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Optimal tuning of a PID controller based on Ant Colony algorithm for frequency control in bella coola Microgrid with electric vehicles

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SARRA BOUGHARI

CHAIMAA YOUCEF ACHIRA

Dedication

To the one who planted the seeds of ambition in me and nurtured them with her love and prayers...

To my dear mother, who has been my support and strength in every step... To myself, who endured and persevered, striving despite the challenges to achieve this accomplishment...

To my friends, Sarra and Solaf, who have been the best companions on this journey...

To my beloved siblings, who have always given me love and support...

I dedicate the fruit of my efforts to all of you, hoping that this work will be a valuable contribution to my field.

Chaimaa

Dedication

In the name of God, the Most Gracious, the Most Merciful

By His grace and guidance, I have reached where I am today

I dedicate this work to my beloved grandfather, my constant supporter and encourager throughout my journey, to my dear parents, to all my dear family members, to my esteemed teachers at all levels of education, and to all my friends

I dedicate this humble work in gratitude and appreciation for all that you have given me.

BOUGARI Sarra

Abstract

In recent years, the energy sector has witnessed a major shift towards adopting renewable energy sources as a clean and sustainable alternative to conventional energy sources. In this context, microgrid systems have emerged as a promising solution for electricity generation and distribution, particularly in remote and isolated areas, due to their independence and operational flexibility. However, despite their numerous advantages, these systems face technical challenges, most notably frequency fluctuations resulting from load fluctuations and the instability of renewable energy sources such as wind and solar. This leads to deteriorating power quality and threatens grid stability. Based on this problem, this work aims to enhance frequency stability and reduce frequency fluctuations in a microgrid system operating under challenging operating conditions, such as sudden load changes or reduced renewable energy production. To achieve this, a PID controller is proposed due to its simplicity and effectiveness, with its parameters adjusted using the Ant Colony Optimization (ACO) algorithm.

After building a model of the microgrid system and simulating its behavior using MATLAB/SIMULINK, the simulation results showed that the PID controller tuned with the ACO algorithm achieved excellent performance in reducing frequency fluctuations and improving the dynamic stability of the grid.

Keywords: Microgrid, Frequency Fluctuation, PID Controller, Ant Colony Algorithm (ACO), Renewable Energy, Dynamic Stability.

ملخص

شهد قطاع الطاقة في السنوات الأخيرة تحولاً كبيراً نحو اعتماد مصادر الطاقة المتجددة كبديل نظيف ومستدام للطاقات التقليدية. وفي هذا الإطار، برزت أنظمة الشبكة الصغيرة كحل واعد لتوليد وتوزيع الكهرباء، لاسيما في المناطق النائية والمعزولة، نظراً لما توفره من استقلالية ومرونة في التشغيل. غير أن هذه الأنظمة، رغم مزاياها العديدة، تواجه تحديات تقنية أبرزها تذبذب التردد الناتج عن تقلبات الأحمال وعدم استقرار مصادر الطاقة المتجددة مثل الرياح والطاقة الشمسية، مما يؤدي إلى تدهور جودة الطاقة ويهدد استقرار الشبكة.انطلاقاً من هذه الإشكالية، يهدف هذا العمل إلى تعزيز استقرار التردد وتقليل تذبذباته في نظام الشبكة الصغيرة يعمل في ظل ظروف تشغيل صعبة، كالتغير المفاجئ في الحمل أو انخفاض إنتاج الطاقة المتجددة. و لتحقيق ذالك، تم اقتراح استخدام متحكم PID نظراً لبساطته وفعاليته، على أن يتم ضبط معاملاته باستخدام خوارزمية مستعمرة النمل (Ant Colony Optimization – ACO).

بعد بناء نموذج لنظام الميكروغريد ومحاكاة سلوكه باستخدام MATLAB/SIMULINK، أظهرت نتائج المحاكاة أن المتحكم PID المضبوط بواسطة خوارزمية ACO حقق أداءً ممتازاً في تقليل تذبذب التردد وتحسين الاستقرار الديناميكي للشبكة.

الكلمات المفتاحية: ميكروغريد، تذبذب التردد، متحكم PID، خوارزمية مستعمرة النمل (ACO)، الطاقات المتجددة، الاستقرار الديناميكي.

Résumé

Ces dernières années, le secteur de l'énergie a connu une évolution majeure vers l'adoption de sources d'énergie renouvelables comme alternative propre et durable aux sources d'énergie traditionnelles. Dans ce contexte, les systèmes de micro-réseaux sont apparus comme une solution prometteuse pour la production et la distribution d'électricité, en particulier dans les zones reculées et isolées, compte tenu de l'indépendance et de la flexibilité opérationnelle qu'ils offrent. Cependant, malgré leurs nombreux avantages, ces systèmes sont confrontés à des défis techniques, notamment les fluctuations de fréquence résultant des fluctuations de charge et l'instabilité des sources d'énergie renouvelables telles que l'énergie éolienne et solaire, qui entraînent une détérioration de la qualité de l'électricité et menacent la stabilité du réseau.Sur la base de cette problématique, ce travail vise à améliorer la stabilité de fréquence et à réduire les fluctuations de fréquence dans un système de micro-réseau fonctionnant dans des conditions de fonctionnement difficiles, telles que des changements de charge soudains ou une production d'énergie renouvelable réduite. Pour y parvenir, l'utilisation d'un contrôleur PID a été proposée en raison de sa simplicité et de son efficacité, et ses paramètres ont été ajustés à l'aide de l'algorithme colonie de fourmis.

Après avoir construit un modèle du système de micro-réseau et simulé son comportement à l'aide de MATLAB/SIMULINK, les résultats de la simulation ont montré que le contrôleur PID réglé par l'algorithme ACO a obtenu d'excellentes performances en réduisant les fluctuations de fréquence et en améliorant la stabilité dynamique du réseau.

Mots clés : Microgrid, Oscillation de fréquence, Contrôleur PID, Algorithme de colonie de fourmis (ACO), Énergies renouvelables, Stabilité dynamique.

Notation & Abbreviation

AC Alternator Current

ACO Ant Colony Optimization

DC Direct Current

DER Distributed energy resources

DG Distributed Generation

EV Electrical Vehicle

ESS Energy Storage System

GA Genetic Algorithm

ITAE Integral Time Absolute Error

MG Microgrid

NOCT Nominal Operation Cell Temperature

PHES Pumped Hydroelectric Energy Storage

PHEV Plug-In Hybrid Electric Vehicle

PID Propotionnelle Integral Derivation

PSO particle swarm optimization

PV Photovoltaique

RES Renewable Energy Sources

WTG wind turbine generator.

