and the radioactive decay of materials. This thermal energy is stored in rocks and fluids in the center of the Earth. The temperature difference between the Earth’s core and its surface drives the continuous conduction of thermal energy from the center to the exterior. High temperatures, exceeding 4000°C, cause some rock in the Earth's center to melt, forming hot molten rock called magma. These temperatures also cause the mantle to behave plastically, with portions convecting upwards because they are lighter than the surrounding rock. The rock and water in the Earth’s crust can reach temperatures of around 370°C. This thermal energy can be found at shallow depths and extends several miles below the Earth’s surface. [21]

Figure 1.13_ Geothermal Energy.

Advantages:

- Geothermal energy is derived from the Earth's internal heat, which is virtually inexhaustible.
- Produces minimal greenhouse gas emissions compared to fossil fuels.
- Provides a constant and reliable energy supply, unaffected by weather conditions.
- Geothermal plants have a smaller land footprint compared to other renewable energy sources.

Disadvantages:

- Suitable sites for geothermal energy are limited to regions with significant geothermal activity.
- Drilling and establishing geothermal plants can be expensive.
- Overuse of geothermal reservoirs can deplete the resource and reduce efficiency.
- Geothermal drilling and activity can induce seismic events.

1.7.2 Non-Renewable Energy

Non-renewable energy is an energy source that exist in finite quantities and cannot be naturally replenished or regenerated. These energy resources are formed through natural processes, such as the decomposition of organic matter or the nuclear reactions occurring in the Earth’s core. Non-renewable energy plays a significant role in meeting our current energy demands but poses challenges due to its finite nature and environmental impact. Non-renewable energy has been the backbone of modern industrialization and has fueled economic growth for centuries. However, the finite nature of these resources calls for the exploration and development of sustainable alternatives. [9]

This latter consists primarily of fuels derived from fossil deposits. Let's explore some of the most widely used non-renewable energy sources:

1. Coal

Coal has long been a significant contributor to non-renewable energy production. Coal is formed from ancient plants' remains and extracted from underground mines or surface mining methods. It is widely used in electricity generation and industrial processes, making it a prominent non-renewable energy resource. [10]

Advantages:

- Coal is one of the most abundant fossil fuels available, making it a reliable source of energy.
- Coal has a high energy content per unit weight, which makes it efficient for power generation.
- There is a well-established infrastructure for coal mining, processing, and power generation.
- Coal mining and related industries provide significant employment opportunities and contribute to the economy.

Disadvantages:

- Burning coal releases a large amount of carbon dioxide (CO2), contributing to global warming and climate change. It also releases sulfur dioxide (SO2), nitrogen oxides (NOx), and mercury, leading to air pollution and acid rain.
- Coal mining and combustion can lead to respiratory illnesses, lung diseases, and other health problems for workers and nearby populations.
- Although abundant, coal is a non-renewable resource that will eventually deplete.
- Coal mining, particularly strip mining and mountaintop removal, can cause significant environmental damage, including habitat destruction and soil erosion.

2. Petroleum Products

Petroleum products are another essential component of non-renewable energy sources derived from crude oil. Crude oil is extracted from underground reservoirs and refined into various products, including gasoline, diesel, jet fuel, and heating oil.

Advantages:

- Petroleum products have a high energy density, making them very effective for transportation and industrial uses.
- They can be refined into a wide variety of products, including gasoline, diesel, jet fuel, heating oil, and petrochemicals.
- Extensive global infrastructure exists for the extraction, refining, distribution, and consumption of petroleum products.
- Petroleum products are crucial to the global economy, providing jobs and driving economic growth.

Disadvantages:

- Burning petroleum products releases CO2, contributing to climate change. It also produces other pollutants such as NOx, SO2, and particulate matter, leading to air pollution and health issues.
- Accidental oil spills during extraction or transport can cause severe environmental damage to marine and terrestrial ecosystems.
- Petroleum is a non-renewable resource with a finite supply, leading to concerns about long-term availability and price volatility.
- Dependence on petroleum can lead to geopolitical tensions and conflicts, particularly in oil-rich regions.

3. Compressed Natural Gas (CNG)

CNG is sourced from natural gas reserves and compressed for use in vehicles, particularly in transportation fleets and as a fuel for natural gas power plants. CNG is gaining popularity due to its lower emissions and cost-effectiveness.

Advantages:

- CNG produces fewer pollutants compared to coal and petroleum products. It emits less CO2, NOx, and virtually no SO2 or particulate matter, making it a cleaner alternative.

- CNG is often cheaper than gasoline and diesel, making it a cost-effective fuel for transportation and industrial uses.
- Natural gas reserves are abundant, and advancements in extraction technology, like fracking, have increased supply.
- CNG engines typically run more efficiently and have a longer lifespan compared to traditional gasoline or diesel engines.

Disadvantages:

- Although cleaner than coal and petroleum, natural gas is primarily methane, a potent greenhouse gas. Leaks during extraction, transport, and use can negate some of the environmental benefits.
- The infrastructure for CNG refueling stations is less developed compared to gasoline and diesel, limiting its widespread adoption.
- Converting vehicles to run on CNG or setting up CNG fueling stations can be expensive.
- CNG is stored under high pressure, which can pose safety risks if not handled properly, including the potential for explosions in the event of a leak.

These non-renewable energy sources provide a significant portion of our energy needs. However, it is important to recognize their finite nature and explore alternative energy options to ensure a sustainable future. [46-53]

1.8 Advantages of Microgrid

- **Enhanced stability:** Due to MGs' unique characteristics, main grid stability can be increased by integrating MGs into the system.
- **Increased efficiency:** Decreased power losses of transmission and distribution lines result in increased efficiency.
- **Higher RESs integration:** MGs facilitate the integration of low-carbon technologies such as RESs into the power system, resulting in decreasing global warming and pollution.
- **Continuous supply to loads in islanded mode:** Unlike conventional distribution systems, MGs can provide a continuous and independent supply of all micro sources (MSs) to loads during their autonomous/islanded mode.
- **Supporting the main grid:** MGs can support the local power grid and facilitate the generation increase, leading to improving the system's reliability and power quality.
- **Plug-and-play capability:** MGs can switch either to grid-tied or islanded modes.
- **Back-up supply source:** Under the main grid's power supply failure, MGs can play the role of a backup supply source.
- **Maintaining the energy supply and V-f stability of loads in failures:** In the case of any

fault in the main grid, MGs can maintain the energy supply and stability of the voltage and frequency for all local loads by operating in the islanded mode [53].

- **Bidirectional power flow path:** By integrating MGs into a distribution feeder, the concept of unidirectional power flow (from the substation to the load designed for conventional distribution systems) can be changed to a bidirectional structure.

1.9 Main technical and economic issues and challenges of MGs

- **Power Imbalance:**
  - By changing the MG’s mode from grid-tied to islanded mode, due to the slow dynamic response and low inertia of MSs, power imbalances happen.
    - ➢ FACTS [54-56] and ESSs can be considered as applicable solutions for solving this problem.
    - ➢ For islanding an MG, PEL-based devices with a high acceleration and accurate sensing ability must be employed.
    - ➢ An islanded MG should be re-connected to the grid only by considering synchronization issues [57].
  - Load changes and DG failures can also cause power imbalances in MGs.
- **Harmonics:**
  - In a power system, harmonics can have diverse impacts on system reliability and stability.
  - In MGs, several PEL devices are employed, which are the main harmonic sources in power systems.
  - These harmonics can cause many problems, such as threatening ESSs’ safety [58].
  - Active and passive power filtering techniques are used to mitigate harmonics in power systems [59].
- **Stability and power quality:**
  - For the stability and power quality issues of a power system, including MGs and DERs, three main reasons can be named [60]:
    (a) Lower network inertia causing decreased angular stability leading to frequency and voltage instabilities.
    (b) Low-frequency power oscillations caused by changing the power-sharing ratio between DERs.
    (c) Reduced voltage stability caused by decreased energy distribution support.
  - The feasible solutions for these problems are enhancing the quality of supply decentralization, having an accurate ratio between demand and supply, and reducing the generation and transmission outages and downtimes [61].
- **ESS:**
  - Despite the ability of DERs, such as RESs, to provide clean and free/low-cost

energy, it is still challenging to manage their produced energy without any interruption/curtailment [62].

  - ESSs are widely used as an effective approach to solving these problems.
  - By using ESSs, many advantages can be achieved, such as decreased fluctuations, a higher power factor for the whole system, regulated frequency and voltage, and overcoming RESs' intermittent nature.

- **Topological changes:**
  - Besides intermittent RESs, the continuous connection and disconnection of MSs, loads, and ESSs can cause topological changes in MGs [63].
  - MGs can be installed in diverse locations such as houses, farms, buildings, etc.
  - Based on requirements, various kinds of MGs can be designed and established to meet consumer and/or system demands.
- **Environmental issues:**
  - Due to problems such as global warming, increased carbon emissions, increased high-quality power demand, and the depletion of fossil fuels, countries are obliged to increase the share of environment-friendly DERs, such as RESs, in their networks
  - Several studies have been performed on different MSs to compare their harmful emissions [46].
- **Economic aspects:**
  - In an MG, essential variables for governing are the reactive and active powers of DERs and the current/voltage of the interface bus of CSI/VSI [64].
  - By controlling these variables properly, optimal operation, power distribution, RESs integration, and economical operation are achieved in MGs.
  - In grid-tied mode, by controlling the output of the MG, losses incurred from feeders and transformers can be controlled. •
  - Since the total life span of MGs depends on the proper utilization of ESSs, an optimized energy approach must be designed for them [65].
  - In [66], the most critical parameters resulting in an optimal cost of MGs are presented.
- **Protection issues:**
  - A protection system must provide a quick and robust response to all faults for either grid-tied or isolated MGs.
  - In the case of any fault in the main grid, the protection system should be able to quickly detect it and easily isolate the MG to ensure its components' protection.
  - In the case of any fault in the MG, protection systems should be able to quickly detect it and easily isolate the faulty part of the MG from the rest.
- **Communication system:**

  - For the proper operation of an MG, and by considering that MGs are small-sized grids mainly established in remote areas, it is required to establish a cost-effective, robust, and reliable communication system with suitable coverage, security, and latency.
  - In terms of communication technology, communication systems can be categorized into WL and wired systems.
  - In terms of data rate capability, LB- and HB-com systems are mainly used in MGs.

- **Control system:**
  - For controlling MGs, hierarchical control methods are commonly employed due to equipment diversity, unique challenges, and complicated relations among the components.
  - Despite MGs' advantages, a careful and precise control system is required for MGs to provide a robust, proper, and stable operation.
  - In terms of communication systems, MGs' control systems can be classified as communication-based and -free controllers.
  - In terms of the controlling structure, it can be grouped into centralized, decentralized, and distributed methods.
- **RESs integration:**
  - Besides the RESs' benefits (being low-cost and clean sources), most of them have a variable, non-dispatchable, and intermittent nature. For achieving higher/optimum RES integration into MGs, these problems must be considered in designing control systems and by using some other solutions such as ESSs.

1.10 Conclusion

In this chapter, we have provided a comprehensive overview of microgrids, starting from the historical background that contributed to their inception and development, and moving through the key components of these grids and their various types. We also discussed the types of energy sources that can be utilized in microgrids and the numerous benefits they offer, including environmental sustainability, economic efficiency, and high reliability. Our journey was not without challenges; we examined the obstacles and barriers to the widespread adoption of microgrids and explored the diverse practical applications that benefit from this advanced technology. Looking towards the future, it is evident that microgrids hold significant promise for further development and innovation, contributing to a sustainable and secure energy future. Through this chapter, it becomes clear that microgrids are not just a modern technology but a comprehensive system that meets the diverse and growing energy needs of today's world. With continued research and development, microgrids will become an essential part of the global energy landscape, enhancing communities' ability to adapt to future environmental and economic challenges, this chapter serves as a starting point for a deeper understanding of microgrids. In the second chapter, we will delve further into the technical details and advanced applications of these grids, exploring more practical aspects and recent developments in this vital and evolving field

Chapter 2

Modeling of Microgrid System

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2.1 Introduction

The evolution of energy systems has led to the development of microgrids, localized energy networks capable of operating independently or in conjunction with the main power grid. This chapter delves into the comprehensive modeling of microgrid systems, encapsulating various components and renewable energy sources that contribute to the robustness and efficiency of the overall system. We begin with the modeling of microgrids, which involves simulating their behavior under different operational conditions to ensure optimal performance and stability. This includes understanding the dynamics of load demand, generation capacity, and the interaction between different energy resources. Renewable energy sources, such as photovoltaic (PV) systems and wind turbine generators, are integral to microgrids. The modeling of PV systems includes their design, performance characteristics, and the factors affecting their efficiency, while the mathematical modeling of PV generators involves precise equations and parameters to simulate their output under varying environmental conditions. For wind energy, we explore the aerodynamics of wind turbines, the statistical and physical models used to simulate wind speed variations, and comprehensive models to predict wind turbine output. Additionally, the modeling of diesel engine generators is discussed, focusing on their operational characteristics and integration into the microgrid as backup power sources. Plug-in Hybrid Electric Vehicles (PHEVs) are also modeled, considering their charging and discharging behaviors and their impact on the microgrid. Battery energy storage systems are crucial for balancing supply and demand, and this chapter covers the modeling of different battery types, their performance characteristics, and their role in energy storage. Various types of batteries, each with unique properties and applications, are overviewed, highlighting their advantages and limitations. Finally, maintaining frequency stability is essential for reliable microgrid operation, and we discuss models used to predict and control frequency deviations, ensuring consistent power quality. By understanding these models, we can design and operate efficient, reliable microgrids capable of meeting future energy demands.

2.2 Modeling and Control of Microgrids

This dissertation delves into both analytical and applied pathways to explore the intricate interaction among various energy components within a microgrid system. Ranging from solar panels to wind turbines, diesel generators, battery storage systems, and hybrid electric vehicles (PHEVs), the focus lies in studying patterns of behavior and fluctuations in production and consumption [1]. The research offers an integrated approach in modeling, encompassing detailed insights into the behavior of each component while considering influential environmental and technological factors such as solar radiation, wind speed, fuel efficiency, and battery characteristics [2]. The significance of this dissertation manifests in the delicate balance between renewable and traditional energy components, shedding light on the role of battery storage systems in system stability and sustainable energy provision. Moreover, it addresses the analysis of load fluctuations on microgrid frequency, with emphasis on control strategies to ensure system stability and energy quality [3]. The islanded microgrid operation serves as a pivotal juncture in the dissertation, with accompanying **Figure 2.1** illustrating the interconnected relationship between distributed energy components and the microgrid. This reflects the collective capability of energy sources to support continuous energy provision in the event of a main grid outage, underscoring the importance of integrating these components in ensuring system sustainability and its ability to meet future energy challenges [4]. To achieve this, the dynamics of all the distributed generation (DG) units are approximated by a first-order linear model with a time constant and a gain factor, while the network itself is neglected. Transfer functions of various components are obtained, and time-domain analysis is performed by considering these components individually over time. **Figure 2.1** showcases the configuration of the microgrid in one of the modeled cases. As a power generating unit, the microgrid can be represented by a DC source. When modeling a microgrid with an RLC load in islanded mode, it is represented by a DC source connected to a voltage-sourced converter (VSC). The microgrid connects to the grid via an R-L filter, a step-up transformer, and a circuit breaker, which remains open when the microgrid is islanded. This modeling approach helps to understand the microgrid's behavior and develop effective control strategies for both connected and islanded operations [5].

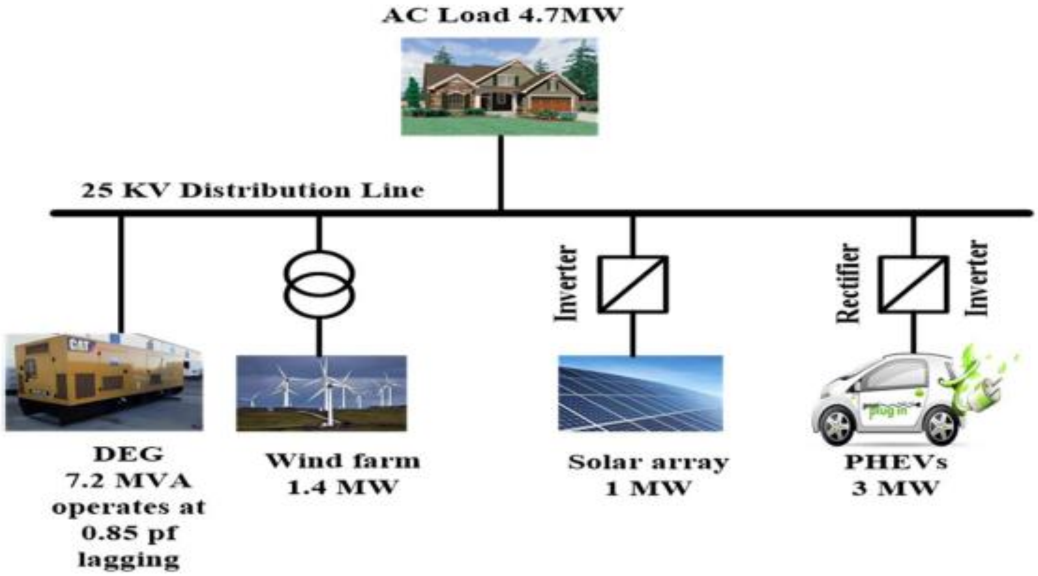

Figure 2.1_ Distributed energy resources and microgrid

2.3 Renewable Energy Sources Modeling (RES)

In this section, the mathematical model of the output power of the photovoltaic system and wind

Turbine is presented in detail.

a. Model of the PV system

The PV principle is the conversion of solar irradiance into electricity that is discovered by the Becquerel family and presented to the French Academy of Sciences by the end of 1839. This conversion is realized by the PV cell, the electrical characteristics of which resemble those of the PV source [6]. **Figure 2.2** (a) − (b) − (c) are models of the most commonly used PV cell: a current source parallel with one or two diodes. The model of single diode [7] contents four elements such as source of current with diode in parallel and resistors series (R_s) en shunt (R_{sh}). **Figure 2.2** (b) presents model of two diode: the extra diode is for better curve-fitting [8].

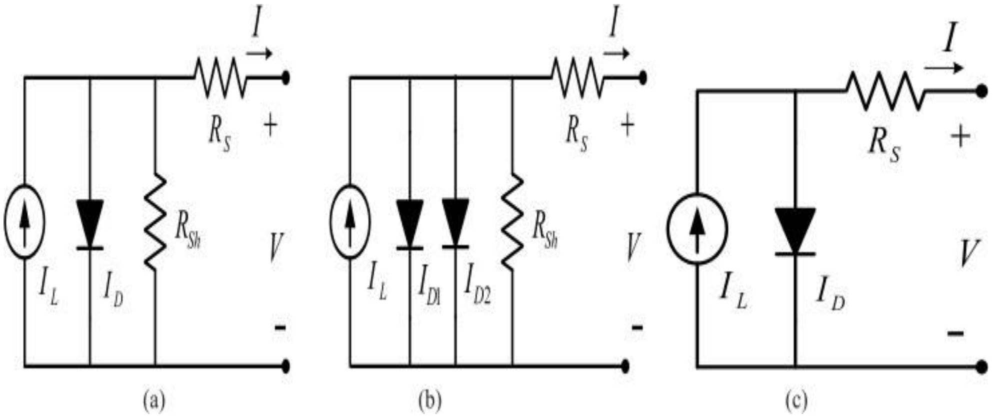

Figure 2.2– Different models of PV.

The photovoltaic system is considered to have the greatest potential among all renewable energy resources worldwide in the future, due to its pollution-free and inexhaustible nature. The solar cell is a p-n junction fabricated in a thin layer of semiconductor.

For modeling the photovoltaic system, it is necessary to estimate the current-voltage and power-voltage characteristics to emulate the real function of this system under various conditions.

The most popular method for modeling the PV system is to use the electrical equivalent circuit represented by the diode model. Various models have been shown in the literature [9]. The simplest model of a PV system is the single-diode model, which consists of a current source in parallel with a diode. The three parameters of this model determine the characteristics of the I-V curve, namely short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and diode ideality factor (a). This model is improved by adding series and parallel resistances, denoted Rs and R_{shunt}, respectively. The series resistance (Rs) is the internal resistance of the cell and depends mainly on the resistance of the semiconductor used, the contact resistance of the collector grids, and the resistivity of these grids. The shunt resistance (R_{shunt}) is due to leakage current at the junction and depends on how it was manufactured. [10]

In literature, it is popularly known as the Rs-model. Due to its simplicity and computational efficiency, the Rs model is by far the most widely used model in PV system simulations. The use of two-diode models is employed to mitigate the effects of module shading. Several modeling methods are proposed in the literature to determine the PV system parameters.

A PV array is a connection of several PV modules, connected in various topologies. Three typical interconnection structures are largely used, namely series-parallel (SP), total cross-tied (TCT), and bridge link (BL). A PV system generates DC voltage that is converted into AC using a DC-AC converter. An MPPT technique is widely applied to extract the maximum power produced by the PV system. In [10] one study, partial modeling of an array system based on an improved two-diode model is proposed. The proposed modeling is interfaced with actual power electronic converters and MPPT algorithms. A PV panel is composed of one or more PV cells, and a PV source consists of one or several PV panels. [11]

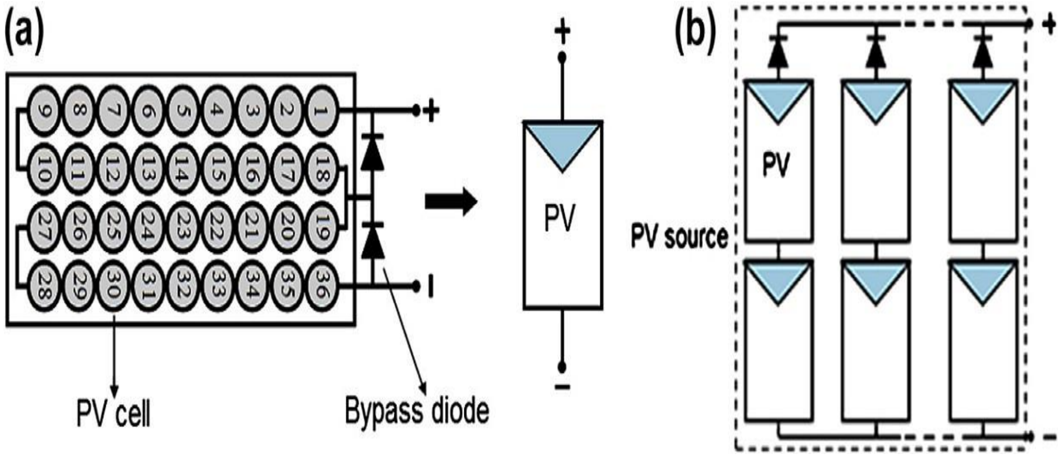

Figure 2-3– Photovoltaic system modules.

The STC relates to the IEC 60904 standards, short-circuit current Isc, open-circuitvoltage Voc, and maximum-point power (P_{mpp}) that are specified for PV modules to ±10% tolerance. Realistically, these conditions occur very rarely; however, if the sun shines with the specified intensity, then, cell temperature will be higher than $25^{\circ}C$. I −V curves and P −V curves were simulated for various irradiances and temperatures by using MATLAB. The PV − AE125MF 5N module was chosen as it is one of the types to be used in the experiment [12].

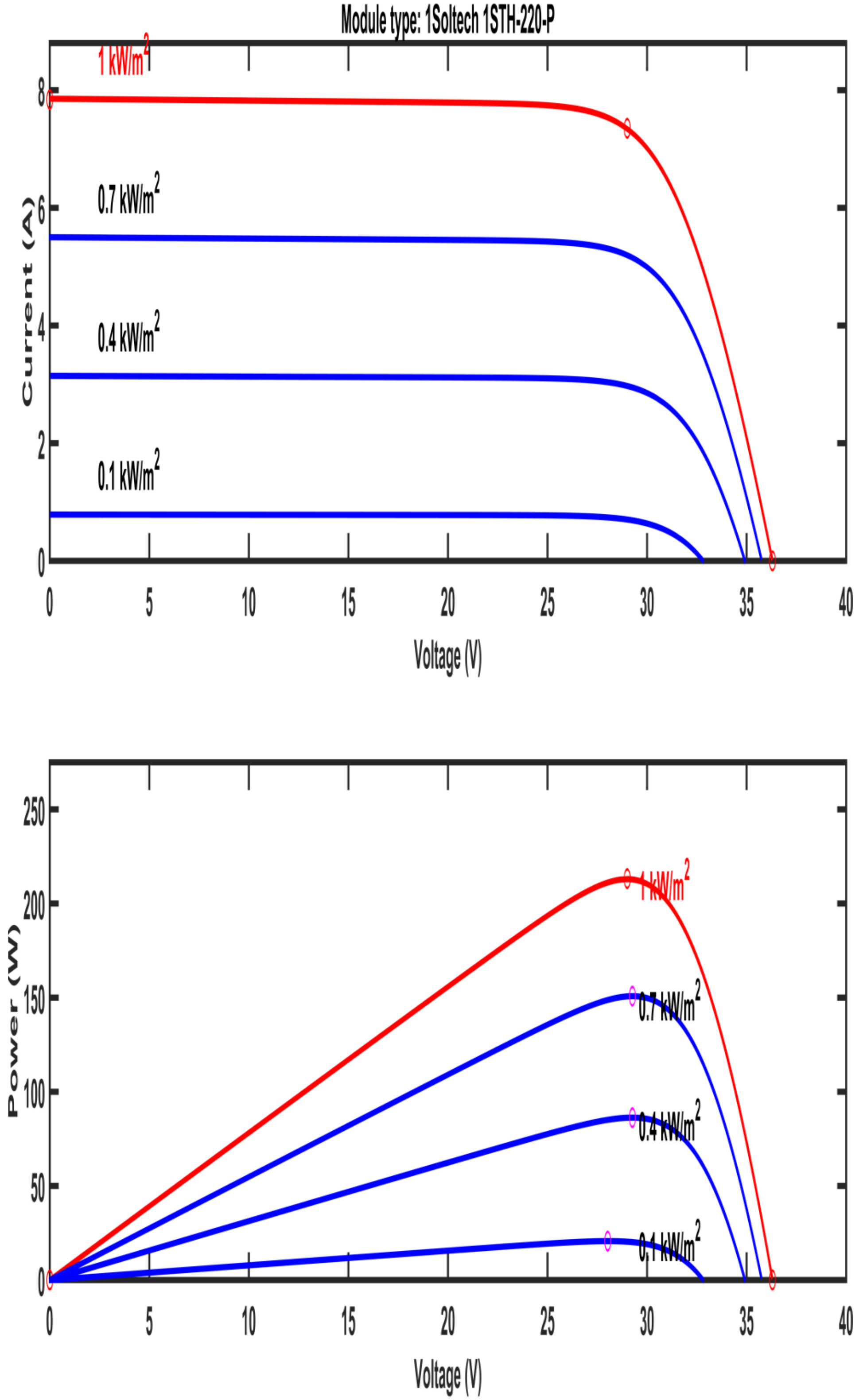

Figure 2.4 _ Characteristic of PV cell for different value of irradiation and constant value of temperature.

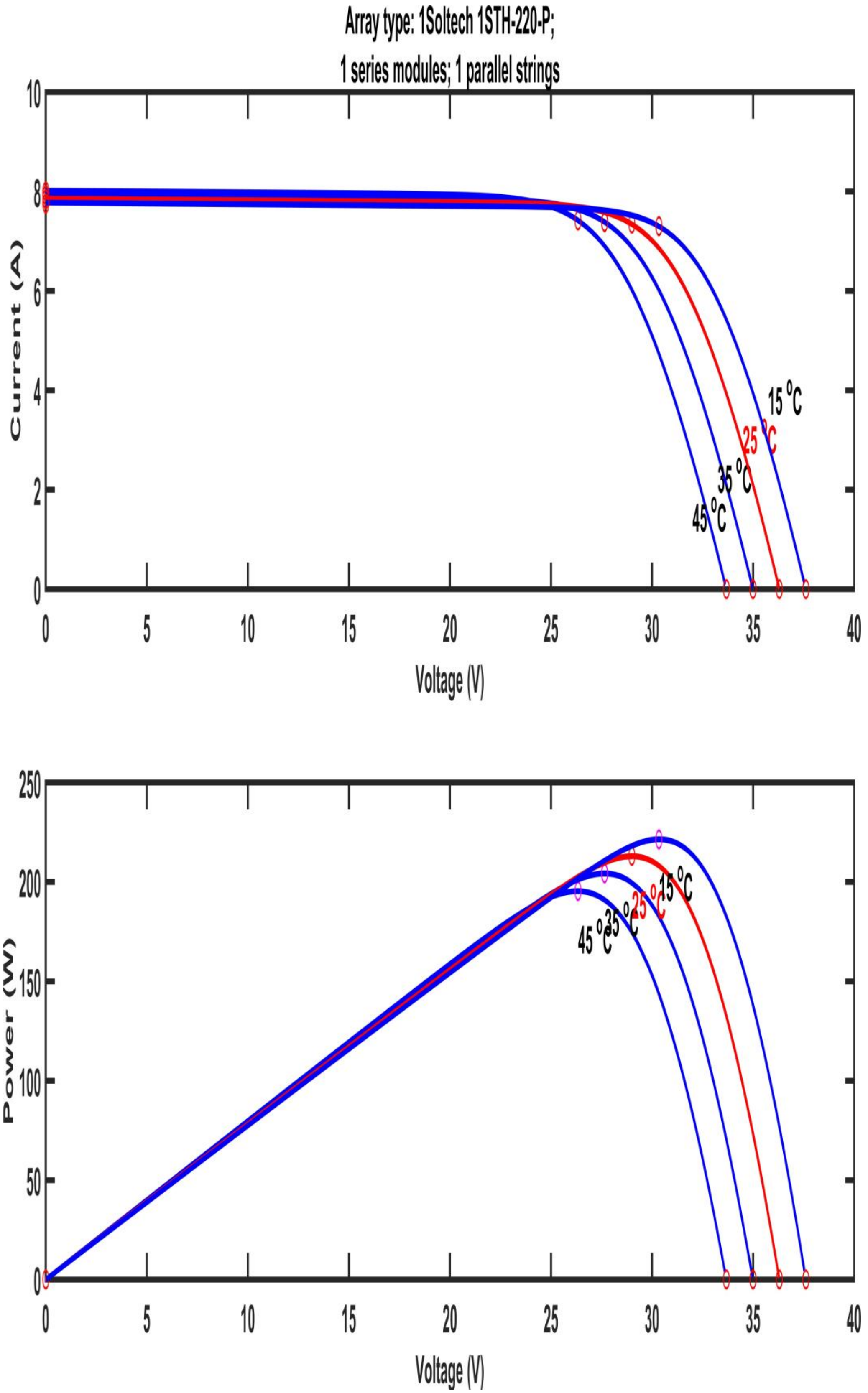

Figure 2.5 _ Characteristic of PV cell for different values of temperature and constant value of radiations.

b. Modeling of solar cell

The simplest equivalent electrical model of the solar cell system is considered as a current source connected in parallel with a diode. The current output is proportional to the light falling on the cell area. A current source in parallel with a diode presents the simplest equivalent circuit of a solar cell. The current source output is directly proportional to the light falling on the cell (photocurrent I_{ph}). During darkness, the solar cell is not an active device; it works as a diode, i.e. a p–n junction. It generates neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it produces a current ID, called diode (D) current or dark current. The diode proves the I − V characteristics of the cell [13].

In an ideal model of cell $R_s = R_{sh} = 0$, that is a relatively common appropriation [14]. For this thesis, a model of moderate complexity was used (suprmimé). The net current of the cell is calculated by the difference between the photocurrent, I_L and the normal diode current I_0:

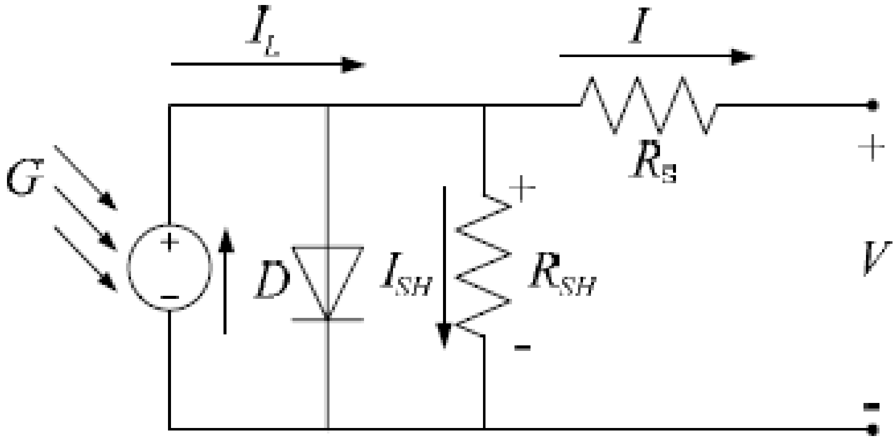

Figure 2.6 _ Model of Solar cell.

$$I = I_L - I_0\left(e^{\frac{q(V+RI)}{nKT}} - 1\right) \tag{2. 1}$$

The model included temperature dependence of the photocurrent I_L and the saturation current of the diode I_0.

c. Mathematical Modeling of PV Generator

For design and installing of PV generator performances under natural irradiation is a key issue to deal with the integration of PV power generation in microgrid and uncertainty. The per unit area PV power output from a PV generator (PV P) with a fixed orientation is represented by :[15]

$$P_{PV} = \eta_{PV}(t) \cdot A_{PV} \cdot I_r(t) \tag{2.2}$$

where, η_{PV} is the power conversion efficiency of the module (power output from the system divided by power input from the sun) ; A_{PV} (m^2), is the surface area of PV panels ; Ir (W/m^2), is the solar irradiations. The PV generator efficiency is given by:

$$\eta_{PV} = \eta_r.\eta_{pc}(1 - \beta(T_c - \text{NOCT})) \tag{2.3}$$

η_r is the reference module efficiency; it depends on the cell material. Polycrystalline silicon technology has been used with 13% efficiency. β is the generator efficiency temperature coefficient, ranging from 0.004 to $0.006/C$. T_C *is* the cell temperature ($^{\circ}C$). A PV module of polycrystalline silicon solar cells can be estimated from the ambient temperature $T(^{\circ}C)$ and the solar irradiation $\mathbf{I}_r$ as follows.

$$T_c = 30 + 0.017(I_r(t) - 300) + 1.14(T(t) - 25 \tag{2.4}$$

The photovoltaic output model can be expressed using the previous definition as

$$P_{PV} = \eta_{PV}(t) \cdot A_{PV} \cdot I_r(t)(1 - 0.0035(T(t) - 25)) \tag{2.5}$$

The output power of the photovoltaic generator can be expressed by another formulaas follow without the time.

$$P_{PV} = \eta.S.\Phi\big(1 - 0{,}0035(T_a - 25)\big) \tag{2.6}$$

where η ranging from 9% to 12% is the conversion efficiency of the PV array, S (= $4084m^2$) is the measured area of the PV array, Φ(= $1kW/m^2$) is the solar radiation, and T_a is the ambient temperature in degree Celsius. Among the factors which affectits power output, the intensity of solar radiation and the atmospheric temperature changes must be considered when the equation is applied for PV power forecasting. These variations of solar radiation and temperature vary with seasons and different weather types. The value of P_{PV} depends on T_a and Φ because η and S are constant. In this thesis, T_a is kept at $25^{\circ}C$ and P_{PV} *is* linearly varied with Φ only. Linear, small-signal models of the photovoltaic system and their converters are required to perform power system stability and eigenvalue analyses. For the frequency domain analysis,the PV system is presented by a first-order lag transfer function. The nature of solar power is fluctuating in nature, so to following the solar model [16] as shown in **Figure 2.5** has been taken to realize the effect of microgrid integration solar plant. The PV output power determined by the first-order transfer function (*TF)* model of PV by neglecting nonlinearities can be expressed as [17,18]

d. Wind speed model

The generated power of the WTG depends on wind speed V_W . The wind is modeled as the algebraic sum of base wind speed, gust wind speed, ramp wind speed, and noise wind speed. The associated equations for different wind-speed components are given next [20].

The base wind-speed component can be expressed by [20]

$$\mathrm{V_{WB}} = \mathrm{K_B} \tag{2.8}$$

where K_B is a constant and it is always assumed to be present in the study when the WTG is operating. The gust wind-speed component can be expressed by :

$$V_{WG} = \begin{cases} 0, & t < T_{1G} \\ V_{COS}, & T_{1G} < t < T_{1G} + T_G \\ 0, & T_{1G} + T_G < t \end{cases} \tag{2.9}$$

$$V_{cos} = \frac{MAXG}{2}\left[1 - \left[\cos 2\pi\left(\frac{t}{T_G}\right) - \left(\frac{T_{1G}}{T_G}\right)\right]\right] \tag{2.10}$$

T_G is the gust period, T_{1G} the gust starting time, and MAXG gust used in wind studies. the gust peak. The gust wind speed is the usual (1_{cosine}) The ramp wind-speed component can be expressed by :

$$\mathrm{V_{WR}} = \begin{cases} 0\,, & t < \mathrm{T_{1R}} \\ V_{\mathrm{ramp}}\,, & \mathrm{T_{1R}} < t < \mathrm{T_{2R}} \\ 0, & \mathrm{T_{2R}} < t \end{cases} \tag{2.11}$$

Where?

$$V_{ramp} = (MAXR)\frac{1-(t-T_{2R})}{T_{1R}-T_{2R}} \tag{2.22}$$

MAXR is the ramp maximum, T_{1R} the ramp start time, T_{2R} the ramp maximum time. The values of MAXR are, respectively, selected to be 3 and 7.5 when 200s < t < 201s and 250s < t < 251s during the simulations. The noise wind-speed component can be expressed by:

$$V_{wN} = 2\sum_{i=1}^{N}\sqrt{S_v(w_i)\Delta w}\,cos(w_i t + \varphi i) \tag{2.13}$$

probability density on the interval [0 − 2π], and where $w_1 = (i-1/2)\ \Delta w$, φi a random variable with uniform

$$S_v(w_i) = \frac{2k_N F^2 |w_i|}{\pi^2[1+(Fw_i/\mu\pi)^2]^{4/3}} \tag{2.14}$$

is the spectral density function, K_N (= 0.004) the surface drag coefficient, F(= 2000) the turbulence scale, and μ the mean wind speed at reference height of 7.5, 4.5 and 15m, respectively. Various studies use N = 50 and Δw = 0.5 − 2.0 rad/s to obtain excellent results. According to the aforementioned four wind-speed components, the employed wind-speed model is defined by :

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \tag{2.15}$$

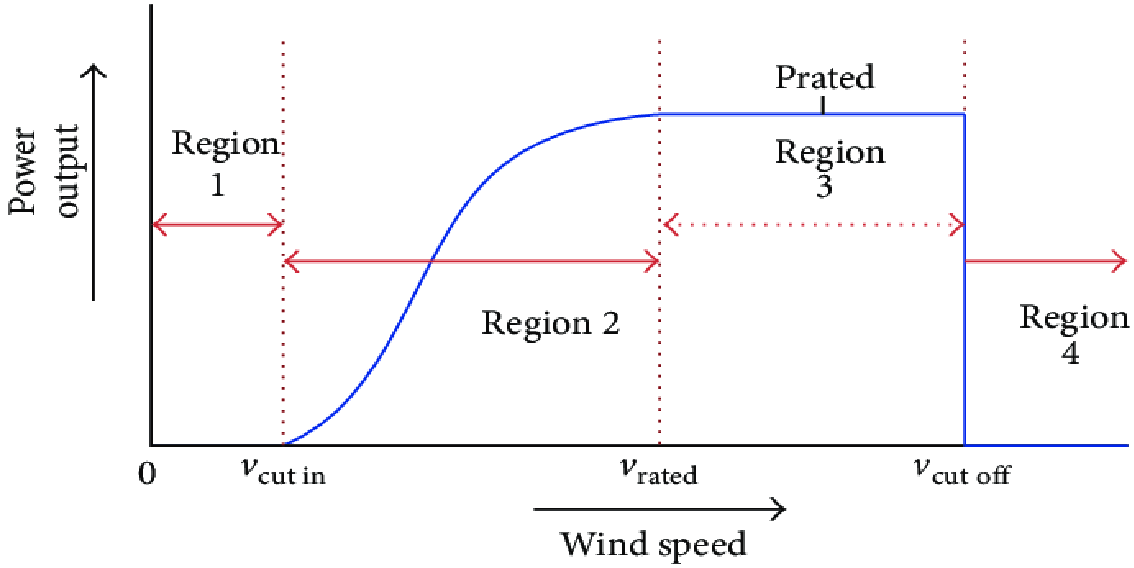

Figure 2.7 _The characteristic curve of output mechanical power versus wind speed of the studied WTGs.

e. Model Wind Turbine Generator ’s Output:

The turbine is composed of a directly coupled with a squirrel cage induction generator through a gearbox. The turbine rotor model provides the aerodynamic power extracted from the wind by the following equation due to uncertainty in wind speed, the output of WTG is highly fluctuating in nature. The output power of the wind turbine generators is dependent on wind speed. The mechanical power of the wind turbine was provided in **Eq 2.16** [21].

$$Pw = \frac{1}{2} \cdot \rho \cdot A_r \cdot C_P V_w^3 \tag{2.16}$$

Where ρ , Ar and CP represent air density, the effective surface area of the blades, and power coefficient respectively as a function of the tip speed ratio of a blade. ρ and Ar parameters in **Eq 2.16** were considered to be 1/25Kgm3 and 1735m2 respectively. The value of CP in **Eq 2.16** can be obtained by **Eq 2.17** [20]

$$\text{Cp}=(0.44-0.0167\beta).\left[\frac{\pi(\lambda-3)}{15-0{,}3\beta}\right] - 0{,}0184(\lambda-3)\beta \tag{2.17}$$

The value of λ in **Eq 2.18** can be obtained

$$\lambda = \frac{R_{blade} w_{blade}}{V_w} \tag{2.18}$$

The value of R_{blade} is the blade radius and w_{blade} is the blade rotational speed in **Eq 2.18** which were considered 23.5 m and 3.14 rads respectively. The comparison between the output power of wind turbine generators and wind speed has been illustrated in **Figure 2.7** This figure shows while wind speed was more than a certain limit, the output power will remain the same. In this study, when wind speed was more than 25m/s the system will fail because of the security of its initial tools. Also when wind speed was more than 15m/s output power of wind turbine generators was fixed at the peak. When wind speed was less than 4m/s, the output power of wind turbine generators was fixed to zero. generators was fixed to zero. The transfer function of wind turbine generators which was shown in **Figure 2.7** is stated in **Eq 2.19** [22]

2.4 Modeling of Conventional Sources

1. Diesel Generator

Diesel generators consist of a diesel engine that converts internal combustion or fuel energy into mechanical energy, and a synchronous generator (with a wound rotor) that converts this mechanical energy into electrical energy. The primary function of a diesel generator is to supply electrical energy with a sinusoidal wave of constant amplitude and frequency. To achieve this, they must adapt to the load, which acts as a disturbance to their operation, through various control loops. Diesel generators come in different sizes, ranging from a few KVA to several tens of MVA. Their electrical efficiency is around 35-40%, but this efficiency drops significantly if the load falls below 40%. Therefore, it is not advisable to operate them below this minimum load. Diesel generators are highly dynamic and well-suited for applications requiring sudden power demands. Additionally, they can seamlessly transition between island mode and parallel mode, making them suitable for microgrid applications. [29]

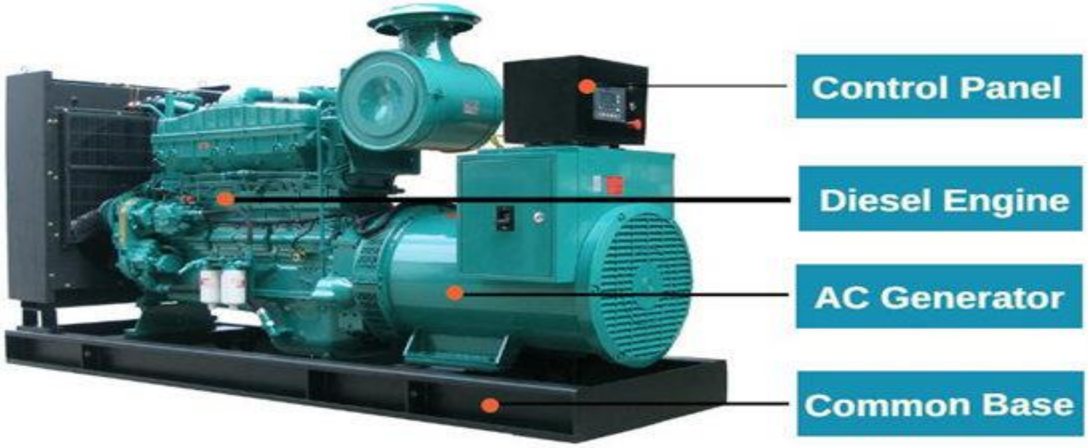

Figure 2.8 _structure of a diesel generator.

The diesel generator is made up of:

a) The Diesel Engine

The diesel engine is the mechanical power generator. The speed and torque are controlled by a speed regulator, which adjusts the fuel flow to regulate the active power supplied to the system.

b) The Alternator

The alternator is a synchronous machine (SM) that serves as the source of electrical energy. It is controlled by an excitation system that maintains a constant output voltage by adjusting the reactive power supplied to the grid. The provided reactive power is limited (cos φ = 0.8, according to the manufacturer’s specifications).

c) Modeling the Diesel Generator

A diesel generator results from the combination of a diesel thermal engine and an electric alternator, most commonly of the synchronous type. When used in hybrid solar PV systems, it generally serves as the master unit, with the PV inverter synchronizing to it. The modeling of a diesel generator focuses on two main characteristics: fuel consumption (hourly or specific) and the electrical parameters of the diesel generator (power, current, frequency, and voltage) [28].