Cp power coefficient

λ speed ratio

Pw Power of Wind

Vw Wind velocity (m/s),

Ar *The* swept area of rotor disc (1735 *m*2),

ρ Density of air (1.225 *kg/m*3)

SOC Stake of Charge

K_p Proportional gain

K_i Integral gain

K_d Derivative gains

α Pheromone influence factor

β Distance heuristic influence factor

ρ Pheromone evaporation rate

Q Pheromone deposit factor

Φ Solar irradiation

K Gain.

T Time constant

M Equivalent inertia constant of the hybrid power system

D Damping constant of the hybrid power system

DPL Variation in power of loed

DPDEG Variation of diesel generator

DPPHEV Variation of power in plug in hybrid electrical vehicles

DPWTG Variation of power in wind turbine generator

DPPV Variation of power in Photovoltaic

PPC Point of common coupling

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General Introduction

With the continuous increase in electrical energy consumption, it is noted that demand often exceeds traditional generation and transmission capacities, naturally leading to imbalances in the electrical system and shortages in materials and network extensions, especially in remote areas. This also entails environmental problems, depletion of fossil resources, and severe pollution. This challenge requires the search for innovative solutions that ensure the sustainable and reliable provision of energy worldwide, especially on islands and waterways. In this context, microgrids emerge as an effective technical solution based on the integration of decentralized systems that enable energy provision independently and reliably, relying on renewable and environmentally friendly energies such as wind and solar energy. This helps reduce the significant pressure on the main electrical grid and also helps illuminate remote areas that are difficult to connect to the main grid.

Microgrids have a long history originating with Thomas Edison’s first power plant, constructed in 1882, known as the Manhattan Pearl Street Station. It essentially acted as a microgrid since the centralized grid was not yet established. By 1886, Edison’s firm had installed 58 direct current (DC) microgrids [1, 2]. However, further development of microgrids waned for decades due to a host of reasons including early adoption of an alternating current (AC) electric grid, the prohibitive cost of grid infrastructure, and the overall monopoly structural model that emerged in the electric power industry. Yet recent technological and legislative changes have led to a resurgence of microgrids [3].

Microgrids are an integrated and efficient system for distributing electrical energy, and they are playing an increasingly important role in the modern energy world [4]. They are characterized by their ability to operate independently or in parallel with the traditional electrical grid. In general, a microgrid consists of a group of renewable energy sources, such as solar panels or wind turbines, in addition to energy storage units, control devices, and an auxiliary system such as diesel. These components are used together to ensure a stable and reliable supply of electrical energy in a stable Microgrid.

The DERs are relatively small in size, and consequently, there is a trend toward their integration at the distribution level. As such, the ability to aggregate these resources into controllable clusters would provide better grid stability than a collection of standalone generators. While microgrids would typically operate connected to the bulk grid, they would have the ability to disconnect from the grid and function in "island mode" when necessary [5]. This would increase customer reliability by reducing their susceptibility to grid disturbances, while offering desirable security features. In the long term, a move towards a more decentralized power infrastructure has the potential to guarantee a more resilient and survivable grid [6].

There are many types of microgrids, but our study focuses on the model applied in the Bella Coola region of Canada, which is considered a successful real-world example of adopting renewable energy with a smart control system. This system is characterized by its ability to integrate multiple energy sources and manage them effectively in a complex environment and a changing climate. Historically reliant on hydropower and diesel generators, Bella Coola microgrid has evolved to include modern renewable energy technologies, reducing dependence on fuel and minimizing environmental impact. The integration of renewable energy sources into Bella Coola's microgrid demonstrates how remote communities can transition to sustainable energy solutions and serves as a model for similar areas around the world. This research will focus on Bella Coola as a case study to explore the impact of microgrid implementation in remote communities.

The dynamic nature of renewable energy sources, such as wind power and photovoltaic (PV), significantly impacts the fluctuation of frequency in microgrid systems due to their pronounced intermittency, inherent randomness, and limited output support. Despite ongoing research, there is still a lack of comprehensive understanding of the control measures needed to enhance microgrid frequency stability [7].

The fluctuation of frequency in microgrids is a real problem that cannot be ignored, because the stability of the whole system depends on keeping the frequency within its normal range. When the frequency goes up or down too much, it can cause serious damage to devices, affect the quality of the power, and in some cases lead to system failure. That’s why it’s so important to find an effective way to control these fluctuations and keep the frequency stable at all times, no matter the changes in load or generation conditions. Solving this problem is essential to ensure the safety, reliability, and good performance of the microgrid.

This work aims to address the problem of frequency fluctuation in microgrids, which, as mentioned, is one of the most significant challenges affecting system stability. To address this problem, the PID controller was chosen due to its high efficiency [8, 9], simple structure, and rapid response to dynamic changes. However, the performance of this controller depends heavily on the precise tuning of its three parameters (K_p, K_i, and K_d), which is difficult to achieve using traditional methods. Therefore, the Ant Colony Optimization (ACO) algorithm was adopted as an intelligent optimization tool to search for the optimal values of these parameters, given its ability to efficiently explore the solution space and arrive at accurate results [10, 11, 12]. Through this combination of the PID controller and the ACO algorithm, we seek to achieve effective frequency regulation and enhance the stability of the microgrid.

Our research, titled "**Optimal Tuning of a PID Controller Based on Ant Colony Algorithm for Frequency Control in the Bella Coola Microgrid Powered by Electric Vehicles**," is divided into three chapters.

In the first chapter, titled "**Microgrid Generalities**," we provide an overview of microgrid concepts, their classifications, and their basic components. We explore the different types of microgrids, including AC, DC, and hybrid microgrids, highlighting their characteristics and the pros and cons of each type. We also discuss the key components of microgrids, focusing on renewable energy sources such as wind and solar power. The chapter also addresses the integration of microgrids with the main grid, detailing the possible operating modes Grid-Connected mode and Islanded mode. Finally, we address the problems and challenges facing microgrids.

The second chapter, "**Non linear modelling of Bella-Coola microgrid**" delves into the technical aspects of microgrid modeling specific to Bella Coola. It begins by outlining the modeling of renewable energy sources, including solar panels, hydroelectrical and wind turbines, starting with the fundamental principles of solar cells and progressing to the mathematical models of photovoltaic generators and wind turbines. Additionally, the chapter covers conventional energy sources such as diesel generators and fuel cells, along with various energy storage systems utilized in Bella Coola, including battery storage and hydrogen storage technologies. Furthermore, it examines the modeling of hydro-electrolyzes, providing a detailed analysis of the mathematical equations and models used to evaluate and optimize their performance.