Energy efficiency of a diesel generator is defined:

$$\eta = \frac{P_{GD}(i)}{H(i)} \tag{2.19}$$

PGD(i) : Power Produced by the Diesel Generator at Time i [kW]

H(i): Hourly Heat Consumption [kcal/h]

$$H = \frac{P_{GD}(i)}{q_{GD}(i)} \tag{2.20}$$

Q(i) DG: The fuel consumption of the diesel generator at time i [l/h].

To model the fuel consumption based on the electrical power demand.

2. Modeling of Fuel Cell System

A fuel cell is a static electrochemical device that converts chemical energy into electrical energy through an electrochemical reaction. Fuel cells utilize hydrogen as fuel and oxygen as the oxidant in the reaction, with by-products being water and heat. Due to the absence of moving parts, their efficiency is high when compared to conventional combustion engines [27].

In frequency analysis, the fuel cell is considered one of the suitable energy generation methods. Recently, fuel cells have been highlighted for their ability to maintain high efficiency in power generation systems while reducing greenhouse gas emissions. They offer many advantages such as higher efficiency, simple structure, and negligible emissions, making them suitable for distributed generation systems in microgrid applications [28]. Power is produced in a fuel cell through an electrochemical reaction between hydrogen and oxygen. The benefits of using fuel cells over conventional generators (like diesel generators) include the production of very pure, pollution-free energy. Typically, a fuel cell generates a very small voltage, insufficient for practical needs, so cells are arranged in series-parallel combinations to form a fuel cell stack. Hydrogen, which aids in power generation in fuel cells, is an expensive resource compared to other conventional energy sources. This is the only drawback of fuel cells. Generally, a fuel cell generator has a higher-order and nonlinear model. However, during low-frequency domain analysis, it can be considered as having a first-order lag model as given and implemented in the DGS model [29].

The Dynamic Generator System (DGS) model for a fuel cell can be simplified to a first-order equation to represent the dynamic behavior of the fuel cell at low frequencies. In this context, we assume that the general equation takes the following form:

$$V(t) = V_{OC} - R.I(t) - L\frac{dI(t)}{dt} \tag{2.21}$$

Where:

- V(t): The output voltage of the fuel cell at time t.
- V_{OC}: The open-circuit voltage of the fuel cell (voltage with no load).
- R: The internal resistance of the fuel cell.
- I(t): The current flowing through the fuel cell at time t.
- L: The equivalent inductance of the fuel cell.
- $\frac{dI(t)}{dt}$: The rate of change of current with respect to time.

2.5 Model of the Plug-in Hybrid Electric Vehicles (PHEV)

Figure 2.9 illustrates the PHEV aggregator's mathematical model for LFC studies. Due to their slow discharge rate, quick response time, and dispersed availability, PHEVs are a great energy storage alternative for LFC needs. The output power from the PHEV aggregator based on frequency deviation is as follows ($\Delta PPHEV$):

$$\Delta P_{PHEV} = \begin{cases} -\Delta P_{MAX}, U_C < -\Delta P_{MAX} \\ -\Delta P_{MAX}, U_C > -\Delta P_{MAX} \\ U_C \text{ , } | U_C | \leq \Delta P_{MAX} \end{cases} \tag{2.22}$$

The control signal (ΔUc) from the controller is used to determine whether the $\Delta PPHEV$ will be used for charging/discharging [69]. Where $Pmax$ is the maximum power available from an individual EV, KEV,i represents the participation gain of an individual EV. The battery's state of charge (SOC) determines the value of KEV,i and **Figure 2.9** depicts the KEV,i vs SOC of PHEV [70]. NEV denotes the number of electric vehicles, Rav denotes the droop characteristics of the PHEV aggregator and TEV, denotes the battery time constant.

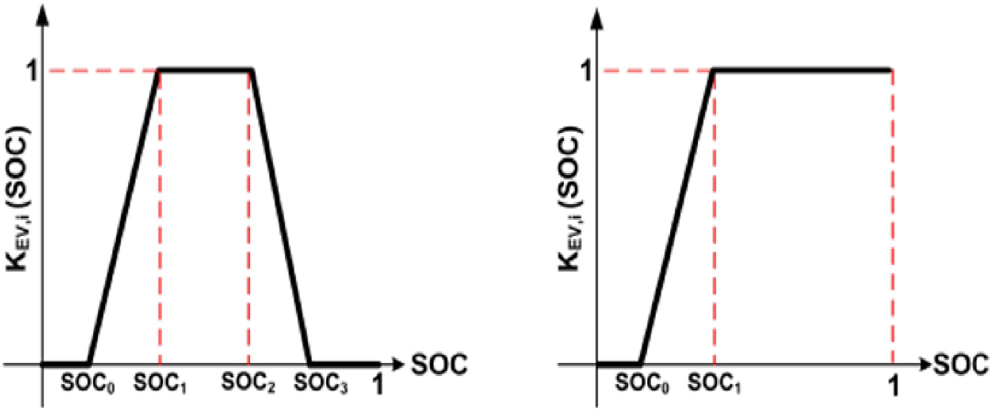

Figure 2.9 _Representing the charging and discharging PHEV.

2.6 Types of Energy Storage System

1. Battery Energy Storage System

BESS is widely applicable for various purposes in all sectors (generation, transmission, and distribution) of electrical power systems and thus provides benefits to consumers [42]. In [47] and [48], the comprehensive review of the storage system of different battery storage technologies, such as lead-acid, lithium-ion, redox flow, NaS, and nickel-cadmium battery has been investigated. The frequency of MG is anticipated to be controlled by BESS technology. A simple equivalent circuit of a battery is presented in **Figure 2.10** [39]. The operating point is the intersection of the source line. V_b is the terminal voltage drop, and V_L is the load line voltage.

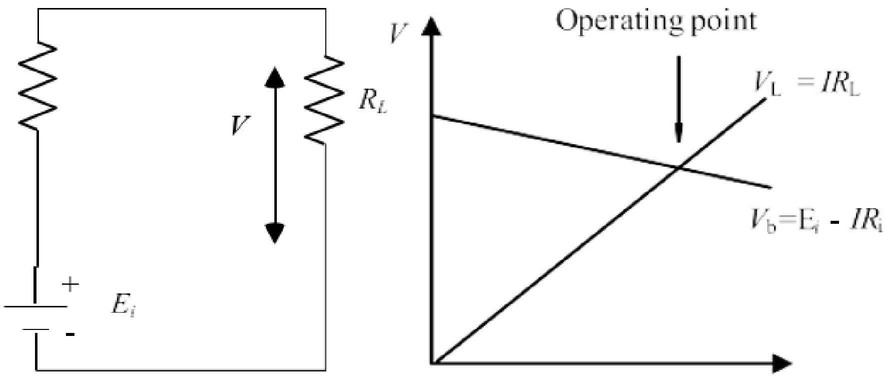

Figure 2.10 _Equivalent circuit of a battery and its operating point [39].

Figure 2.11 depicts the typical power profile of BESS for one day. The power curve above the horizontal axis (time) denotes the discharging characteristics of battery to regulate the frequency. Power below the time axis depicts the charging state of the cell to maintain the frequency within the reasonable range [49]. Battery capacity is an important determinant in selecting a storage device. The capacity of a battery may be defined as the total quantity of electrical charges that can be delivered.

in a single discharge by the cell. The state of charge (SoC) can be described as the ratio of remaining capacity.

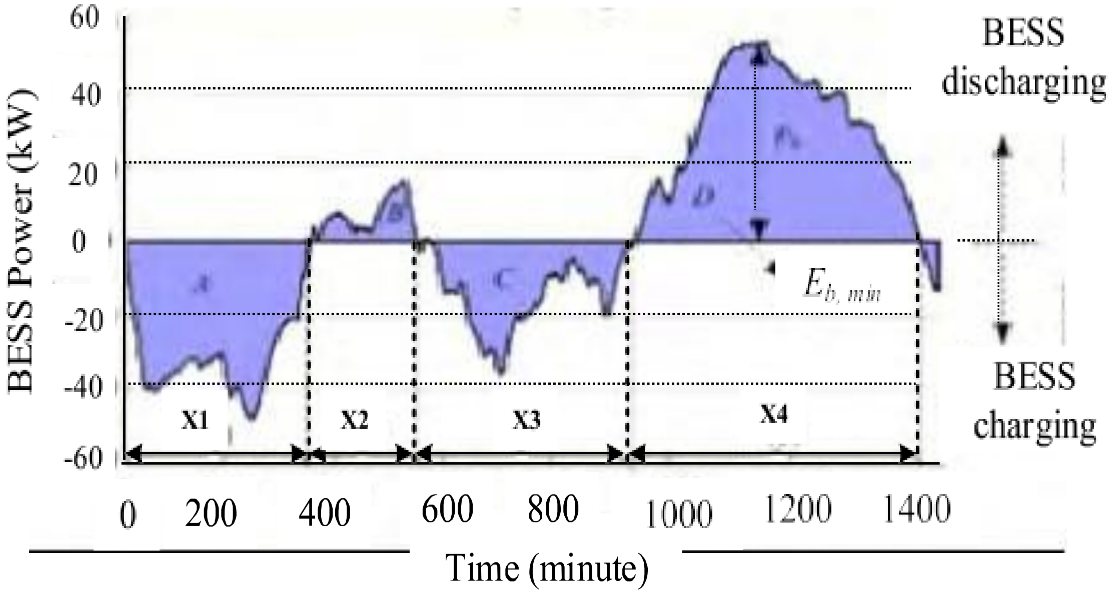

Figure 2.11 _Typical BESS power profile that considers one day [49].

to the nominal capacity. **Eq (2.23)** depicts the variation of SoC(dSoC) that depends on time and capacity C_i.

$$\mathrm{dSoC} = \frac{idt}{C_i} \; and \; \mathrm{dSoC} = \mathrm{SoC} - \int \frac{idt}{C_i} \tag{2.23}$$

Different studies reveal that a quasi Z-source inverter is a suitable technique for the parallel operation of the battery. In Reference [50], a quasi Z-source inverter for BESS has been proposed for the application in MG. In this model, the shoot-through duty cycle of the quasi Z-source inverter is applied to share the load current between the batteries operated in the islanded connection scheme. However, in the case of a grid-connected mode, to obtain the independent regulation of current in both battery systems, the proposed model depends on the inverter modulation index and the shoot-through duty cycle. The result of this study proved that microgrid voltage remains balanced in the unbalanced load conditions. Various battery technologies are illustrated in the next subsections.

a. Lead-Acid Storage System

Lead-acid (PbA) battery is the most widely used rechargeable storage with various sizes and designs in different applications [37], [41]. Among all electrolyte batteries, the PbA battery shows high efficiency (70%–80%) and possesses the highest cell voltage [37], [46]. The cathode and anode are made of PbO_2 and Pb, respectively. Sulfuric acid is used as the electrolyte. They are less expensive compared with other battery technologies, such as NiCd and NiMh, and are highly suitable for large-scale MG applications [40], [43]. Other advantages of this technology are that PbA battery provides excellent charge retention and energy density with fast response and long-life cycle (5–15 years) [35], [46]. However, traditional PbA battery has a short cycle-lifetime (500–2000 cycles), low specific energy, periodic water maintenance, and premature failure due to sulphation. To overcome the limitations mentioned, advanced PbA batteries have been developed, which possess nine times higher power handling capability and four to ten times increased life cycles [34], [37]. PbA batteries can be categorized into flooded, and valve regulated (VRLA) batteries. The latter has become increasingly popular due to its high specific power, relatively low installation and maintenance cost, and rapid charging characteristics [51]. VRLA includes the adsorbed glass material (AGM) and GEL. AGM batteries have compact volume and recombines hydrogen and oxygen to form the water in the charging mode; thus, water usage is limited [52]. However, GEL batteries need to have the controlled mechanism for charging. The main disadvantage of this GEL battery is that inside the GEL electrolyte, gas bubbles may be produced, which could damage the battery.

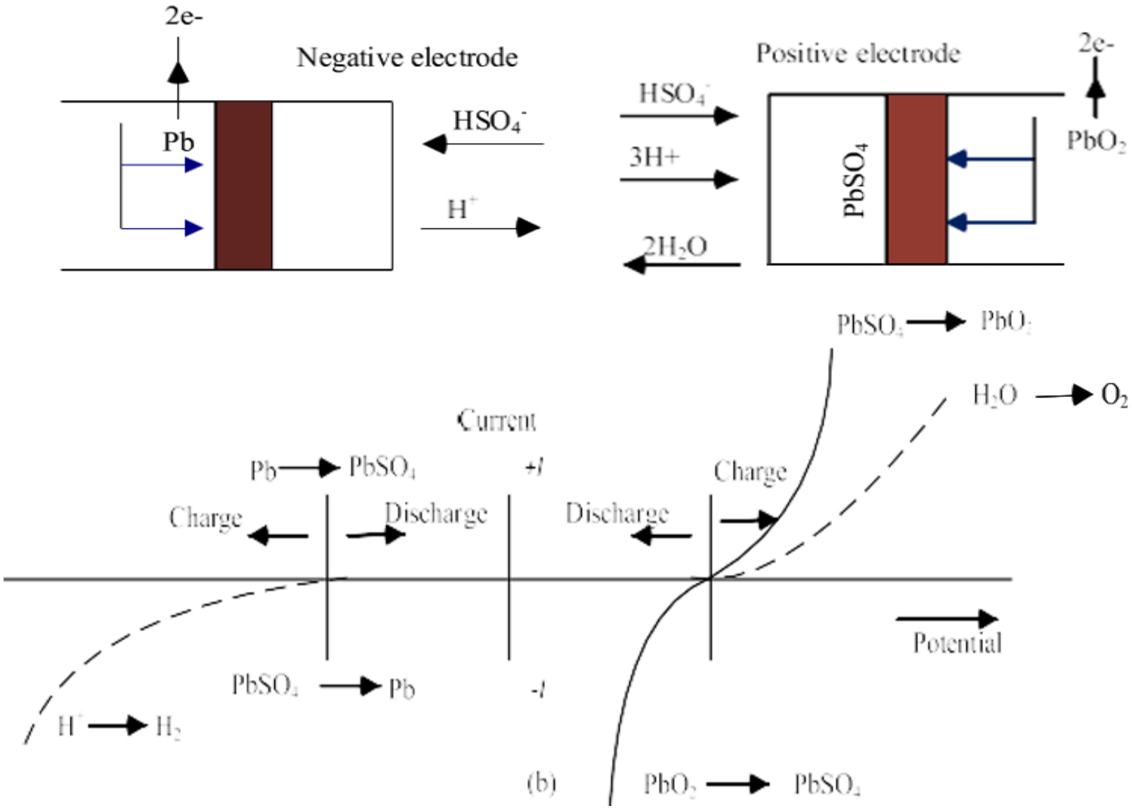

Figure 2.12_ (a) Charging and discharging operation of a lead-acid battery and (b) schematic representation of the current potential traits of both electrodes [56].

Figure 2.12 (a) describes the charging and discharging operation of lead-acid battery chemistry. During the discharge phenomena, $HSO^{-}{}_{4}$ ions pass through the negative electrode and form a chemical reaction with Pb to produce $PbSO_4$ and H^+ ions. During charging, $PbSO_4$ is converted to Pb or PbO_2. Hydrogen and oxygen are generated at the negative and positive electrode, respectively. **Figure 2.12 (b)** depicts the current potential characteristics of both electrodes. The overall electrochemical reactions that take place during charging and discharging in the PbA battery can be deduced as follows [53], [54]:

$$2PbSO_4 + 2H_2O \xrightarrow{\text{Charging}} PbO_2 + Pb + 2H^+ + 2HSO_4^- \quad (2.24)$$

$$PbO_2 + Pb + 2H^+ \xrightarrow{\text{Discharging}} 2PbSO_4 + 2H_2O \quad (2.25)$$

$$2H^+ + 2e^- \rightarrow H_2 \text{ (at negative Electrod)} \quad (2.26)$$

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- (\text{at positive Electrod}) \tag{2.27}$$

Overall, $$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.28}$$

b. Lithium-Ion (Li-Ion) Storage System

Although lithium-ion batteries were first commercialized in the 1990s, this energy storage technology has become the fastest growing technology in recent years [34], [55]. A Li-ion storage device can store energy at the megawatt scale. The significant advancement of this technology in increasing the levels of energy storage capacity is due to the characteristics of high efficiency (>90%), high energy density, rapid response time (in milliseconds), and attractive self-discharge rate (5% per mount) [44], [56]. A schematic of the Li-ion battery along with the charging and discharging method is presented in **Figure 2.13** [57], [58]. The cathode and anode are made from lithium metal oxide (L_iCoO_2) and graphite carbon cell, respectively. During the charging period, Li-ion passes from cathode to anode. The process is reversed in the case of the discharge period. The electrolyte used here can be formed using an organic solvent with dissolved lithium salt or solid polymer [36]. Complete electrochemical reaction that takes place during the operation of Li-ion battery can be written as follows:

$$\mathrm{LiMeO_2 + C \leftrightharpoons Li_{1-x}MeO_2 + Li_xC} \quad (2.32)$$

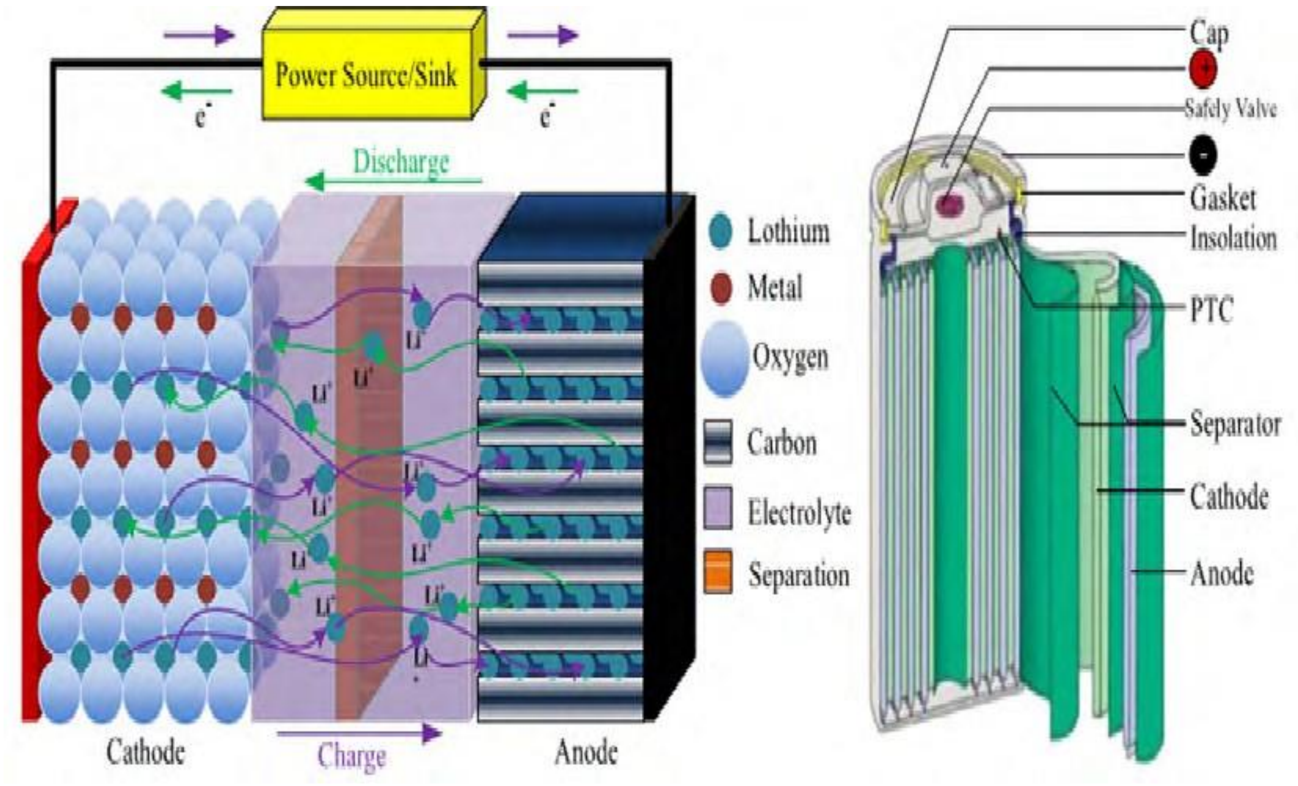

Figure 2.13_ Charging and discharging method of Li-ion battery and schematic of Li-ion battery [57], [58].

Figure 2.14 describes the typical charge profile for the medium power Li-ion battery. In [59], a medium-power Li-ion battery was examined for MG integration. The evaluation of the proposed method was considered in the following scenarios, such as black start operation, the rejection capability of positive and negative current disturbance during voltage regulation, and low voltage fault. The experimental result reveals that the proposed method exhibits an acceptable performance under typical MG scenarios. To prolong the battery life, the current level must maintain the range of maximum dynamic charge current and maximum dynamic discharge current. Moreover, the battery voltage should also maintain the range of maximum charge voltage and maximum discharge voltage. The disadvantages of the Li-ion battery are its cycle depth of discharge (DoD) and high cost. However, the cost of the Li-ion cell is expected to decrease with largescale production. **Table 2.1** illustrates the features of different energy storage devices and helps in the selection of Li-ion battery as an energy storage device given its improved performance [35].

Table 2.4_ Characteristics of electrochemical energy storage technologies in modern grids [35]

Technologies	**Name**	**Capacity (MWh)**	**Power (MW)**	**Response Time**	**Discharge Time**	**Life Time (Years)**	**Efficiency (%)**	**Advantage**	**Disadvantage**
Electrochemical	Lead-acid	0.25 – 50	≤ 100	millisecond	$\le 4h$	≤ 20	≤ 85	Highly Recyclable And Low-cost	Heavy poor energy density
	Lithium-ion	0.25 – 25	≤ 100		$\le 1h$	≤ 15	≤ 90	High Storage Capacity and long life cycle	
	NaS	≤ 300	≤ 50		$\le 6h$	≤ 15	≤ 80	High storage capacity and Low cost	Works only When Na and S are liquid (290-300°C)
	Vanadium Redox	≤ 250	≤ 50	≤ 10 min	$\le 8h$	≤ 10	≤ 80	Possible to use in various renewable sources	

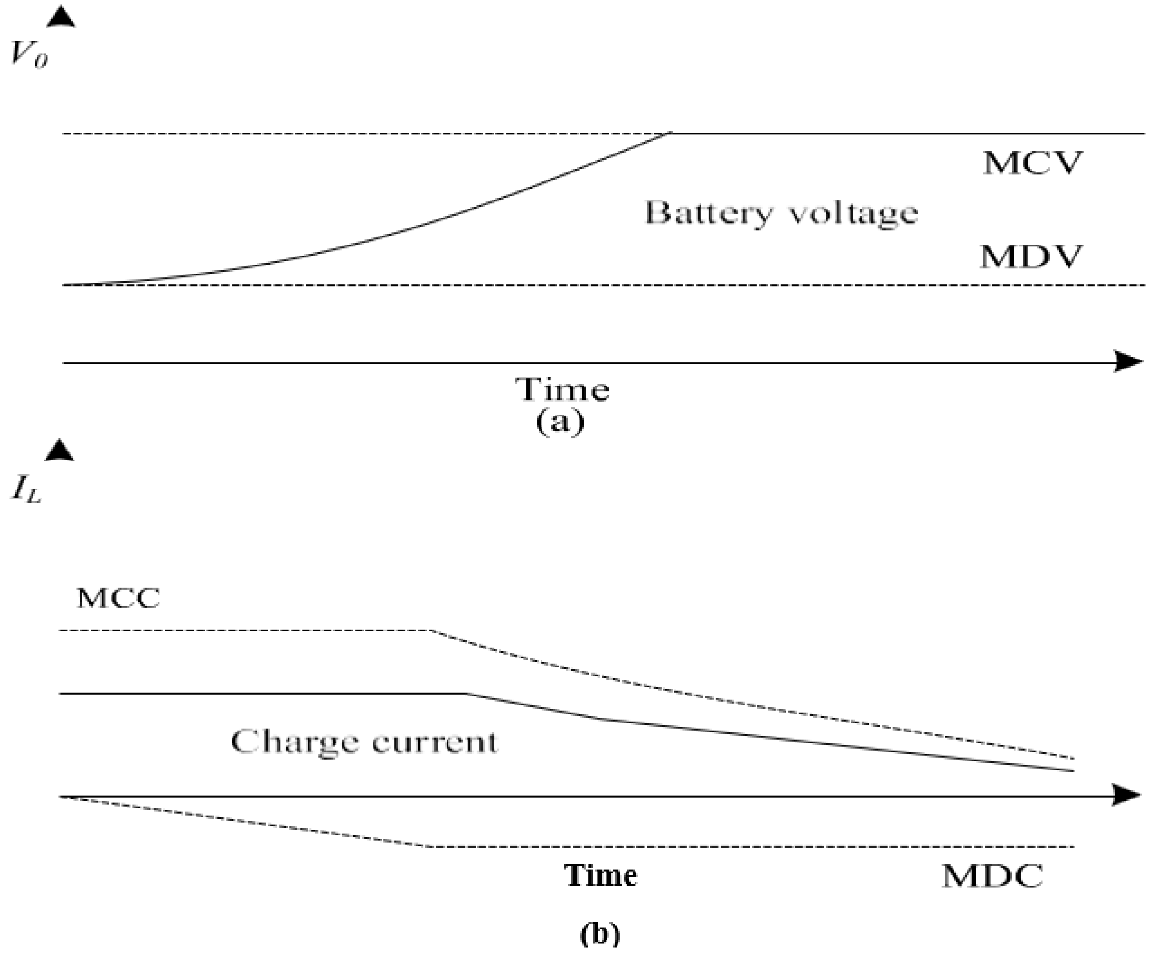

Figure 2.14_ Sketch of typical charging characteristics for medium-power Li-ion battery [59].

Li-ion batteries are designed for high-temperature applications. The design of batteries depends on new and improved chemistries (e.g., $LiFePO_4$ and $Li_4Ti_5O_{12}$). Thus, these batteries are characterized by high gravimetric and volumetric energy density (75–200 Wh/Kg and 200–500 Wh/L). It also shows improved efficiency (90%–95%), high power capability (nine times with respect to nominal power), extended lifetime (of approximately 20 years), prolonged cycle operation (8000 full cycles), and a wide temperature range (−20 ◦C to 55 ◦C [34], [37], [45]. Thus, this technology has become increasingly popular due to its small size, light weight, and potential. MGs are small power systems that operate independently from the distribution grid, and Li-ion batteries can be the best-suited storage technology for the islanded operation of MG [60]. Moreover, a concrete idea for a lithium-iron-phosphate ($LiFePO_4$) battery is discussed in [64]. However, Reference [62] proposed that a lithium-sulfur battery can be a good alternative due to its high specific energy, reliability, comparatively low cost, and reduced environmental hazard. Recently, Tesla has implemented the world's largest storage technology with Li-ion battery. The capacity of this Hornsdale wind plant is 100 MW. Thus, an advanced Li-ion battery can be developed by incorporating all these characteristics, which show acceptable performance with good efficiency, large storage facility, long calendar life, and low discharge rate.

c. Sodium-Sulfur (NaS) Storage System

NaS battery comprises of molten electrodes (both sodium and sulfur) and non-aqueous beta alumina electrolyte. Sodium is used as the negative electrode and sulfur is treated as the positive electrode. **Figure 2.15** shows the charge and discharge reactions of the NaS battery. During the discharging period, sodium (Na) is oxidized at the Na-beta interface to produce sodium ion Na^+ when passing through the electrolyte. This ion is combined with sulfur to form sodium polysulfide (Na2Sx). The ion is also observed to produce the desired output voltage. Electrons flow through the external circuit. Reverse mechanism occurs when the battery is recharged [34], [46], [57]. The overall electrochemical reaction in the NaS battery can be written as

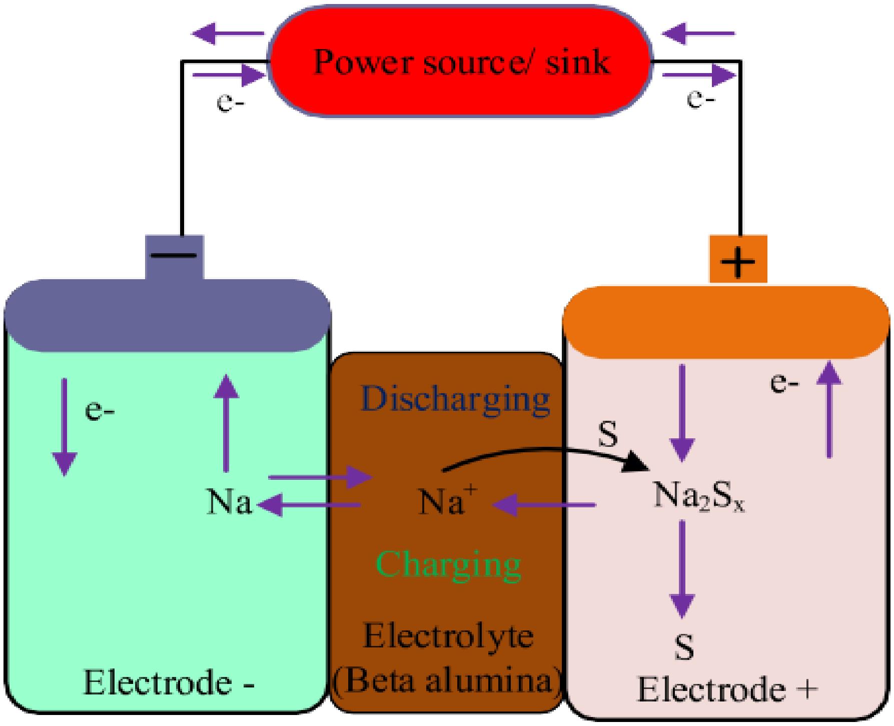

Figure 2.15_Charging and discharging phenomena of NaS battery [37], [63].

$$Na + xS = NaS_x \qquad (2.28)$$

where the value of x should be within 3–5.

This technology is widely applicable for load leveling, voltage sag minimization, and stabilizing renewable energy power generation [63]. However, as mentioned, this type of electrochemical energy storage device needs to operate at high temperature (350 ◦C/ 623 K) to maintain high reactivity and ensure that sodium and sulfur turn into liquid [33], [38]. This mechanism leads to difficulties in using the NaS battery in various applications given that the cost increases due to its implementation [43]. However, with the advancement of technologies since 1980 and applying the modular fabrication process, the energy density of this battery becomes much higher (four times from lead-acid battery), and cost becomes lower compared with other storage devices. Moreover, research is ongoing to control the limit of temperature and maintain high energy density, as presented in [64]. As a potential device to implement in MG, it shows high efficiency, a long cycle period up to 15 years, and fast response (in millisecond) during full charging and discharging operation. Thus, countries such as Japan and China are investing in large-scale industrial applications of this technology [65]. The application of NaS battery in some parts of the world is presented in **Table 2.2** [63], [66].

Table 2.5_ Application of selected NaS battery with energy storage facilities [63], [66].

Name of project	Power rating of plant	Particulars
Kawasaki EES Testing Facility, Japan	0.05 MW	First large-scale application of NaS battery
Long Island Bus's BES System, USA	1 MW/7 MW h	Refueling vehicles in a particular route
Rokkasho Wind Farm ES project, Japan	34 MW/ 244.8 MWh	Power fluctuation control
Saint Andre, La Reunion, France	1 MW	Wind energy storage
Graciosa Island Younicos, Germany	3 MW/18 MWh	Wind & solar energy storage
Abu Dhabi Island, UAE	40 MW	Load leveling

2. Flywheel Energy Storage System

A flywheel is a rotary system that allows the storage and return of kinetic energy. A mass fixed on an axis is set into rotation by the application of torque, increasing its rotational speed to store energy. Flywheel energy storage systems (FESS) are a type of mechanical battery that stores energy in the form of kinetic energy. The basic principle involves using a rotating flywheel to store and release energy. Here's an overview of the modeling aspects of a FESS:

a) Rotational Kinetic Energy

Kinetic energy is by definition the energy associated with the movement of a body. When it undergoes translation, the kinetic energy (K) depends on the translational inertia, which is the mass (m) multiplied by the square of the velocity (v).

$$K = \frac{1}{2} m v^2 \tag{2.29}$$

Given that:

- (k): Kinetic energy of translation, in joules (J) (kg × m^2/s^2).

- (m): Mass of the object, in kilograms (kg).

- (v): Velocity of the object, in meters per second (m/s).

b). Moment of Inertia

When a body rotates at a speed ω around an axis, the body is in motion and possesses kinetic energy. Since the entire body moves with a common angular velocity ω, we can define another form of kinetic energy based on the moment of inertia as follows:

$$K = \frac{1}{2} I \omega^2 \tag{2.30}$$

Where:

- (K): Kinetic energy of the rotating object, in joules (J).

- (I): Moment of inertia of the object rotating around an axis, in $Kg.m^2$

- (ω): Angular velocity, in radians per second (rad/s).

The rotational inertia (I) for this energy expression is not solely the mass (m) because the energy, measured in joules, is defined in newton meters (N×m). Many rotor forms have been explored, with almost all flywheels used being constructed as solid cylinders or hollow cylinders. For a solid disk or cylinder of radius (r), the moment of inertia is given by: [26].

$$I = \frac{1}{2} m r^2 \tag{2.31}$$

For a thin-walled hollow cylinder, where the mass is concentrated at the periphery, the moment of inertia is given by:

$$I = mr^2 \tag{2.32}$$

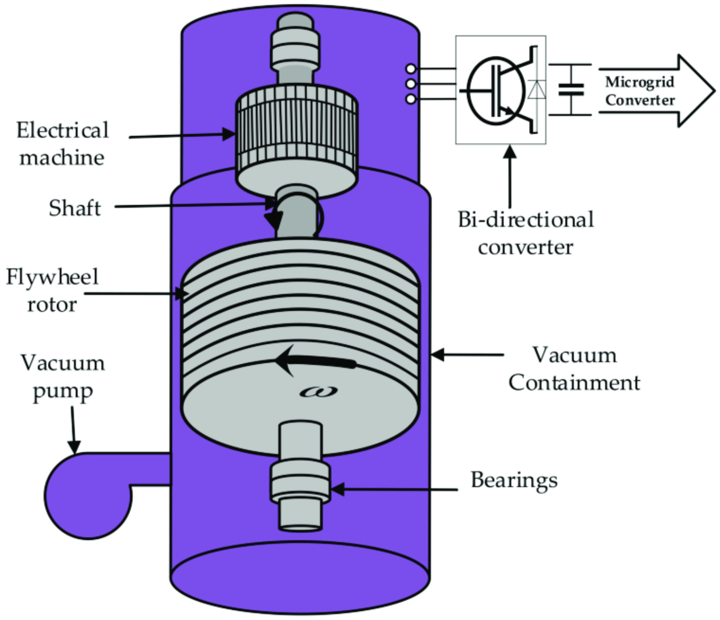

Figure 2.16 _FESS storage structure.

3. Ultra Capacitor:

Ultracapacitor is an electrochemical device which stores energy via electrostatic charges on opposite surfaces of the electric double layer which is formed between each of the electric and electrolyte. No chemical reaction takes place during [67] charging and discharging even though it is electrochemical device UC construction is same as that of battery having to non reactive porous electrodes immersed in an electrolyte solution separated by an electronic barrier such as a glass paper. Electrodes are fabricated from porous carbon material (activated carbon fiber material) deposited on metal foils having a pores in the nanometer range and very high surface area (1000-2000 cm2 /gm) the properties of the double layer capacitor strongly depends on how porous carbon activated material is and how small the electrolyte ions are. Activated carbon electrodes used in ultracapacitor have a large specific surface area and charge separation distance is in the order of 10 Armstrong or less. This allows ultracapacitor to store large amount of energy [67] **Figure 2.17** shows schematic of Ultracapacitors with module and cell.

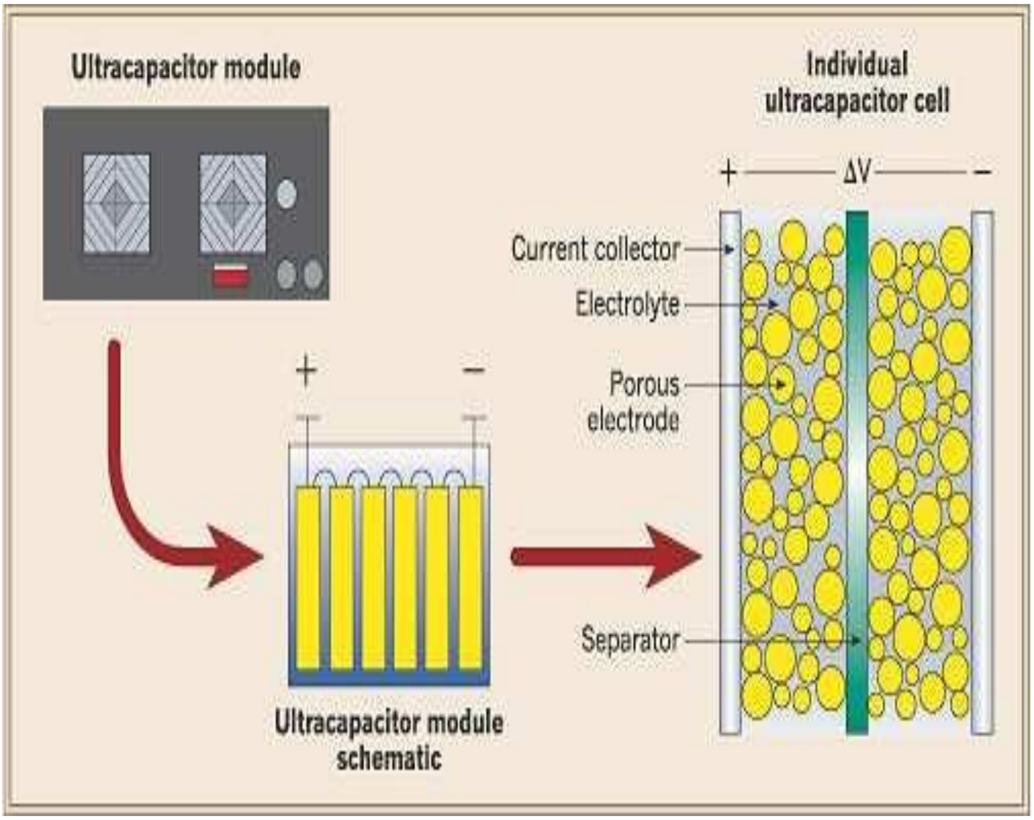

Figure 2.17_ Schematic of ultracapacitors.

During charging the positive and negative ions of electrolyte are drawn to electrodes of opposite polarity where they accumulate into layers inside the activated carbon pores. The penetration of electrolyte ions is governed by pore size of activated carbon. The double layer phenomenon is strongly determined by the activated carbon pore size and electrolyte positive and negative ions diameter. Electrolyte ions diameters are of the order of 1 nano meter. If the average pore diameter is 3 nanometer good capacitance value exists for both organic and aqueous electrolytes when it is less than or equal to 2 nanometer, good capacitance value exist for only aqueous electrolyte and if it is below 1 nano meter no double layer capacitance exists. The specific capacitance for ultracapacitor for aqueous electrolytes is in the range of 75 -175 F/gm and for organic electrolyte 40-100 F/gm. This is because of larger size of ions in organic electrolyte. If larger the ion size less penetration of ions into pores of activated carbon. The cell voltage of the ultracapacitor is dependent on electrolyte used and the maximum voltage is limited by the insulating ability of the electrolytes. For aqueous electrolyte the cell voltage is about 1 V and for the organic electrolyte the same voltage is about 3- 3.5 V. UC offered some resistance, as conductivity of organic electrolyte is low it has higher ESR then aqueous electrolytes. As charging and the discharging of the ultracapacitor do not involve any chemical reaction they can be cycled with almost no deterioration. UC can withstand more than 1 million charge and discharge cycle. As the capacitance offered by UC is very high, energy density UC is also very high (10 times) compared to conventional capacitor and the power density is very high (10 times) compared to battery. A comparison of conventional storage technologies is shown in **Table 2.3**.

Table 2.6_A comparison of conventional storage technologies [68].

Available Performance	**Lead Acid Battery**	**UC**	**Electrolytic Capacitor**
Charge Time	1 to 5 hrs	0.3 to 30 s	10-3 to 10-6s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10-3 to 10-6s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1,000	>500,000	> 500,000
Specific Power (W/kg)	<1000	<10,000	> 100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	> 0.95

To compare relative matrices of UC energy storage technology against batteries and others, it is to place them on a Ragone plot. The plot is between Wh/kg against the W/kg and it shows that how energy density decreases for increase in the power density. They are good means of qualifying an energy storage system and to size the storage system for variety of applications. Extracting energy from an UC is more demanding on the inverter (static power converter) than in the case of a battery system. This is because the DC voltage input into the inverter will vary over a much larger range than it will with a battery. With a lead-acid battery, voltage decreases about 20% between full-charge state and essentially 100% discharged state. In an UC, extracting 75% of the energy requires a 50% decrease in the capacitor voltage.

4. Ultra capacitor system Model

The ultra-capacitor system is made up of two conducting electrodes, an aqueous electrolyte solution, and a porous membrane separator [31]. This structure is responsible for imparting characteristics of both conventional capacitors and electrochemical based battery to the ultra-capacitor. Long cycle duration, reaching approximately 105 cycles with a high efficiency ranging between 84 and 97%, are some of its features. The major drawback associated with this storage technology is the high capital cost and high discharge rate varying from 5 to 40% [32]. This technology is suited for applications that require high bursts of power for the short term. Large-scale power systems do not prefer employing this technology. Recent developments and active research in this field have vastly improved this technology [31].

$$\Delta P_{UC} = (1 - e^{-\frac{t}{T_{UC}}}) \tag{2.33}$$

5. The water Electrolyzer

The water electrolyzer is a system that uses electricity to produce hydrogen from water. It typically consists of an electrolysis cell containing two electrodes enveloped in an electrolyte membrane. When an electric current passes through the cell, hydrogen and oxygen ions form on the surface of the electrodes, producing hydrogen at one electrode and oxygen at the other. This process can be used to produce hydrogen for various applications, including energy production, reducing dependence on fossil fuels, and producing advanced materials. A water electrolyzer system generates electrical energy by using an electric current to separate water into hydrogen and oxygen. When electricity passes through the electrodes of the electrolyzer, water molecules are split into hydrogen ions and oxygen ions. The hydrogen and oxygen ions are then collected at separate electrodes to form pure gaseous hydrogen and oxygen, respectively. This gas can be stored and later used as a renewable energy source for electricity production.

There are several mathematical equations related to water electrolyzer technology. Here are some of the most commonly used equations:

a. Faraday's Law

This equation describes the quantity of electrons transferred during an electrolysis reaction. This equation can be expressed as follows:

$$\mathrm{Q} = \mathrm{NF} \tag{2.34}$$

Where.

Q is the electric charge in coulombs, N is the number of electrolyte molecules, and F is the Faraday constant.

b. Nernst Equation

This equation describes the voltage necessary to drive an electrolytic reaction forward at a given rate. The Nernst equation can be expressed as follows:

$$E = E° - \frac{RT}{nF} Ln(a) \tag{2.35}$$

Where

E is the actual voltage, E° is the standard voltage, R is the ideal gas constant, T is the temperature in Kelvin, n is the number of electric charges transferred, F is the Faraday constant, and a is the activity of the ion in solution. [26].

c. Charge Balance Equation

This equation describes the equilibrium of charges at the electrode surface. It can be expressed as follows:

$$\Delta G = Z.F.n.i \tag{2.36}$$

Where

Z is the number of electric charges, F is the Faraday constant, n is the number of moles of particles, i is the current in Amperes, and ΔG is the change in free energy. These equations are very useful for understanding and optimizing electrolytic reactions in water electrolysis systems. [27]

d. The water Electrolyzer Model

The water electrolyzer helps to decrease the rapid fluctuations in the microgrid system. It receives a part of the surplus power generated by wind and solar thermal systems to generate hydrogen based on the oxide reduction by the electrolyte. The generated hydrogen is used by the fuel cell as a foil.