The third chapter, titled " **Control and improve the performance of the frequency in microgrid** ", we will address the importance of frequency regulation in microgrid systems using an AI-powered PID controller, the Ant algorithm. This will be achieved through modeling and simulating the Bella Cola microgrid system, providing appropriate commentary and analysis on the simulation results. We will also compare this technique with other techniques to reinforce the importance of the approach, highlight its efficiency, and demonstrate the appropriateness of our choice.

I.1 Introduction

It is known at the present time that we have an increasing need for electrical energy, which has led to a decline in the amount of fossil energy, in addition to the negative effects on the environment resulting from its use. It has become necessary to develop alternative energy systems to achieve energy sufficiency. Among this development, new electrotechnical systems have emerged aimed at improving the stability and independence of the electrical network.

One of the challenges facing electricity distribution companies is supplying deserts and remote areas with electricity and networks. It is better to find networks independent of the traditional main network that allow the generation of local energy with advanced control methods that guarantee the continuity of the supply of electrical energy.

In this chapter, we will highlight the microgrid system, as one of the modern electrical solutions that allows efficient generation in innovative power generation and control technologies. In this context, we will discuss the components; types; Operating Modes; The characteristics; Applications; Challenges and Protection of microgrid.

I.2 Definition of Microgrid

A microgrid is a controllable and distributed energy system consisting of interconnected generation units, storage systems, and electrical loads. It can operate in grid-linked or islanded mode. It is an integrated technical system, which includes all types of energy sources (like renewable energy, for example, solar energy, wind energy, conventional generators, fuel cells and storage systems (like batteries and super capacitors) to provide a stable and reliable energy supplying.

Microgrids are well suited for desert and rural regions where centralized grid infrastructure is lacking. They offer energy independence, decrease reliance on national power grids, and bolster energy security. Microgrids facilitate direct support for EV infrastructure, such as smart charging stations using renewable energy, which helps decrease carbon footprints and promote transportation using sustainable energy. The Figure I.1represents example of the Microgrid with old the components and sources of renewable energy(wind, solar) and diesel generator and storage energy with some application for example hospitals, the Houses and factories.

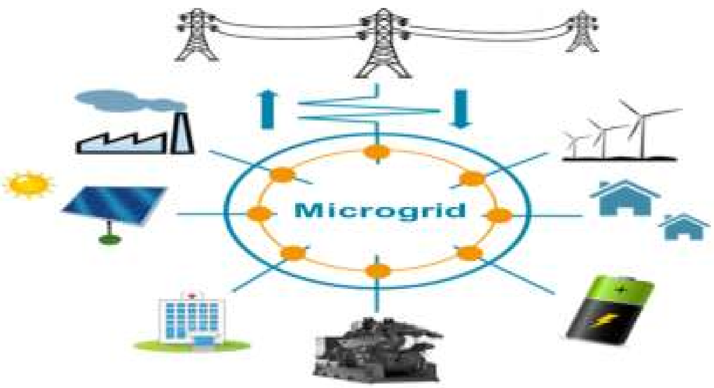


Figure I.1: Example of the Microgrid

I.3 Components of the Microgrids

I.3.1 Local generation

It presents different sorts of era source that encourage power to client. These sources are partitioned into two noteworthy gatherings – ordinary vitality sources (ex. Diesel generators) and inexhaustible era sources (e.g. wind turbines, sunlight based) [13].

Figure I.2: Local generation

I.3.1.1 Wind energy

Wind energy is a form of renewable energy sources, in which turbines convert the kinetic energy of the wind into mechanical or electrical energy, and this energy is used to provide the necessary power needed by many different fields, such as industry, agriculture, and others. [14]

I.3.1.1.1 Principle of the wind energy

Wind energy is generated by using turbines. The wind moves the blades of the turbines, which are similar to a fan, causing them to rotate, which in turn operates the generator responsible for generating mechanical and electrical energy. [15] Turbines convert wind energy into electrical energy by using the aerodynamic force generated by the rotating blades, which works on the same idea as the wings of an airplane or a propeller. When the wind flows and reaches the blade, the air pressure on one side of the blade decreases, and this difference in pressure creates the forces of lift and drag.

[15] The lifting force is stronger than the drag force, which causes the blade to rotate, which is connected to the generator either directly through the turbines or indirectly through a shaft and gearbox, which operates the generator that generates electricity. [15] Most wind turbines are divided into two main types: Horizontal turbines, vertical turbines, and wind turbines can be built either on land or on large bodies of water such as oceans and lakes [15]. Figure I.3 represent the Principle of the wind energy

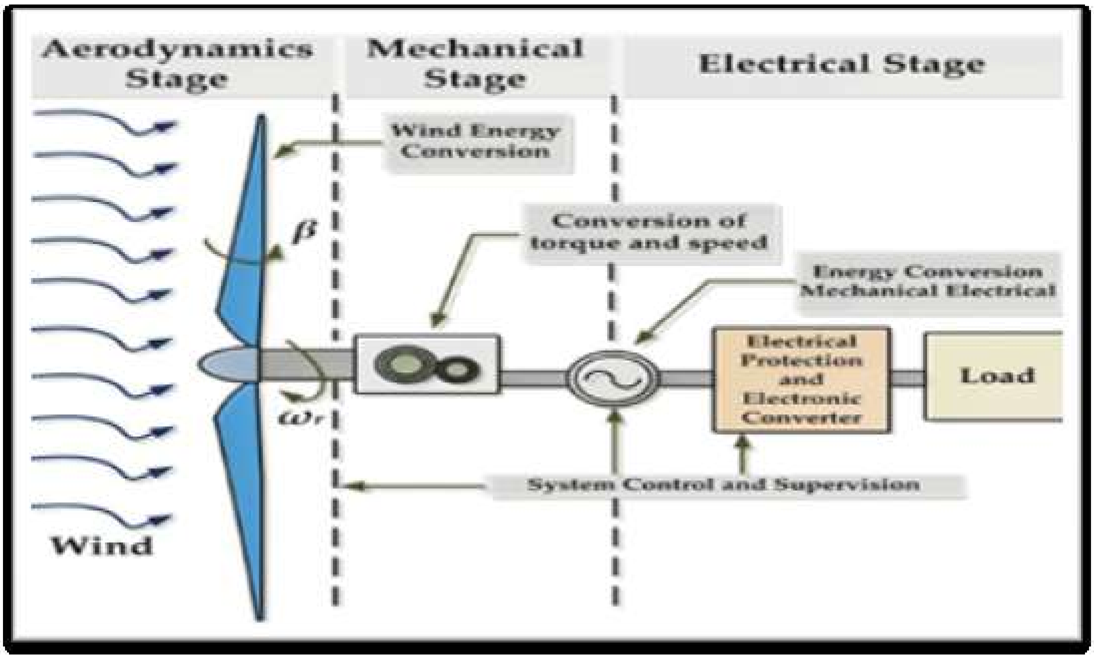


Figure I.3: Principle of the wind energy

I.3.1.1.2 Constitutions of a wind turbine

A wind turbine is made up of several elements as shown in the following figure:

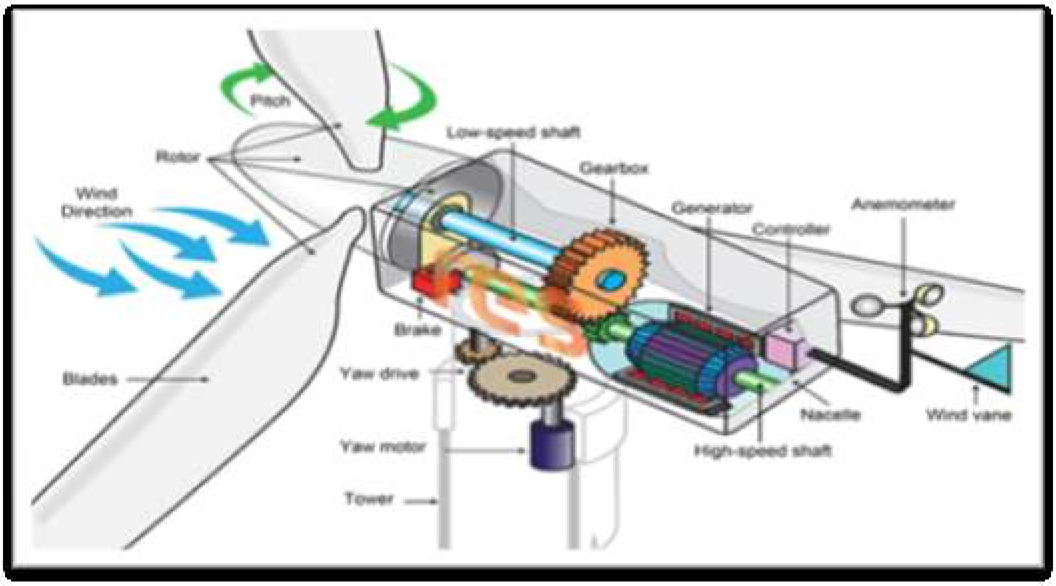


Figure I.4: Constitutions of a wind turbine

a. Advantages

- Wind energy is a sustainable and environmentally friendly energy source.
- Wind farms create jobs in manufacturing, installation and maintenance.
- It produces a large amount of electrical energy compared to other renewable energies.

b. Disadvantages

- Wind energy production varies depending on wind conditions.
- Wind turbines can be considered noisy by nearby residents and they take up a lot of space and land.
- High construction and maintenance costs.

I.3.1.2 Solar energy

The Solar Energy is produced by the Sunlight is a non-vanishing renewable source of energy which is free from eco-friendly. Every hour enough sunlight energy reaches the earth to meet the world's energy demand for a whole year. In today's generation we needed Electricity every hour. This Solar Energy is generated by as per applications like industrial, commercial, and residential. It cans easily energy drawn from direct sunlight. So it is very efficiency & free environment pollution for surrounding. In this article, we have reviewed about the Solar Energy from Sunlight and discussed about their future trends and aspects [16].

I.3.1.2.1 Photovoltaique hierarchy

A photovoltaic array (PV system) is an interconnection of modules which in turn is made up of many PV cells in series or parallel.

The power produced by a single module is seldom enough for commercial use, so modules are connected to form array to supply the load. The connection of the modules in an array is same as that of cells in a module. Modules can also be connected in series to get an increased voltage or in parallel to get an increased current. [17]

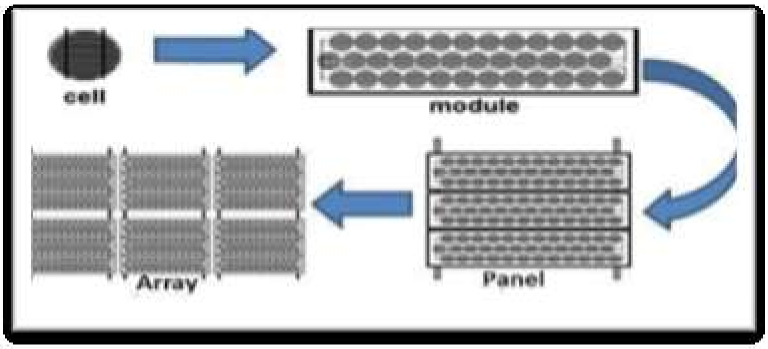


Figure I.5: Photovoltaique hierarchy

I.3.1.2.2 Solar cells function

Solar cellsoperate based on the photovoltaic effect, which converts radiant energy from sunlight into electrical energy. The process excites electrons in a semiconductor like silicon in a reaction that occurs when sunlight is incident upon it will yield the solar cell. Thus, the cell contains a junction between two types of silicon: enriched by electrons (n-type) and with a deficiency of electrons (p-type). So, there is a difference in the material's electronegativity. This difference sets up an electric field that forces electrons to move in the direction of one pole, thereby creating an electric current that can be used to energize electrical loads. The main solar cells effectively work on the chemistry of the material as well as the incident light and temperature of the surrounding areas, causing their performance to be influenced by those factors.