To solve this problem, we use an The water electrolyzer that produces hydrogen. Hydrogen is produced in The water electrolyzer by the method of electrolysis of water for which electric current is obtained from the power system. The transfer function model of The water electrolyzer is presented by the function shown bellow [30].

$$G_{AE}(s) = \frac{\Delta P_{AE}}{P_{WTG}(1-K_n)} \; OR \; \frac{\Delta P_{PV}}{P_{WTG}(1-K_n)} \tag{2.37}$$

2.7 Conclusion

In this chapter, we delved into the critical aspects required to develop a comprehensive and accurate model of a microgrid system, reflecting a high level of understanding in this advanced field. This modeling serves as a foundation for ensuring the stability and optimal performance of the microgrid under various operating conditions. We began by establishing the fundamental principles for modeling and controlling the microgrid, focusing on control techniques that ensure the stability and efficiency of the grid. We then moved on to modeling renewable energy sources, starting with the photovoltaic (PV) system. We detailed the modeling of solar cells, their electrical characteristics, and the conversion of sunlight into electrical energy. The mathematical models of PV generators included precise analyses to predict the system's output under varying environmental conditions. Regarding the wind energy system, we conducted a comprehensive study of wind turbine generators, including structural and functional analyses. The wind speed models we developed are crucial for turbine performance, and we created accurate models to estimate electrical output based on wind speed and multiple parameters. The modeling also covered conventional energy sources such as diesel engine generators and fuel cell systems, elucidating their roles in the microgrid configuration with detailed analyses of their operational efficiency and output characteristics. We addressed models of plug-in hybrid electric vehicles (PHEVs), providing accurate models of charging and discharging patterns and their impact on the microgrid, adding a new dimension to our understanding of the interaction between different energy sources in the system. Additionally, we included models for battery energy storage, discussing various types of batteries such as lithium-ion and lead-acid batteries, emphasizing the importance of storage in enhancing grid stability and performance. Finally, we addressed the frequency deviation model to ensure grid balance by maintaining frequency within acceptable limits, contributing to overall system stability. In the upcoming chapter, we will simulate the frequency and sources of the islanded microgrid, which is the core of our research. We will employ both Type-1 and Type-2 fuzzy logic to develop a precise and efficient control model, thereby deepening our understanding and improving the performance of microgrids under isolated operating conditions, offering advanced insights into renewable energy and smart grid systems.

Chapter 3

Improving the Performance of Microgrid Systems Using Classic Fuzzy Logic Controller and Type-2 Fuzzy Logic

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3.1 Introduction

The concept of an islanded microgrid represents a groundbreaking innovation in the field of electrical power systems, aiming to achieve autonomy and integration in energy provision through diverse and multiple sources. This comprehensive study, in its final chapter, delves into a range of critical topics associated with this system, from understanding the concept and functioning of the islanded microgrid to analyzing and enhancing performance using advanced artificial intelligence techniques such as Type-1 and Type-2 fuzzy logic.

In this chapter, we provide a detailed examination of the transfer function and diagrams for each energy source used in the islanded microgrid, including photovoltaic (PV) systems, wind energy, plug-in hybrid electric vehicles (PHEV), and diesel generators. These sources are analyzed using various graphical methods, such as the ΔL graph, to understand their dynamic impacts on the system. Furthermore, we explore intelligent control techniques, starting from the application of classical fuzzy logic to the implementation of Type-2 fuzzy logic. The advantages and disadvantages of each type are discussed, focusing on their effectiveness in improving the performance of the islanded microgrid. We present simulation results for both classical fuzzy logic and Type-2 fuzzy logic, along with a comprehensive comparison between the two sets of results to provide a deeper understanding of the best practices in this field. This chapter also includes an in-depth discussion of the results and practical implications of these techniques in enhancing the stability and efficiency of the islanded microgrid. Such insights are crucial for researchers and engineers aiming to design and implement advanced and efficient energy systems in the future. The study not only offers theoretical solutions but also aims to provide practical insights that can be applied to develop smarter and more sustainable energy systems, making it a valuable contribution to the field of renewable and intelligent energy systems research.

3.2 Concept of islanded Microgrid

An islanded microgrid represents a self-sufficient power distribution system that operates independently from the main electrical grid. This independence is achieved through a strategic combination of renewable energy sources, energy storage systems, and backup generators. Such systems are designed to ensure a reliable and flexible power supply, enhancing energy security and resilience, particularly in scenarios where the main grid might be unavailable or unreliable [9]. The microgrid selected for this study, illustrated in **Figure 3.1**, integrates multiple components to achieve this goal. The primary renewable energy sources include photovoltaic (PV) systems and wind turbines. PV systems harness solar energy, converting sunlight directly into electricity through solar panels. Wind turbines, on the other hand, capture wind energy, transforming kinetic energy from wind into electrical power. These renewable sources are critical for reducing dependency on fossil fuels and lowering the carbon footprint of the energy supply [10]. Energy storage is another crucial element of the microgrid. In our study, we utilize Plug-in Hybrid Electric Vehicles (PHEVs) as energy storage units. PHEVs can store excess energy produced by the PV and wind systems during periods of high generation. This stored energy can then be deployed during times when production from renewable sources is low, such as during the night for PV systems or during calm weather for wind turbines. By effectively managing energy storage, the microgrid can maintain a consistent power supply despite fluctuations in renewable energy generation [11]. To further enhance the reliability of the microgrid, we incorporate a diesel generator as a backup power source. The diesel generator acts as a contingency measure, providing electricity when both PV and wind systems are unable to meet the demand. This ensures that the microgrid can deliver uninterrupted power, even under adverse conditions or during prolonged periods of low renewable energy production [12]. Combining these diverse elements—PV systems, wind turbines, PHEVs, and diesel generators—results in a robust and adaptable power supply network. The islanded microgrid can support various applications, from providing electricity to remote communities and critical infrastructure to serving businesses and residential areas. Its ability to operate independently from the main grid makes it an attractive solution for enhancing energy independence and resilience. Moreover, the integration of renewable energy sources within the microgrid promotes environmental sustainability. By leveraging solar and wind energy, the microgrid reduces greenhouse gas emissions and contributes to the global effort to combat climate change. Additionally, the use of energy storage systems like PHEVs not only supports energy management but also represents a step towards more innovative and efficient use of existing resources [13].

In summary, an islanded microgrid is a sophisticated energy solution that offers a reliable, flexible, and sustainable power supply. By integrating renewable energy sources, energy storage, and backup generators, it can provide uninterrupted electricity even in the absence of a main grid connection. This capability is particularly valuable for enhancing energy security, promoting sustainability, and increasing the resilience of power systems in various applications.

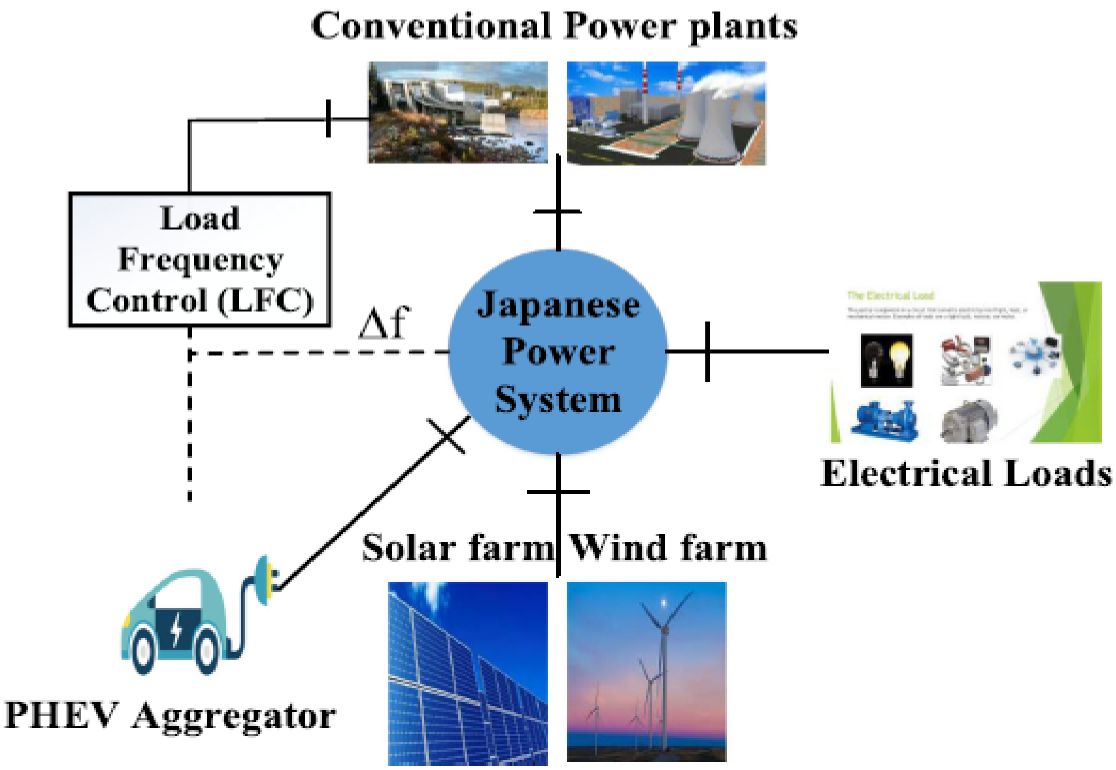


Figure 14_Configuration of the Islanded Microgrid with Integrated sources.

3.3 Functioning of an Islanded Microgrid

The microgrid chosen for our study is designed to optimize energy utilization by selectively harnessing either solar (PV) or wind power, rather than utilizing both sources simultaneously. This approach involves a strategic comparison of the energy outputs generated by PV and wind sources. We evaluate which source provides the greater energy yield at any given time and prioritize its integration into the microgrid system, Once the source with the higher energy output is determined, it is seamlessly integrated with the battery storage system. In our study, we employed a Plug-in Hybrid Electric Vehicle (PHEV) as a representation of battery storage. This allows us to store excess energy generated during peak production periods for later use when energy production from renewable sources is lower; However, in the event of a failure or insufficient energy storage capacity of the PHEV, a contingency plan is in place. The diesel generator serves as a backup power source, ensuring continuous and reliable power supply to meet the demands of the microgrid. This dynamic approach to energy management enhances the efficiency and reliability of the microgrid system, ensuring uninterrupted power supply even under varying conditions and contingencies.

3.4 Modeling and Diagram of each source

In this section, we will present diagrams for each energy source within the islanded microgrid system, aiding in understanding the performance of each source individually and analyzing its impact on overall energy production:

a. PV Model:

Photovoltaic solar modules capture solar energy and convert it into direct current. This phenomenon is based on the behavior of semiconductor materials when exposed to solar radiation. The generated power varies with solar radiation and ambient temperature. To analyze frequency deviation behavior in the frequency domain, it can be modeled with a first-order transfer function as follows:

$$G_{STPG}(s) = \frac{\Delta P_{STPG}}{\Delta P_{SOL}} = \frac{K_S.K_T}{(1+s\cdot T_S).(1+s\cdot T_T)} \tag{3.1}$$

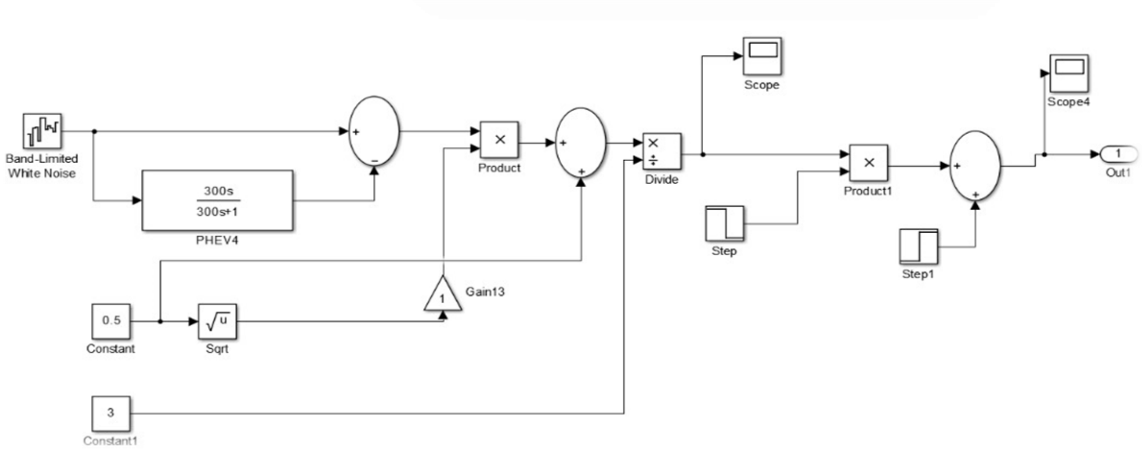


Figure 15_ Mathematical model for PV.

b. Wind Model

Wind turbines harness kinetic energy from wind and convert it into mechanical energy, which is then transformed into electrical energy through a generator. The power output of a wind turbine is influenced by factors such as wind speed, air density, and turbine characteristics. To model the behavior of wind turbines in frequency deviation analysis, a similar approach can be used, where their power output variation with wind speed and other relevant parameters is represented by appropriate mathematical functions or models **Figure 3.3**

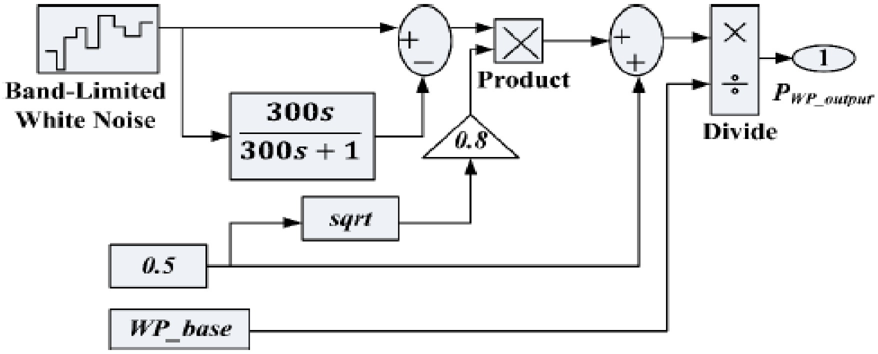


Figure 16_ Mathematical model for wind output power with random wind velocity pattern.

c. PHEV Model

Plug-in Hybrid Electric Vehicles (PHEVs) combine an internal combustion engine with an electric motor and a rechargeable battery. They can operate in all-electric mode, using only the electric motor and battery, or in hybrid mode, where the internal combustion engine supplements the electric motor when needed, to model the behavior of a PHEV in frequency deviation analysis, its power contribution to the microgrid can be represented by a dynamic model that considers factors such as battery state of charge, driving mode (electric or hybrid), and charging/discharging rates. This model would account for the fluctuating power output of the PHEV as it switches between different operating modes and adjusts its power flow based on driving conditions and battery status **Figure 3.4.**

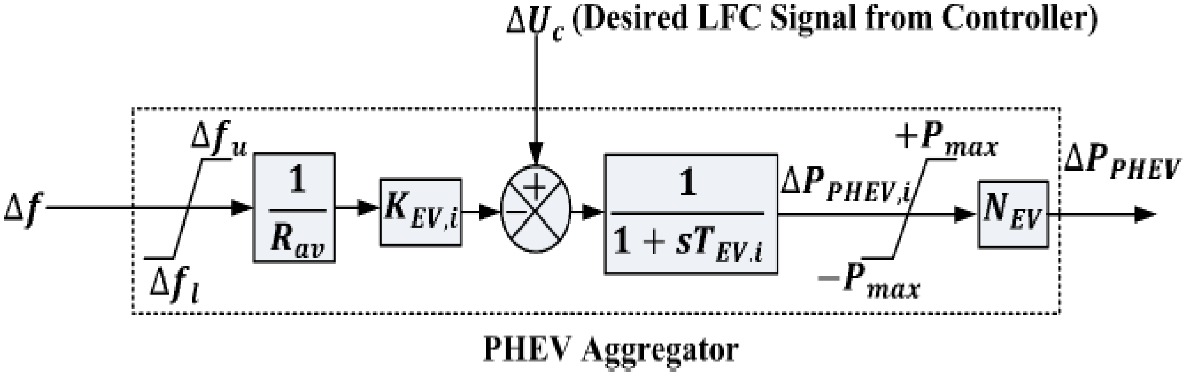


Figure 17_PHEV Aggregator Model for Frequency Control Studies.

d. Diesel Generator Model

The diesel generator is a commonly utilized conventional energy source for generating electricity, serving as an emergency solution to address power shortages within the hybrid energy system. It operates independently to maintain a balance between electricity generation from wind and solar systems and the load demand. The diesel generator's functionality can be described using a straightforward first-order transfer function (3.2).

$$G_{DED}(s) = \frac{\Delta P_{DEG}}{\Delta u} = \frac{K_{DEG}}{1+S.T_{DEG}} \tag{3.2}$$

e. Graphic of ΔL model

Load variation, represented by ΔL, is a critical factor in the stability and reliability of an islanded microgrid. ΔL reflects external influences and fluctuations in power demand that the microgrid must manage. A dynamic model can be developed to simulate the behavior of ΔL within the grid, allowing for an understanding of the impacts of external load changes and the development of strategies to improve grid performance. This dynamic model takes into account various factors such as sudden changes in power demand and grid conditions. It can identify the effects of these variations on grid stability and reliability, aiding in the development of strategies to address challenges related to load variations. By using the dynamic model for ΔL, we can identify the best ways to manage load variations and ensure the stability of the microgrid in the face of these challenges. **Figure 5** serves as an example representing the dynamic model for ΔL, illustrating how to analyze the effects of load variations on the microgrid.

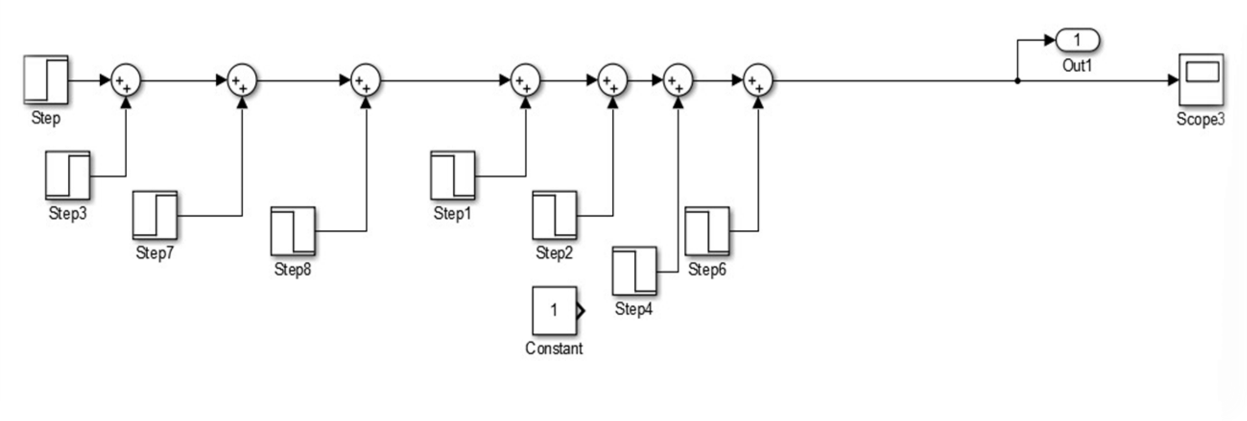


Figure 18_ Graphic of ΔL Model.

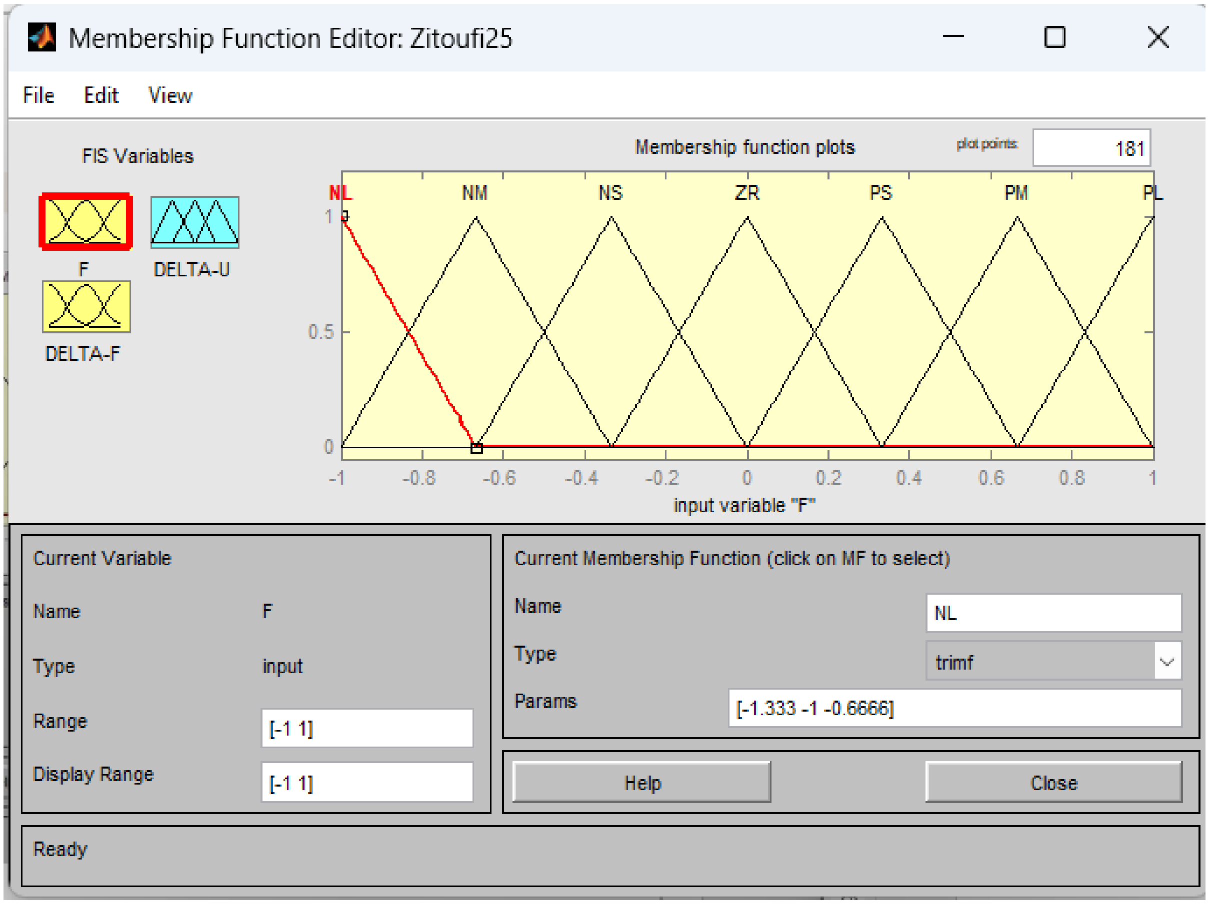
3.5 Classic Fuzzy Logic

Fuzzy systems are knowledge based or rule-based systems. The heart of a fuzzy system is a knowledge base consisting of the so- called If-Then rules. A fuzzy If-Then statement in which some words are characterized by continuous membership functions. After defining the fuzzy sets and assigning their membership functions, rules must be written to describe the action to be taken for each combination of control variables. These rules will relate the input variables to the output

variable using If-Then statements which allow decisions to be made. The If (condition) is an antecedent to the Then (conclusion) of each rule. Each rule in general can be represented in the following manner:
If (antecedent) Then (consequence) [15].

- Fuzzification:

The success of this work, and similar projects relies on how well this stage is executed. In this stage, the crisp variables eω(k) and deω(k) are converted into fuzzy variables eω and deω respectively. The membership functions associated with the control variables are chosen to have triangular shapes, as shown in **Figure 3.6**. The range of all input and output variables is established, and appropriate scaling factors are selected to map the input and output variables into this range. Each range is divided into seven overlapping fuzzy sets:
NL (Negative Large), NM (Negative Medium), SN (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PL (Positive Large).
Each fuzzy variable is a member of these subsets with a membership degree μ ranging from 0 (non-member) to 1 (full-member). All membership functions are asymmetrical with greater density near the origin (steady state), allowing for higher precision in the steady state. [14]



Current Variable
Name F
Type input
Range [-1 1]
Display Range [-1 1]

Current Membership Function (click on MF to select)
Name NL
Type trimf
Params [-1.333 -1 -0.6666]

Ready

Figure 19_Triangular Membership Functions for Control Variables.