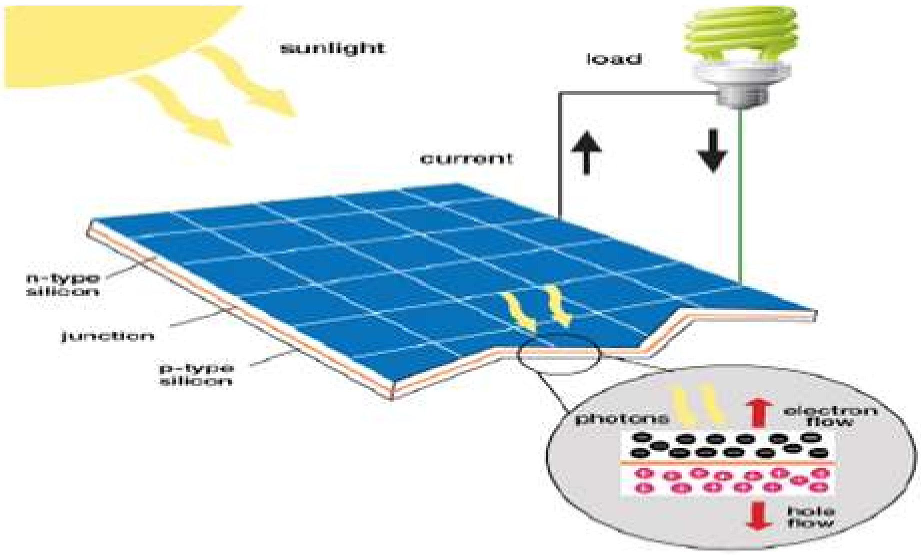


Figure I.6: Photovoltaic operation

a. Advantages

- Solar energy is a sustainable and environmentally friendly energy source.
- It can be used in a variety of applications from small residential facilities to large commercial facilities especially in areas with constant sun.
- Solar panels have low maintenance and operating costs.

b. Disadvantages

- Solar energy production depends on the weather and varies depending on the hours of the day.
- Solar panels require large areas of land.
- It is necessary to store energy to provide it during non-sunny periods, as its production of electrical energy is low.

I.3.2 Consumption

Microgrids are used to meet a variety of energy needs, such as heating, lighting, and powering vital facilities, but they have also become an essential element in charging electric vehicles. Their integration with smart charging stations enables effective demand management, reducing pressure on the grid, especially with the use of two-way charging (V2G) that allows vehicles to feed energy back when needed. This integration enhances the sustainability of electric transport, ensuring more efficient consumption of renewable energy sources, supporting the transformation of cities into smart and sustainable energy systems [13].

I.3.3 Energy Storage

In Microgrid, vitality stockpiling can play out numerous capacities, for example, guaranteeing power quality, including recurrence and voltage control, smoothing the yield of sustainable power sources, giving reinforcement energy to the network and assuming critical part in cost enhancement. It incorporates all of electrical, weight, gravitational, flywheel, and warmth stockpiling innovations [13].

Figure I.7: Example of 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 [18]. 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 [19].

Energy storage technologies encompass a variety of systems, which can be classified into five broad categories, these are: mechanical, electrochemical (or batteries), thermal, electrical, and hydrogen storage technologies. Advanced energy storage technologies are capable of dispatching electricity within milliseconds or seconds and can provide power back-up ranging from a few minutes to many hours. The suitable duration (long or short) of storage, scale of systems (in MW and MWh) and response time is technology dependent making it important to choose the appropriate technology as per the application requirements and constraints [20].

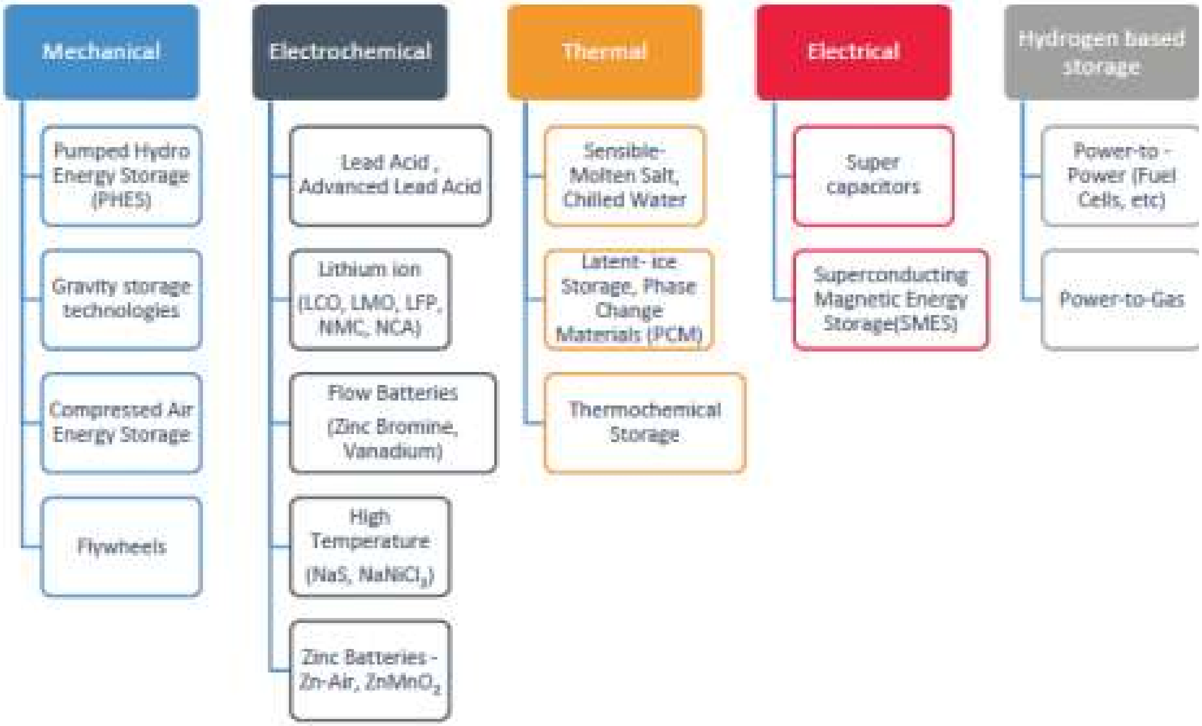


Figure I.8: Classification of Energy Storage Technologies

I.3.4 Point of Common Coupling (PCC)

It is the point in the electric circuit where a Microgrid is associated with a fundamental grid. [21] Microgrids that don't have a PCC are called confined Microgrids which are typically exhibited on account of remote locales (e.g., remote groups or remote mechanical destinations) where an interconnection with the primary network is not doable because of either specialized as well as financial imperatives [13].

I.4 Types of Microgrid

There are three types of microgrids as shown in this diagram:

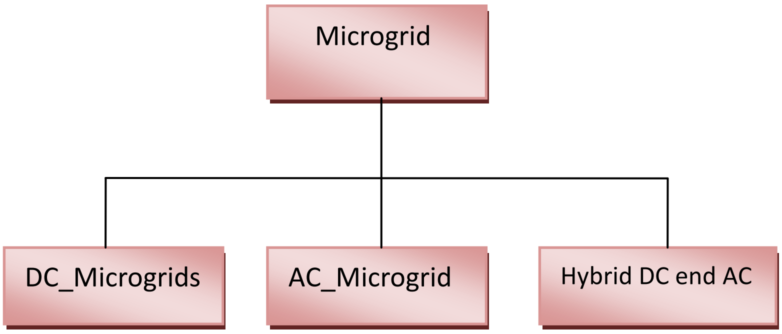


Figure I.9: Three types of grids [16]

I.4.1 DC Microgrid

In the Microgrid context, direct current (DC) Microgrids are seen as a major advantage, since renewable (PV, Wind, fuel cells), electronic loads, electric vehicles, and storage (batteries, super capacitors) have DC nature. If they are connected through a DC grid, they would need a smaller number of converters, and those converters would be simpler than if they are connected through an AC grid. The result would be less expensive materials, and better efficiency (fewer losses). Also, direct current can be more efficient due to its simpler topology; the absence of reactive power and frequency to be controlled; the harmonic distortion is not a problem anymore; and there is no need of synchronization with the network. The consequence is a simpler control structure based on the interaction of currents between the converters, being the DC bus voltage the main control priority, that is, the voltage is a natural indicator of power balance conditions. At the same time, the DC microgrid is a challenge because the structure of the current power grid, power supplies, transformers, cables, and protection is designed in alternating current. [22, 23, 24].The Figure 1.10 represents the synoptic diagram for the architecture of an AC hybrid system [25].

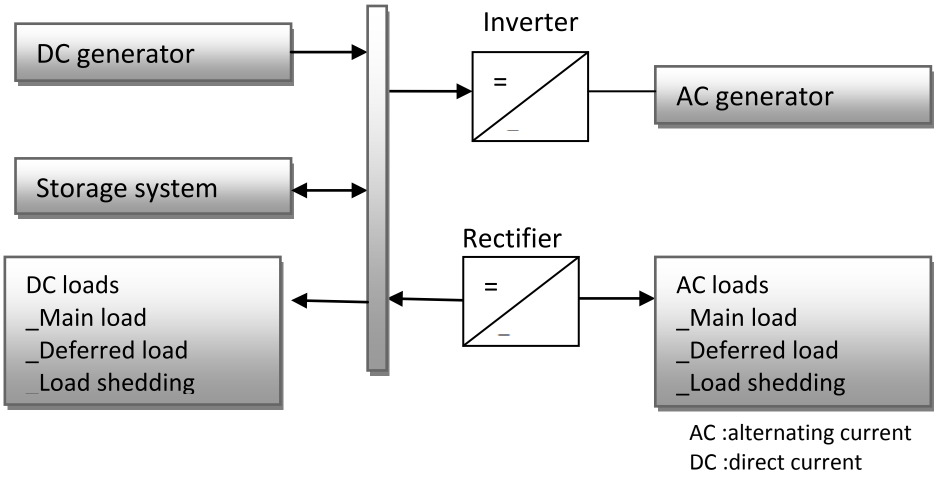


Figure I.10: Synoptic diagram of a DC microgrid [25]

a. Advantages of DC Microgrid

- The simplicity of its control system compared to AC.
- Highly efficient in power transmission to reduce energy loss resulting from repeated conversions between DC and AC.
- Improves network quality and stability.

b. Disadvantages of DC Microgrid

- Requires the use of additional transformers because most electrical devices depend on alternating current.
- Difficulty in transferring energy over long distances.
- Direct current is very dangerous compared to alternating current in case of a fault or electric arc.

I.4.2 AC Microgrid

As traditional power system is based on AC, microgrids are considered to be naturally AC based at early stage. A three-phase AC bus is commonly employed as the point of common coupling (PCC) [26]. PCC is normally set as the only power interface between a utility grid and the microgrid. The schematic structure is shown in Figure I.11. A microgrid can be either operated in grid-connected condition or in some situations, switched to the stage of isolation, i.e., islanding operation [27]. A fast switch can be placed in between PCC and utility grid as the cutoff point between the microgrid and utility grid.

Comparing with traditional power grid, the emergence of DGs and ESSs is the major difference. In a microgrid, renewable DGs and ESSs are interfaced with power electronics converters with distributed control [28].

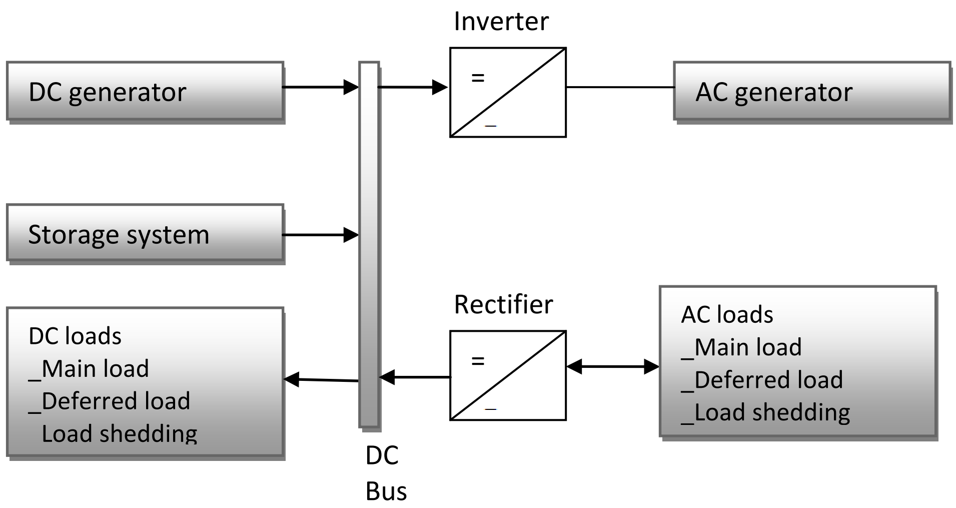


Figure I.11: Synoptic diagram of an AC microgrid [25]

a. Advantages of AC Microgrid

- It has high flexibility that allows it to integrate with various renewable or old energy sources, which expands its applications.
- It also has the ability to adjust the voltage through simple electrical transformers.
- It has a simple design.

b. Disadvantages of DC Microgrid

- Energy waste due to battery.
- Need for expensive electrical equipment such as generators and transformers.
- Technical and engineering challenges associated with synchronization between different generators.