- Inference Engine:

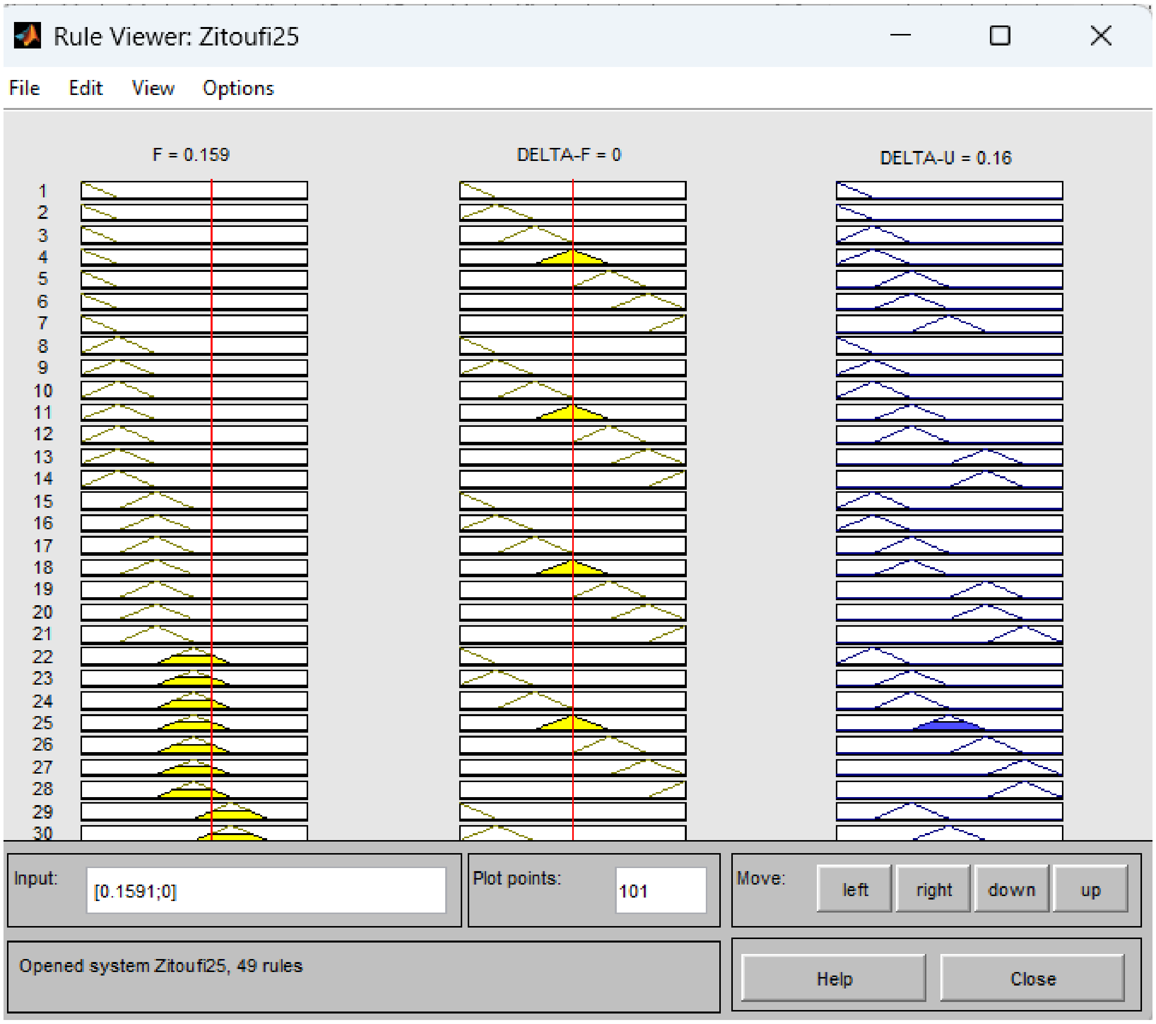
The knowledge base involves defining rules represented as IF-THEN statements that govern the relationship between input and output variables using membership functions. In this stage, the variables F and ΔF are processed by an inference engine that executes 49 rules (7×7), as shown in **Table 3.1**. These rules are established based on the system behavior and the experience of control engineers. Each rule is expressed in the following manner: for example, "If (F is Negative Large) and (ΔF is Positive Large), then (output variable is Zero)." Various inference engines can be used to generate the fuzzy set values for the output fuzzy variables. In this paper, the max-product inference method is utilized [14].

Table 3.7_ Rules Base

ΔF/F	**NL**	**NM**	**NS**	**ZR**	**PS**	**PM**	**PL**
NL	NL	NL	NM	NM	NS	ZR	ZR
NM	NL	NM	NM	NS	ZR	PS	PS
NS	NM	NM	NS	NS	PS	PS	PM
ZR	NM	NS	NS	ZR	PS	PM	PM
PS	NS	NS	PS	PS	PM	PM	PL
PM	NS	PS	PS	PM	PM	PL	PL
PL	ZR	PS	PM	PM	PL	PL	PL

- Rule base:

A decision-making logic that simulates a human decision process and infers fuzzy control actions from the knowledge of control rules and linguistic variable definitions. The rules are in an "If-Then" format, where the "If" side is called the conditions and the "Then" side is called the conclusion. The computer executes these rules and computes a control signal based on the measured inputs **F** (frequency) and **ΔF** (change in frequency). In a rule-based controller, the control strategy is stored in a more or less natural language. A rule-based controller is easy to understand and maintain for a non-specialist end user, and an equivalent controller could be implemented using conventional techniques [15].



F = 0.159

DELTA-F = 0

DELTA-U = 0.16

Input: [0.1591;0]

Plot points: 101

Opened system Zitoufi25, 49 rules

Figure 20_Rule Base Representation: Relationship between Variables and Fuzzy Control.

- Defuzzification:

The reverse process of Fuzzification is known as Defuzzification. Employing a Fuzzy Logic Controller (FLC) yields the desired output in linguistic variables, represented as fuzzy numbers. To meet real-world demands, these linguistic variables must be converted into crisp outputs.

In order to define fuzzy membership function, designers choose many different shapes based on their preference and experience. There are generally four types of membership functions used:

1. Trapezoidal MF
2. Triangular MF
3. Gaussian MF
4. Generalized bell MF.

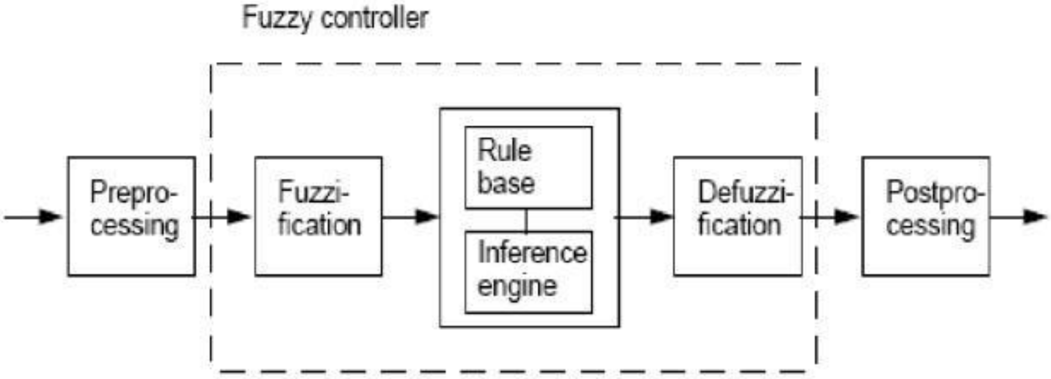


Figure 21_ Structure of fuzzy logic controller.

Implementation of an FLC requires a choice of four key factors [15].

1. Number of fuzzy sets that constitute linguistic variables.
2. Mapping of the measurements onto the support sets.
3. Control protocol that determines the controller behavior.
4. Shape of membership functions.

3.6 Simulation Result with Classic Fuzzy Logic:

Our work on the graduation thesis and our topic in it, we worked in MATLEB 2018, MathWorks today introduced Release 2018a (R2018a) with a range of new capabilities in MATLAB and Simulink, For the work simulation we did in **MATLEB 2018,** we used a time of **250s** and worked with these settings:

Table 3.8_ Optimized Controller Gains & System parameters.

Parameter	Value	Parameter	Value
D	0.015	**M**	0.1667
KEV	1	**NEV**	600
KPV	1	**R**	0.4167
KWTG	1	**RAY**	2.4
T1	0.025	**T3**	3
T2	2	**TEV**	0.1
TPV	1.8	**TWTG**	2

After writing the program and entering settings, we made a plan block diagram:

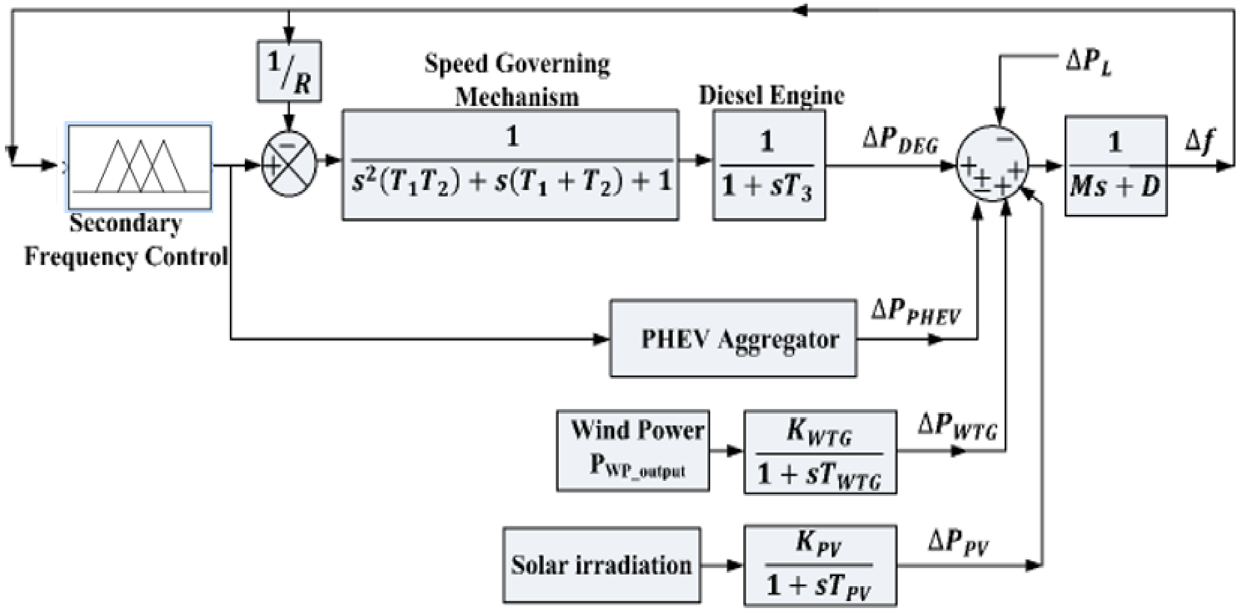


Figure 3.22_ Islanded Microgrid Model

As for this diagram , it is the overall schape of the Microgrid that we worked on, in which we added the diagram for WIND, PV. PHEV, and ΔL, and we also added the Fuzzy logic in order to modify thefrequence.

The significant fluctuations observed in the curve reflect the effective utilization of fuzzy logic in analyzing and predicting frequency variations within the system. Through fuzzy logic techniques, we can comprehensively understand the dynamic and interactive phenomena within the microgrid, enabling us to provide flexible and efficient responses to these fluctuations.

Now we will discuss each one in detail :

- PV Simulation Result:

Given the significance of understanding the performance of each energy source within the islanded microgrid system, the graphic of the PV model serves as an essential component of our analysis. This graphic illustrates the structure and operation of the photovoltaic cells within the system, laying the groundwork for a deeper understanding of their performance and impact on overall energy production, As shown in the illustration below:

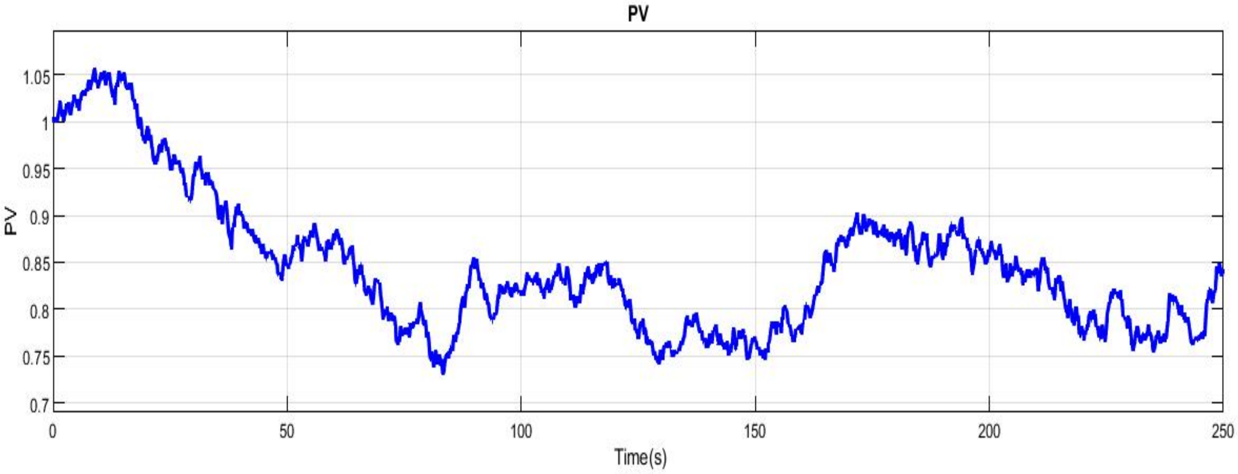


Figure 3.23_ Graphic of PV model.

This curve represents the changes in pv as function of time , as we notice irregularty in pv values over time , wich will affect the frequence curve in the final result ,and that is what we aspire to achieve in terms of changes source of microgrid to play on the value of frequence .

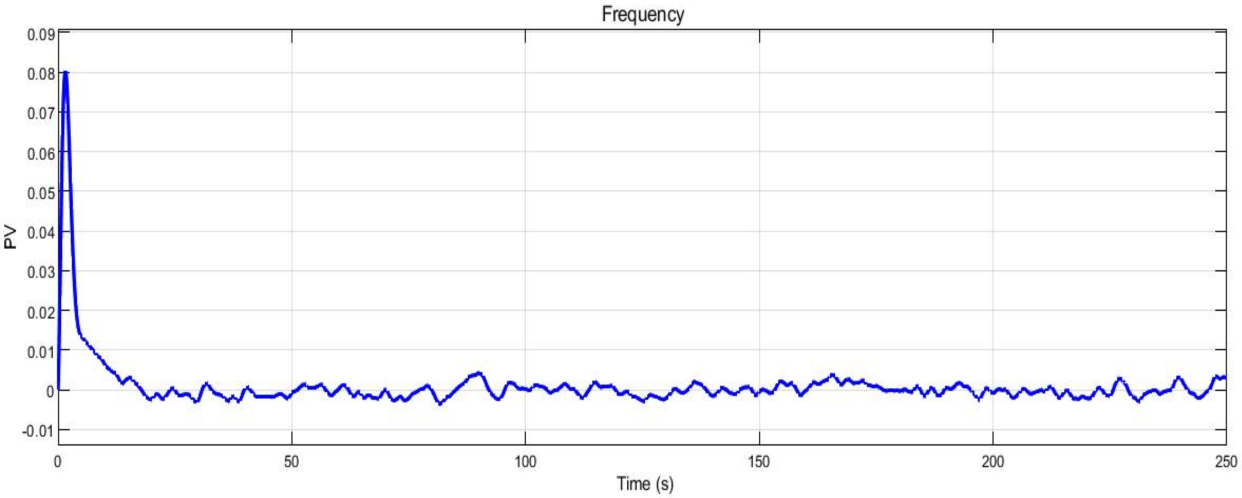


Figure 3.24_ Frequency Response of Islanded Microgrid with PV Source.

The simulation result curve illustrates the frequency changes over time for the islanded microgrid influenced solely by the PV source, using fuzzy logic. It is evident that the frequency fluctuates significantly due to variations in the power output from the solar panels. Upon analyzing the curve, we observe that the frequency peaks at 0.08, then drops to -0.001, before starting to exhibit small, continuous oscillations. This fluctuation reflects the impact of the instability in power generation from the PV source on the frequency stability of the grid. Employing fuzzy logic in this simulation aids in improving frequency stability by providing a dynamic response to power variations. This helps in reducing the impact of these fluctuations and maintaining better grid stability. These results highlight the importance of using intelligent control techniques like fuzzy logic to enhance the performance of islanded microgrids, especially when dealing with renewable energy sources that are inherently variable and unstable.

- Wind Simulation Result:

Given the significance of understanding the performance of each energy source within the islanded microgrid system, the graphic of the wind power model serves as an essential component of our analysis. This graphic illustrates the structure and operation of the wind turbines within the system, laying the groundwork for a deeper understanding of their performance and impact on overall energy production, as shown in the illustration below:

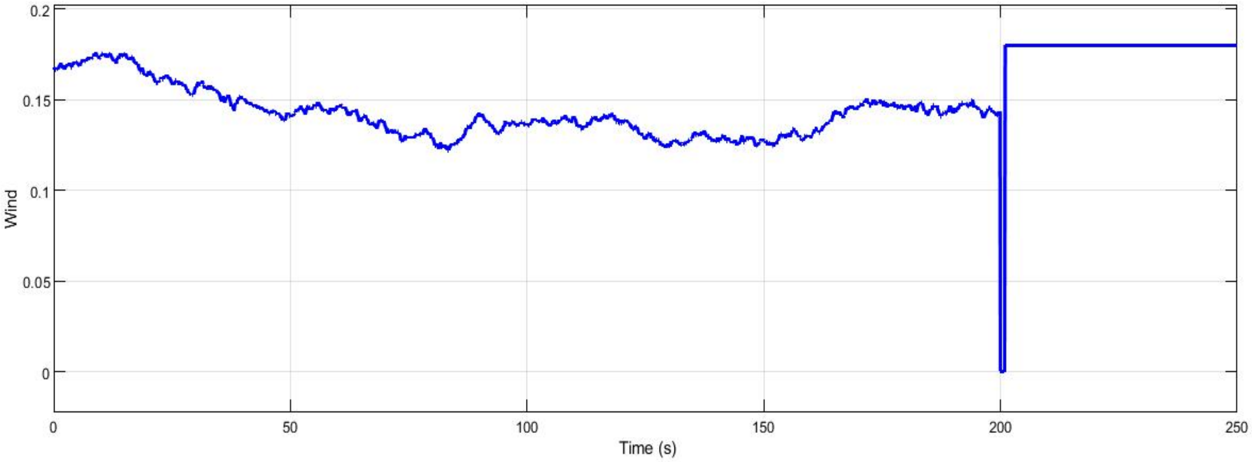


Figure 3.25_ A graphical representation of wind power production fluctuations over time.

This plot illustrates the variations in wind power production over time. The graph displays fluctuations in wind energy values throughout the observed period, which directly influences the final frequency curve of the grid. Analyzing these fluctuations aims to understand their impact on frequency stability within the microgrid, thereby striving to enhance overall performance and ensure sustainability in power supply.

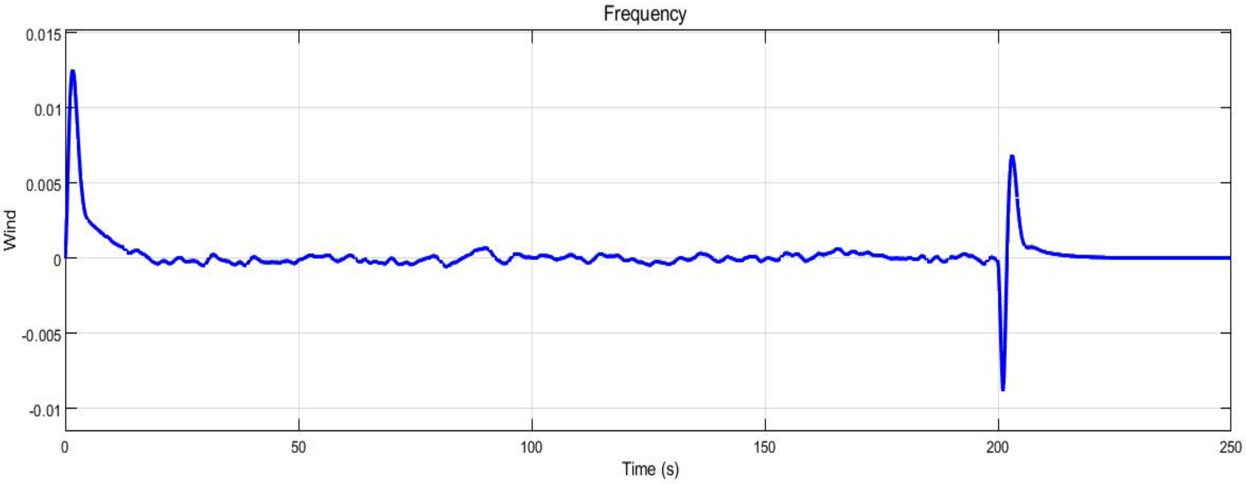


Figure 3.26_ Simulation Results of Frequency Variation in Islanded Microgrid with Wind Source Only.

The simulation result curve shows the changes in frequency over time for the islanded microgrid influenced solely by the wind source, utilizing fuzzy logic. It is evident that the frequency experiences significant fluctuations due to variations in power production from wind turbines. Analyzing the curve, we observe that the frequency reaches its peak value at 0.0125, then drops slightly below zero before beginning a small, continuous oscillation. This oscillation persists until the 200th second, where the frequency rises to 0.0066 and falls to -0.0082, then returns to the initial oscillations in a continuous manner. These fluctuations reflect the impact of the instability of wind power production on the frequency stability of the grid. Using fuzzy logic in this simulation helps improve frequency stability by providing a dynamic response to power variations. This helps reduce the impact of these fluctuations and maintain better grid stability. These results underscore the importance of employing intelligent control techniques like fuzzy logic to enhance the performance of islanded microgrids, especially when dealing with renewable energy sources characterized by inherent variability and instability.

- ΔL Simulation Result:

Studying ΔL variations is crucial for understanding how these external factors affect the stability of the microgrid. Significant or sudden changes in load can lead to frequency fluctuations, requiring precise management to ensure system stability and prevent outages. By analyzing these variations accurately, we can improve energy management strategies within the microgrid, ensuring more effective and reliable power distribution.