I.4.3 Hybrid DC/AC Microgrid

In the two-bus configuration, renewable energy sources can supply one part of the load with AC and the other part with DC. Both buses must be connected by a bi-directional converter.

The generator and the inverter can operate independently or in parallel. When the load is low, either can generate the necessary energy. However, both sources can operate in parallel during peak loads; the nominal power of the generator and inverter can be reduced without affecting the capacity of the system to supply peak loads. But the realization of this system is relatively complicated because of the parallel operation of the inverter which must be able to operate in autonomous and non-autonomous modes by synchronizing the input voltages with the output voltages of the generator [29]. The architecture of DC/AC hybrid system is shown in the Figure 1.12 [25].

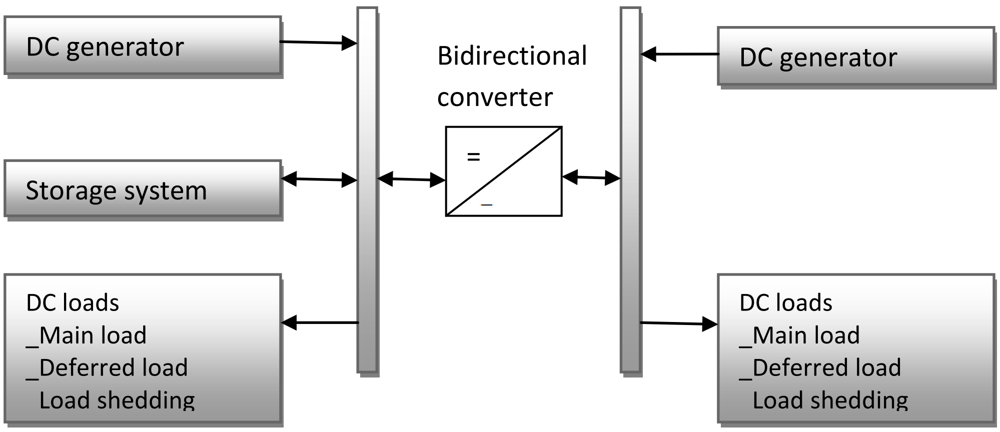


Figure 1.12: Synoptic diagram of a DC/AC microgrid [25]

a. Advantages of Hybrid DC/AC Microgrid

- Its ability to adapt to changes in load, voltage and frequency.
- The generator and inverter can be operated separately and connected, resulting in flexibility in operation.
- Its ability to operate various sources simultaneously during peak periods to meet its energy needs.

b. Disadvantages of Hybrid DC/AC Microgrid

- When switching modes in standalone and networked operation.
- This requires complex control, a high cost of primary and operational resources such as power transformers and control systems.
- And energy losses due to conversion between DC and AC.

I.5 Operating Modes of Microgrid

The MG incorporates numerous renewable energy resources such as small hydro, ocean, wind, PV, energy storages, and so on for rural electrification where utility connection is not accessible. The addition of many distributed generations to the MG reduces the need for high voltage transmission-distribution systems significantly. Instability plagues microgrids powered by a single source of DER. Microgrids with several DERs solve this problem, as these sources contribute to better stability, efficiency, and supply quality, and reliability. MG gives greater flexibility and support because they may be operated in both grid-connected and islanded modes and DERs can be physically adjacent to one other or geographically distributed [30]. The following are descriptions of two working modes.

I.5.1 Islanded Mode

As the name implies, the microgrid is isolated and can run independently of the main grid in this mode. When grid power is unavailable, the breaker linked at the PCC disconnects the microgrid from the grid while keeping the loads powered by local DGs connected. The microgrids islanded mode assists in providing backup power to sensitive loads linked to it that are susceptible to voltage disruptions. There are two sorts of islanding: purposeful and accidental. It is intentional islanding when a microgrid is disconnected from the main grid due to maintenance or repair work on the main grid. Unintentional islanding is islanding caused by defects in the utility grid [30].

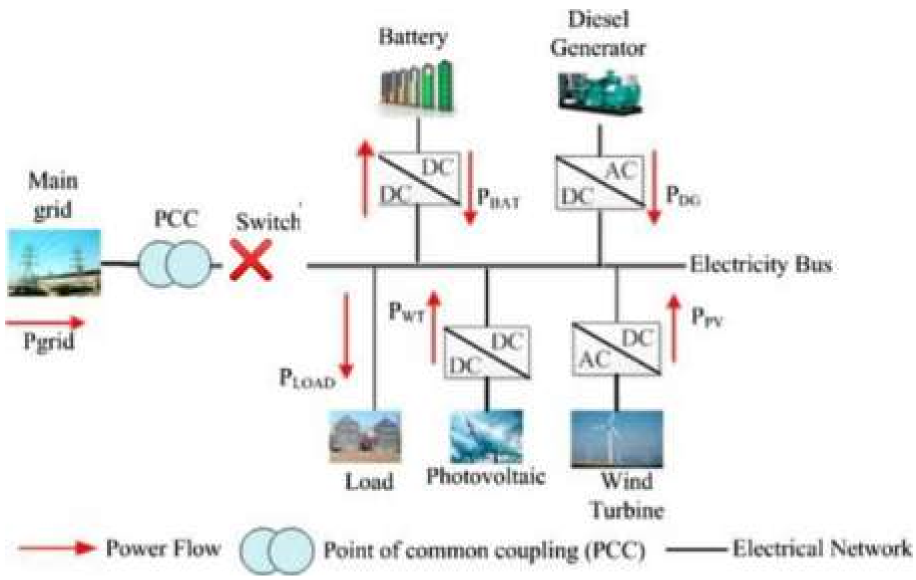


Figure I.13: Structure of Grid-Island Microgrid

I.5.2 Grid-Connected Mode

In this mode, the microgrid is connected to the main grid via PCC, provided that any power quality issues do not afflict the main grid. Critical loads can be run in this mode, requiring a dependable energy source that meets conventional power quality criteria. Grid-connected mode of operation has the following advantages: it provides power reliability and a steady operating state for the grid by acting as a backup supply. Also, the demand for ESS is significantly decreased, lowering the investment cost. Because surplus electricity generated can be fed into the main grid, this option helps to increase revenue. Fuel operation expenses can be decreased by using grid power when cheap during off-peak hours [30].