This graphic **Figure 3.14**, also allows us to identify periods of peak energy demand caused by external influences, helping to optimize the allocation of available energy and reduce stress on renewable and backup energy sources. Additionally, it enables us to understand how the microgrid responds to load variations due to external factors in real-time and develop solutions to mitigate any negative impacts.

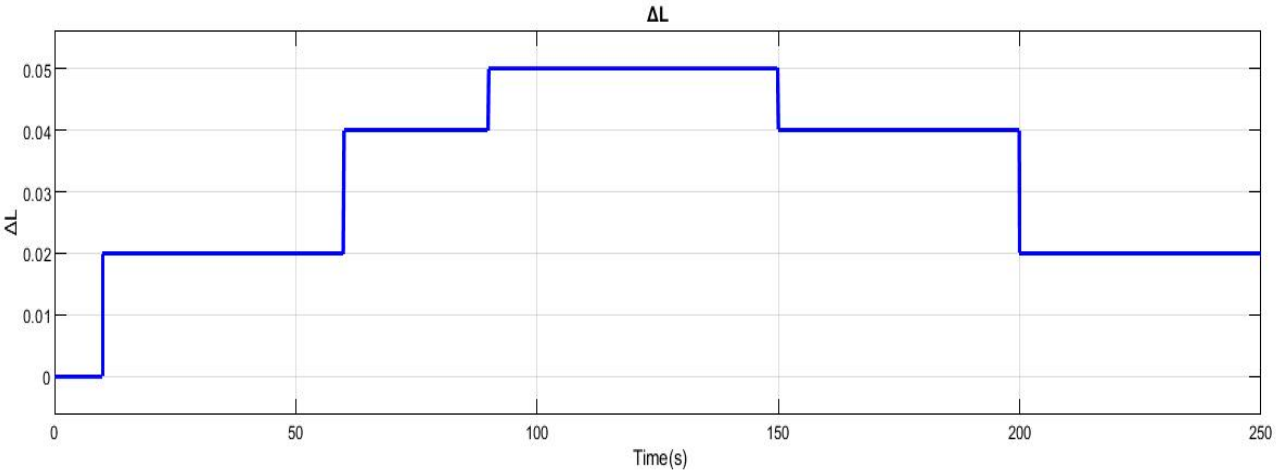


Figure 3.27_ Graphical Representation of External Impacts (ΔL) on Islanded Microgrid Stability

This curve represents changes in ΔL values as a function of time, as we notice changes in the form of gradients that increase and then decrease with time after using 8 steps in the diagram, which gave me this curve.

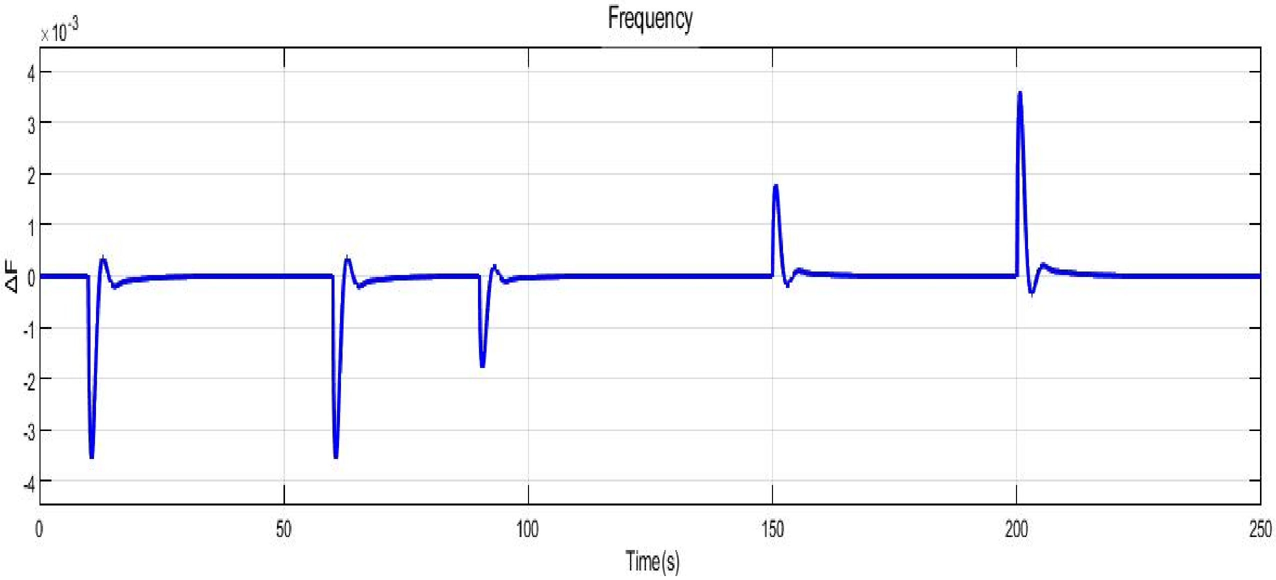
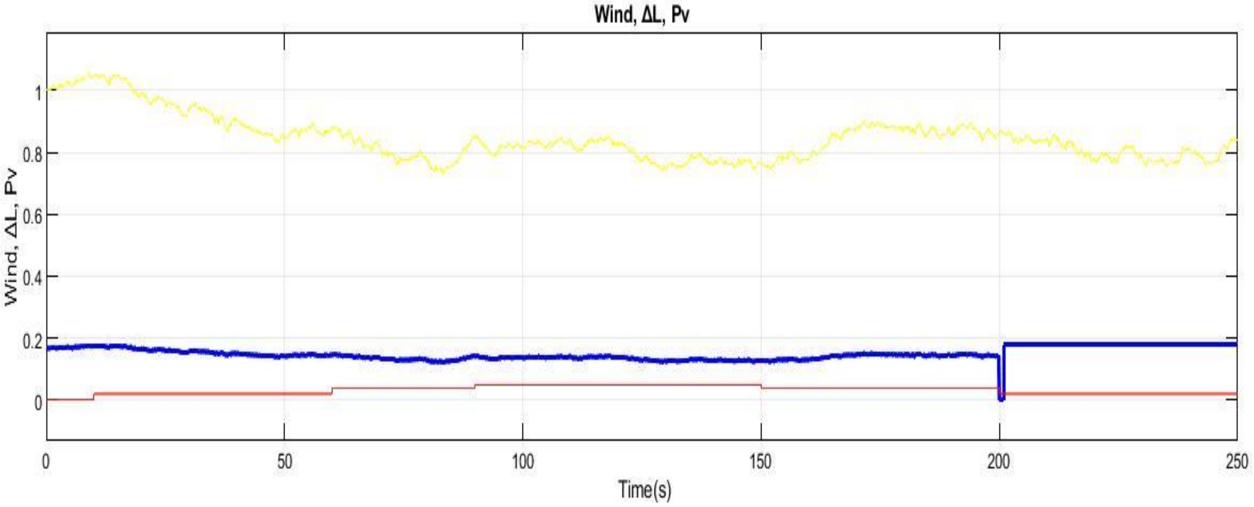


Figure 3.28_ Frequency Response to Load Disturbance in Islanded Microgrid.

The addition of ΔL (load disturbance) to the simulation introduces further complexity to the frequency dynamics of the islanded microgrid. Analyzing the simulation results, we observe significant changes in frequency due to the fluctuating load demand. Initially, the frequency curve experiences fluctuations similar to those observed in previous simulations, reaching a peak value and then oscillating around zero. However, with the introduction of ΔL, the frequency curve exhibits more pronounced variations. As the load disturbance affects the power balance within the microgrid, the frequency experiences rapid changes in response to these disturbances. The curve shows sharper peaks and valleys, reflecting the dynamic nature of load changes and their impact on frequency stability. Despite these challenges, the fuzzy logic controller effectively responds to the load disturbances, helping to mitigate the impact on frequency stability. By dynamically adjusting control parameters based on real-time changes in load demand, the fuzzy logic controller helps maintain grid stability in the face of varying load conditions.

- Simulation Result of PV + wind + ΔL:

At this stage, we worked on the curve of the values of PV, Wind and ΔL as a function of time before giving the final result for the frequency after agreeing to these data in the curve, so that the yellow curve represents the PV curve, the blue color represent the Wind curve, and the red curve represent the ΔL curve.



The integration of data from PV, wind, and ΔL sources into a single curve reveals the collective impact of these variables on the microgrid's frequency. Despite individual fluctuations observed in each source, the combined curve illustrates a coherent pattern, highlighting the dynamic interplay between renewable energy sources and load variations. This holistic view enhances our understanding of the microgrid's overall frequency dynamics and aids in devising effective control strategies for ensuring grid stability and resilience, As for this curve, which represent the changes of frequency as a function time, which represent the final result after collecting the source of Microgrid Islanded, which brought us this curve.

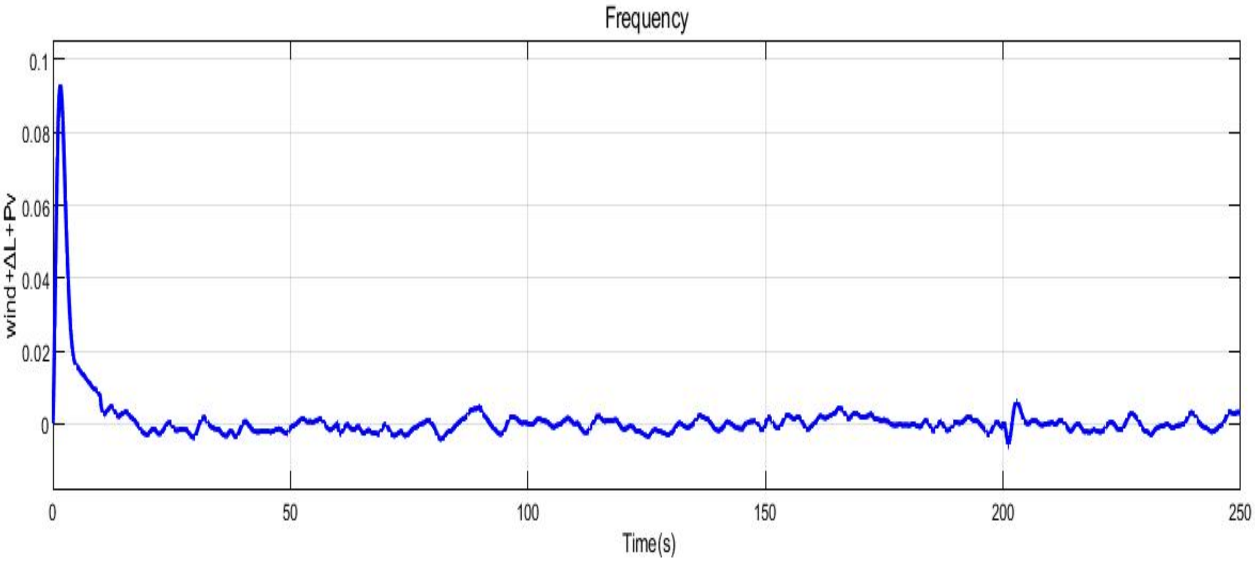
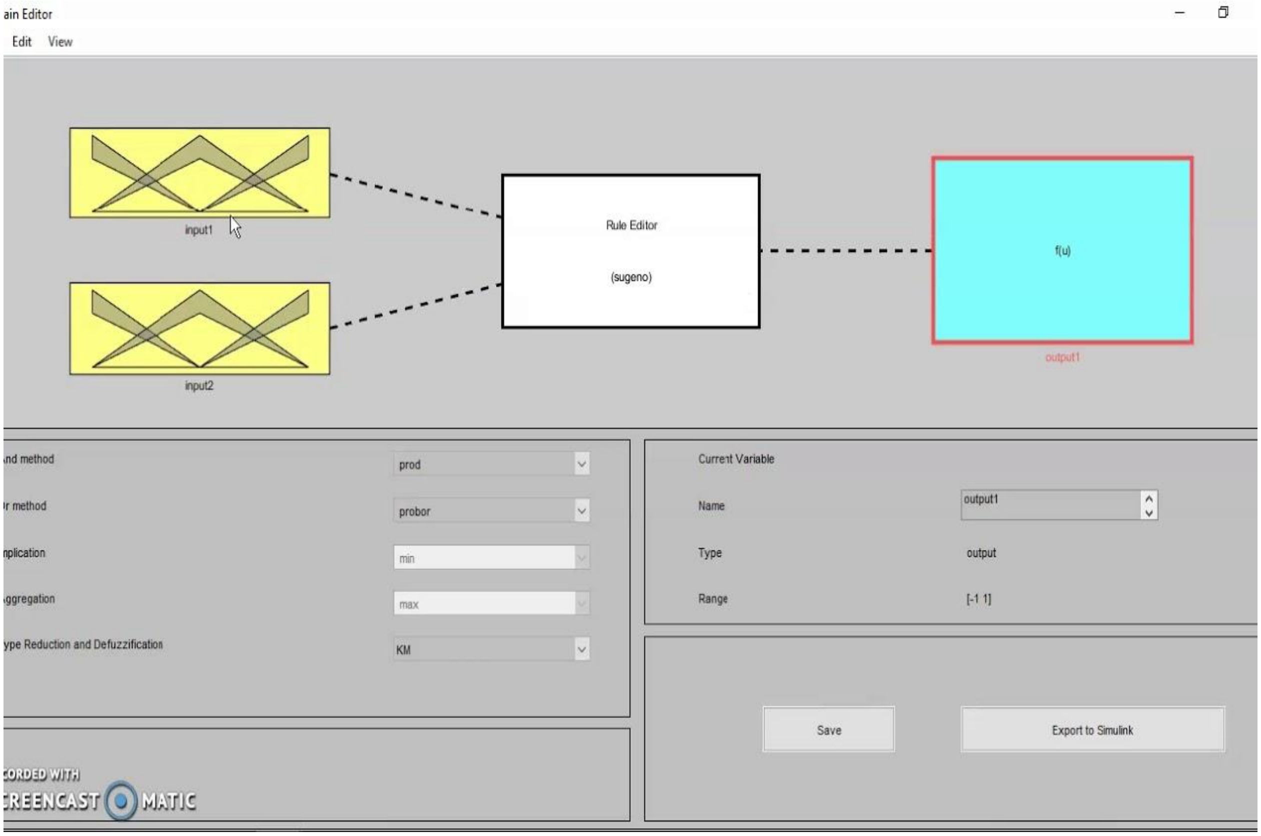


Figure 3.29_ The changes of frequency as a function time.

3.7 Fuzzy Logic Type2

In this section, a brief overview of type-2 fuzzy systems is provided. This overview aims to provide the fundamental concepts needed to understand the methods and algorithms presented later.

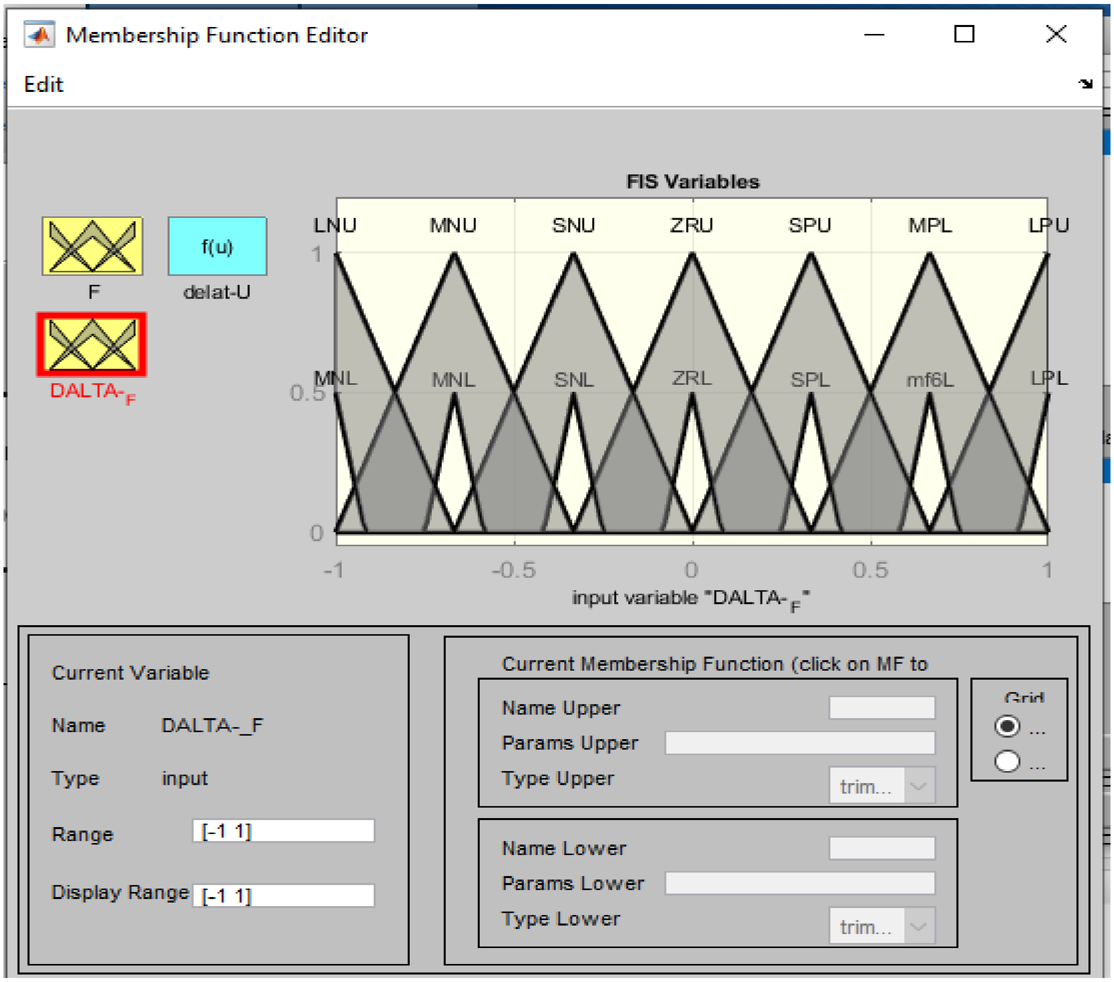


nd method: prod
r method: probor
nplication: min
ggregation: max
ype Reduction and Defuzzification: KM

Current Variable
Name: output1
Type: output
Range: [-1 1]

Figure 3.30_ Type-2 Fuzzy Systems Main Editor Interface in MATLAB.

Type-2 fuzzy systems extend the capabilities of traditional fuzzy logic by allowing uncertainty to be modeled with more flexibility and depth. In a type-2 fuzzy system, the membership functions associated with linguistic variables have varying degrees of uncertainty, which are represented by intervals rather than crisp values. This added dimension of uncertainty enables type-2 fuzzy systems to better capture and represent complex and ambiguous information, making them particularly useful in applications where precise and crisp definitions are difficult to obtain.



Current Variable

Name DALTA-_F

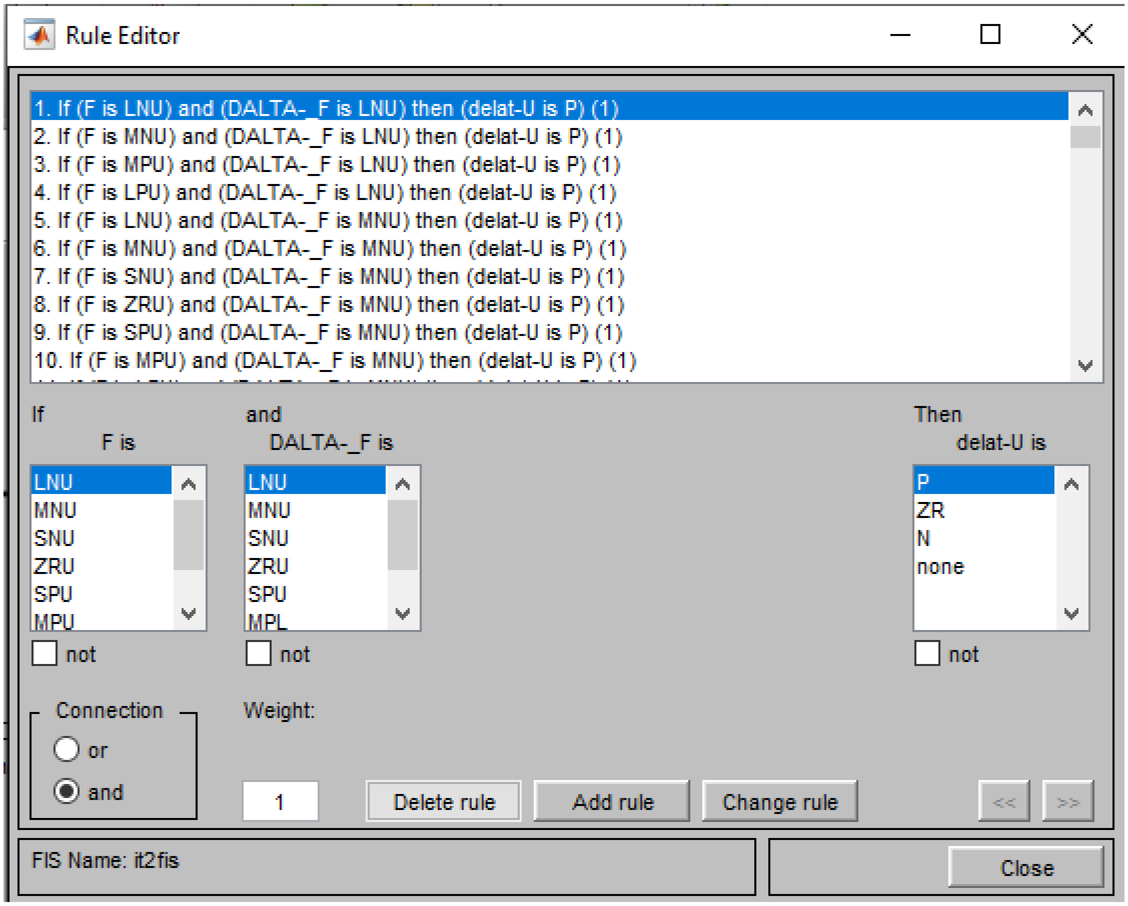
Type input

Range [-1 1]

Display Range [-1 1]

Figure 3.31_Representation of Type-2 Fuzzy Membership Functions

A type-2 fuzzy system typically consists of several components, including fuzzy inference systems (FIS) variables, membership functions, rules, and a fuzzy inference mechanism. The FIS variables represent the input and output variables of the system, while the membership functions define the degree of membership of each variable in fuzzy sets. Rules govern the relationships between the input and output variables, determining how input values are mapped to output values. The fuzzy inference mechanism processes the input variables according to the defined rules to produce crisp output values.



1. If (F is LNU) and (DALTA-_F is LNU) then (delat-U is P) (1)
2. If (F is MNU) and (DALTA-_F is LNU) then (delat-U is P) (1)
3. If (F is MPU) and (DALTA-_F is LNU) then (delat-U is P) (1)
4. If (F is LPU) and (DALTA-_F is LNU) then (delat-U is P) (1)
5. If (F is LNU) and (DALTA-_F is MNU) then (delat-U is P) (1)
6. If (F is MNU) and (DALTA-_F is MNU) then (delat-U is P) (1)
7. If (F is SNU) and (DALTA-_F is MNU) then (delat-U is P) (1)
8. If (F is ZRU) and (DALTA-_F is MNU) then (delat-U is P) (1)
9. If (F is SPU) and (DALTA-_F is MNU) then (delat-U is P) (1)
10. If (F is MPU) and (DALTA-_F is MNU) then (delat-U is P) (1)

Connection: ● and

Weight: 1

FIS Name: it2fis

Figure 3.32_The rules related to the displayed image are presented.

In practice, designing and implementing a type-2 fuzzy system involves several steps, including defining the fuzzy sets and membership functions, specifying the rules, and tuning the system parameters. MATLAB provides a powerful platform for developing type-2 fuzzy systems, with tools such as the Fuzzy Logic Toolbox and Simulink enabling easy visualization, simulation, and analysis of fuzzy systems.

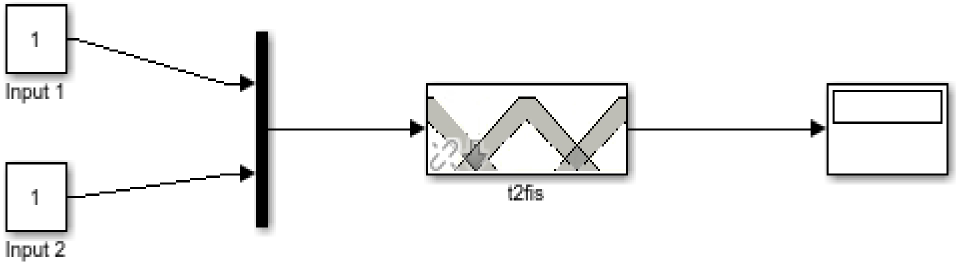


Figure 3.33_The Typical Fuzzy type-2 Model of the Simulated System.

By leveraging the enhanced modeling capabilities of type-2 fuzzy systems, engineers and researchers can tackle complex real-world problems with greater accuracy and robustness, ultimately leading to more effective decision-making and control in uncertain environments. And I talk about my experience with fuzzy logic type2 that in the beginning, I encountered difficulties with Type-2 Fuzzy Logic, as it only worked with MATLAB 2015 or newer versions. We couldn't operate it until I added the Type-2 Fuzzy Logic file that I downloaded and placed it alongside the MATLAB 2018 files. The steps I followed included downloading the file, opening MATLAB, using the "path-tool" command to add the downloaded folder, saving the changes, and then typing "fuzzyt2" in the MATLAB command window.

➢ Advantage and Disadvantages of type-2 Fuzzy Logic:

Fuzzy logic, particularly Type-2 fuzzy logic, offers several advantages and disadvantages in handling uncertainty and imprecision in various applications.

a. Advantages:

1. Enhanced Uncertainty Handling:

- Type-2 fuzzy logic is superior to Type-1 in dealing with uncertainties. It provides a more comprehensive framework by incorporating uncertainty about membership functions. [1]

2. Improved Robustness:

- Type-2 fuzzy systems are more robust to variations and noise in input data, making them suitable for real-world applications where precise measurements are difficult. [2]

3. Better Modeling of Complex Systems:

- They can model complex and nonlinear systems more accurately due to their ability to handle higher levels of uncertainty. [3]

4. Flexibility and Adaptability:

- Type-2 fuzzy logic systems can be more flexible and adaptable to changing environments compared to Type-1 systems. [4]

b. Disadvantages:

1. Increased Computational Complexity:

- The main drawback is the increased computational complexity, which can be significant, making it computationally intensive and slower than Type-1 fuzzy systems. [5]

2. Complexity in Design and Implementation:

- Designing and implementing Type-2 fuzzy systems can be more complex and challenging, requiring a deeper understanding of the theory and more sophisticated tools. [6]

3. Limited Practical Applications:

- Despite its theoretical advantages, the practical application of Type-2 fuzzy logic is still limited and not as widespread as Type-1 due to its complexity and resource requirements. [7]

4. Difficulties in Parameter Estimation:

- Estimating the parameters for Type-2 fuzzy systems can be more difficult and time-consuming compared to Type-1 systems. [8]

➢ Type-2 fuzzy logic offers substantial benefits in handling uncertainty and improving system robustness and adaptability. However, these benefits come with the cost of increased computational and design complexity, which can limit its practical application.

3.8 Simulation result with Fuzzy Logic Type 2:

I will present the simulation results based on Type-2 fuzzy logic in this section. First of all, we gave an outline for our previous work that described the generalized micro-grid we considered for simulation with a type-1 fuzzy logic, in which we included the wind energy diagram (WIND), Solar energy diagram (PV), Plug–in hybrid electric vehicles (PHEV), & the ΔL, and we applied the Type-1 fuzzy logic to modulate the frequency. Results were better than before by adding Type 2 fuzzy logic The findings continue this trend as the advanced version can cope with uncertainty better and theoretically deliver better controlled performance with higher stability in the system. Here in this section we are presenting the simulation results with Type-2 Fuzzy logic compared with that with Type-1 Fuzzy logic and showing improvement in results achieved.

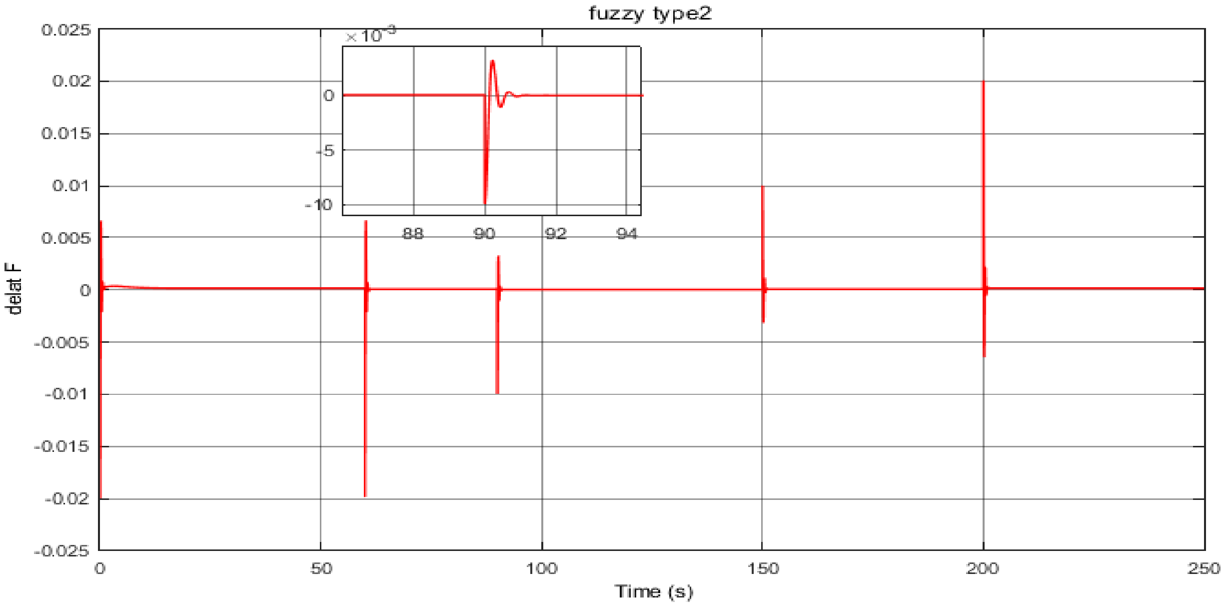


Figure 3.34_ Evaluation of Load Variability (ΔL) in the System.

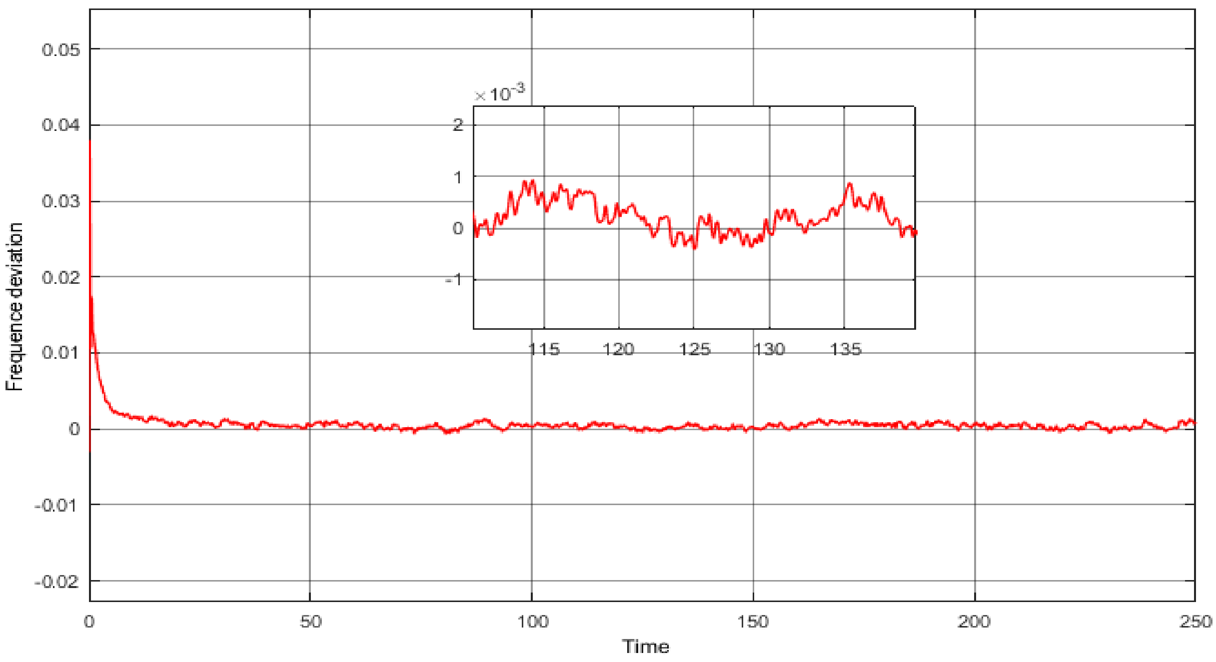


Figure 3.35_ Analysis of Photovoltaic (PV) Power Curve.

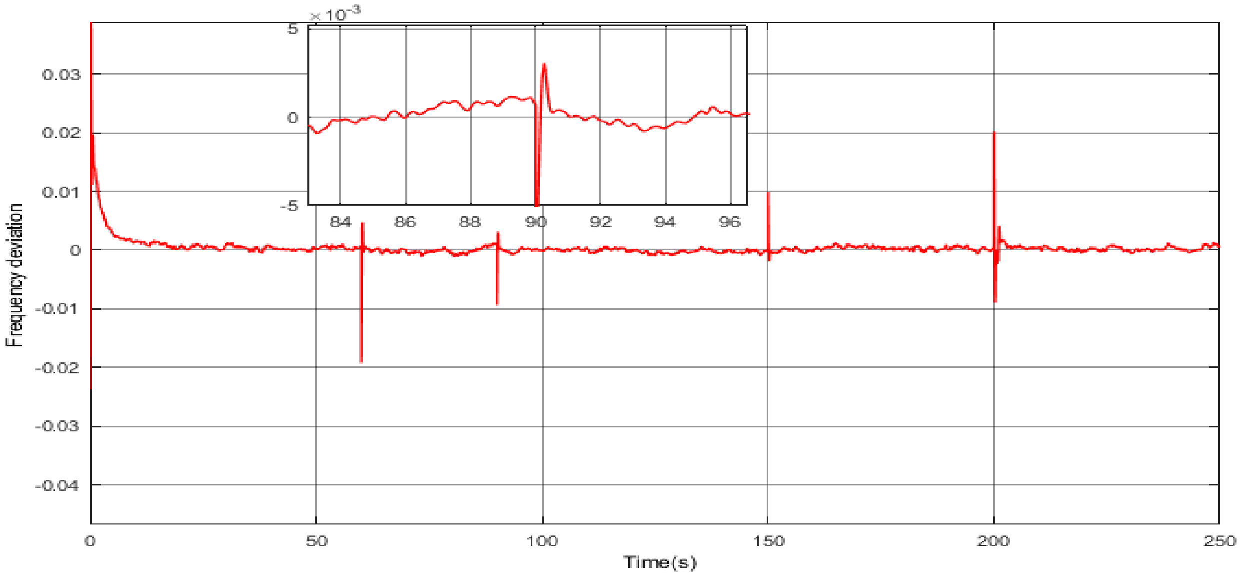


Figure 3.36_ Integration of Effects: Solar Energy (PV), Load Variations (ΔL), and Wind Energy (WIND).

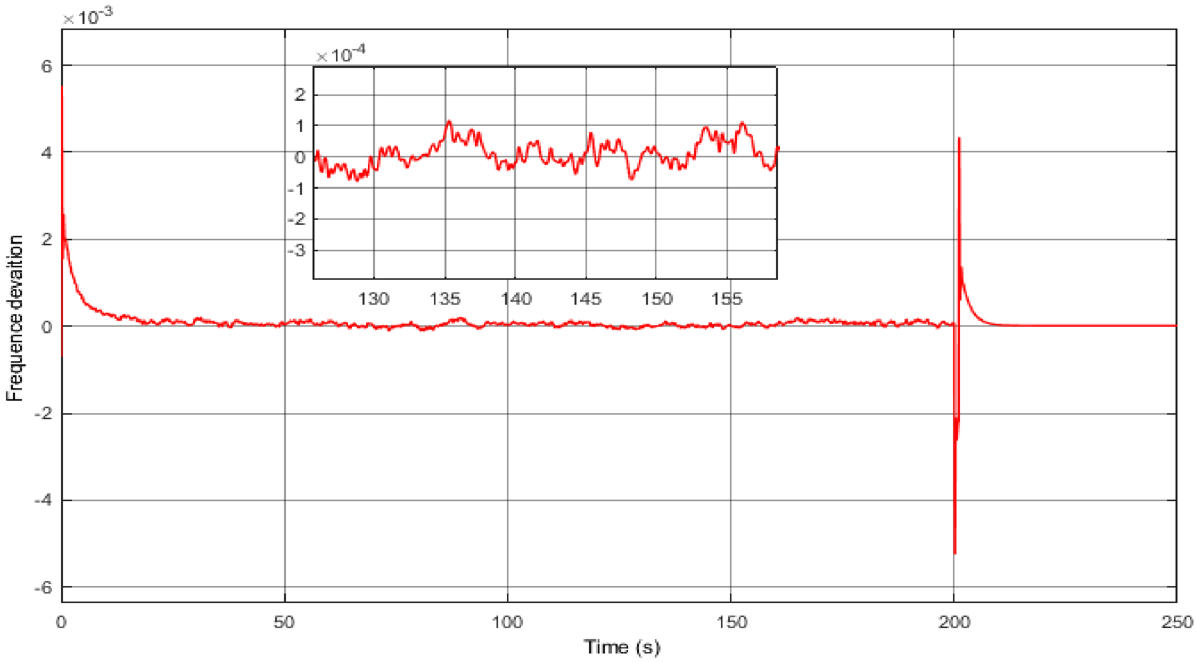


Figure 3.37_ Study of Wind Energy Curve.

3.9 Comparison between First Simulation and second Simulation:

The comparison between the first and second simulations, using Fuzzy Logic Classic and Fuzzy Logic Type-2 respectively, we examined various aspects and metrics to measure the performance and effectiveness of these methods. In this study, we utilized components of the islanded microgrid including photovoltaic (PV) power generation, wind power generation, and load variations (ΔL). The simulations were conducted using MATLAB 2018 with a simulation time of 250 seconds.

In the first simulation using Fuzzy Logic Classic, we analyzed frequency stability, system response to disturbances, energy utilization efficiency, and control complexity. The system was able to maintain relative frequency stability, but with larger deviations compared to the second simulation. The average frequency deviation was greater, and the response to disturbances was slower, indicating that the classic fuzzy logic system might be less efficient in handling rapid load changes.

In the second simulation using Fuzzy Logic Type-2, the system showed a better capability to handle uncertainties and load variations. Frequency deviations were significantly lower, and the system could restore stability faster after disturbances. Energy utilization efficiency was higher, as the system improved the utilization of energy generated from PV and wind sources, reducing energy losses. Although the control algorithm complexity was higher in Fuzzy Logic Type-2, the enhanced performance justified the additional complexity.

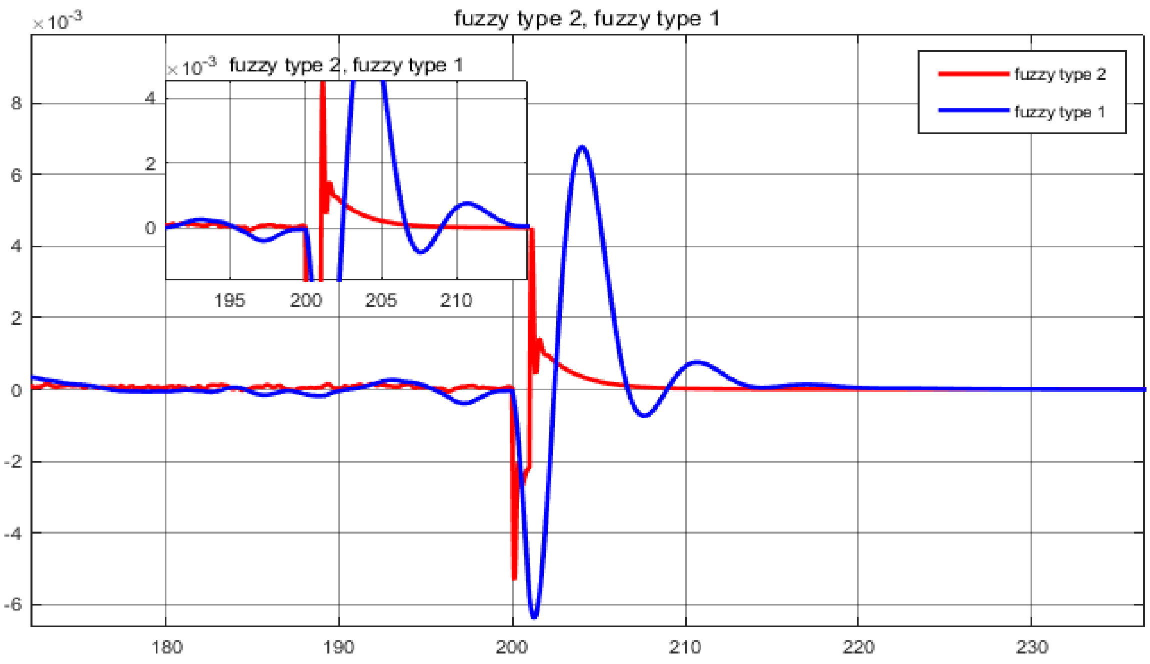


Figure 3.38_ Performance Analysis of Fuzzy Logic Controllers Type-1 and Type-2.

At time 200, we observed a significant improvement in system performance when using Type-2 fuzzy logic compared to Type-1, with enhanced response time and a noticeable reduction in chattering.

To precisely compare the results, we summarize them in the following table:

Table 3.9_ Comparison of Performance Between Classic and Type-2 Fuzzy Logic Systems in Microgrid Simulation

Comparison	Classic Fuzzy Logic	Type-2 Fuzzy Logic
Frequency Stability	Higher Deviations	Significant Improvement
System Response	Slow	Fast
Control Adaptability	Low	High
Energy Utilization	Low Efficiency	High Efficiency

System Complexity	Simple	Complex
Number of Rules	49 rules	49 rules

The simulation using Fuzzy Logic Type-2 demonstrated superior performance in terms of frequency stability, faster response to disturbances, and higher energy utilization efficiency. On the other hand, the simulation using Fuzzy Logic Classic was simpler and required fewer computational resources, making it more suitable for applications with limited resources. For scenarios requiring high performance and adaptability to changing conditions, Fuzzy Logic Type-2 is more appropriate. However, Fuzzy Logic Classic remains a good choice for simpler applications. Future work and considerations include further testing in various scenarios and conditions to evaluate system performance across a wide range of cases. Additionally, exploring hybrid control methods that combine both Fuzzy Logic Classic and Type-2 could potentially yield balanced and integrated performance benefits.

3.10 Conclusion

In conclusion, the exploration of islanded microgrid systems and their complex components throughout this Master journey has been an enlightening and fruitful experience. From delving into the concept of islanded microgrids to analyzing the operation of each component, including photovoltaic (PV) cells, wind, plug-in hybrid electric vehicles (PHEVs), and diesel generators, we embarked on a comprehensive journey toward understanding the intricacies of modern energy systems. The analysis of transfer functions and graphical representations for each energy source provided valuable insights into their individual contributions and interactions within the microgrid framework. Furthermore, the introduction of classical and advanced Type-2 fuzzy logic enhanced our understanding of smart control techniques and their impact on system stability and performance. As we endeavor to appreciate the advantages and disadvantages of Type-2 fuzzy logic, we recognize the significant potential it offers to enhance system reliability and adaptability, while acknowledging the need for further research to address existing limitations. Through simulation and extensive discussions, we witnessed firsthand the tangible benefits of employing fuzzy logic techniques, whether classical or Type-2, in improving the operations of microgrids. The comparison of simulation results underscored the superior performance of Type-2 fuzzy logic in reducing uncertainty and enhancing system responsiveness. In summary, this doctoral journey not only enriched our understanding of islanded microgrid systems but also equipped us with the knowledge and tools to contribute meaningfully to the advancement of sustainable and resilient energy solutions. We look forward to continuing our exploration, innovation, and collaboration towards a future reliant on smart and efficient energy systems.

General Conclusion

Regardless of the standard format, the value of scientific research lies in its ability to explore challenges, offer solutions, and stimulate societal development. This thesis on "Frequency Control of an Islanded Microgrid based on Type 2 Fuzzy Logic Controller" is part of this ongoing process of improvement and advancement. Through this study, we have succeeded in looking beyond specific challenges and thinking more broadly about how to enhance efficiency and sustainability in future energy systems. The findings of this research are expected to inspire researchers and professionals in the energy field to continue working towards developing new technologies and more effective solutions. It is important to place this research in a broader context where it contributes to achieving economic, environmental, and social goals. It contributes to enhancing sustainability and maximizing the use of natural resources, ultimately leading to the creation of more sustainable and prosperous communities for everyone. We are confident that what has been addressed in this thesis represents a new and valuable contribution to understanding energy control, and that analyzing complex concepts at a deeper level contributes to building sustainable and applicable knowledge. By focusing on type 2 fuzzy logic control techniques, we add value to research in this evolving field, reflecting efforts towards progress and innovation. In summary, this thesis is not just scientific recommendations; it represents a comprehensive effort to build a better world for current and future generations. It is a call for continuous work towards innovation and progress, and ensuring the sustainability of the energy systems on which our lives and future depend.

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