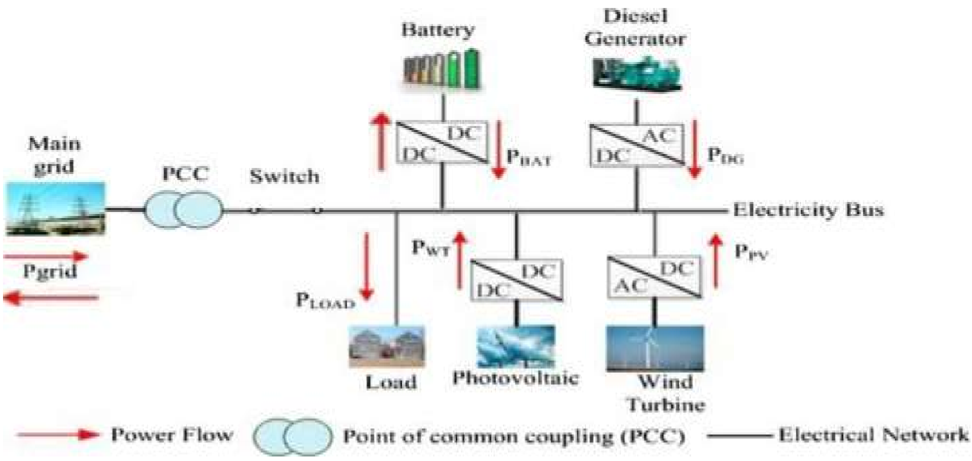


Figure 1.14: Structure of Grid-Connected Microgrid

I.5.3 Networked Microgrids

These types of microgrids consist of several separate distributed energy resources (DERs) and/or microgrids connected to the same utility grid circuit segment and serve a wide geographic area. Networked microgrids are typically managed and optimized by a supervisory control system to operate and coordinate each grid-connected or island mode at different tiers of hierarchy along the utility grid circuit segment. Community microgrids, smart cities and new utility adaptive protection schemes (like closed-loop self-healing) are examples of networked microgrids [31].

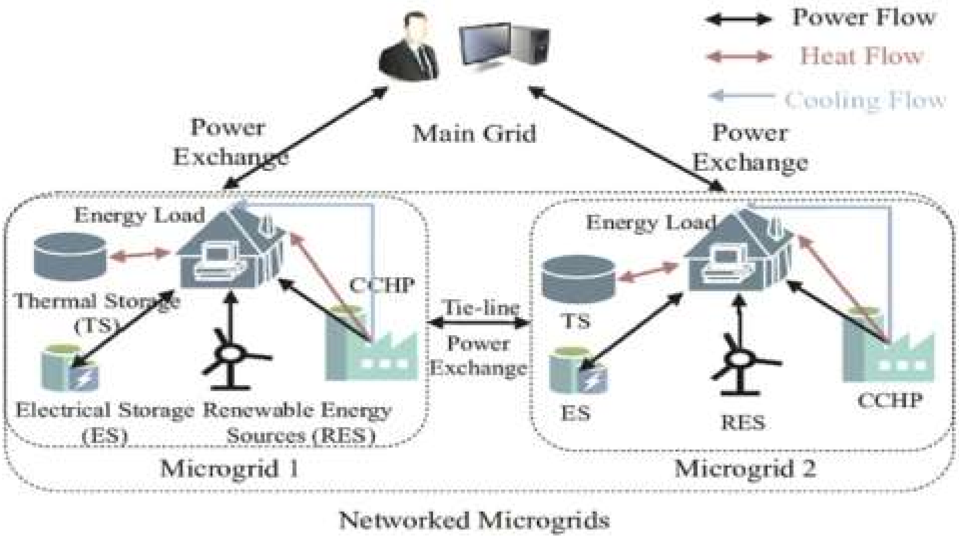


Figure 1.15: Structure of Grid-Network Microgrid

I.6 The caractéristics of the Microgrid

Microgrid can operate in an autonomous mode, making it an ideal solution for integrating renewable energy sources such as solar and wind. Although these sources may be intermittent in production, the system can handle them with smart energy storage technologies that capture excess electricity during periods of high production and release it during periods of low production in order to stabilize the grid and reduce fossil fuel consumption.

Microgrids operate efficiently in areas far from traditional power sources and can be powered by area-based devices. Without the constraints of distance, microgrids provide the ability to generate electricity anywhere and consume it directly from the source, reducing energy loss during transmission. This increases efficiency and reduces operating expenses.

DC microgrids have high power conversion efficiency due to the small number of switches between power sources and loads, which reduces electrical losses. They also have better power transmission capacity due to the absence of reactive power, which improves distribution efficiency and reduces losses in transmission lines. In addition, DC systems provide effective integration with renewable energy sources such as solar panels and batteries, as these sources are already DC-powered, which contributes to reducing the need for additional power converters [32].

AC microgrids are the most popular due to their compatibility with traditional electricity grid infrastructure, which facilitates their integration with public grids. These systems support the operation of a wide range of electrical loads, including residential, commercial and industrial loads, without the need for major infrastructure modifications. They also provide flexibility in accommodating changes in energy demand, as power distribution can be easily controlled through smart grid technologies. However, these systems suffer from losses associated with reactive power, which can affect the efficiency of power distribution and transmission [32].

Islanded microgrids operate without a connection to the main grid, making them ideal for remote areas. They rely on renewable energy sources and storage systems.

Grid-connected microgrids connect to the public electricity grid, allowing for energy exchange, with surpluses exported or electricity imported when needed. They offer greater stability and reduce the need for energy storage.

I.7 Applications of Microgrids

They prove essential in enhancing energy security, supporting sustainability, and providing reliable power in remote areas. They are particularly valuable in integrating renewable energy, improving grid stability, and enabling communities and businesses to manage energy independently [33].

I.7.1 Remote Communities

Microgrids are an ideal solution for remote communities or areas with limited access to centralized power infrastructure. In off-grid or underserved regions, microgrids offer a dependable and sustainable energy source, promoting economic development, enhancing quality of life, and strengthening community resilience [33].The figure1.17 shows a remote area where microgrids were applied and which will be studied in our research.

Figure I.16: Example of Remote Communities (Bella Colla)

I.7.2 Hospitals

Hospitals that use microgrids now have guaranteed power to maintain continuity of services, while also increasing efficiency and sustainability. They are a dependable power source during grid outages, keeping essential medical devices like resuscitators and ventilators functioning. They streamline the incorporation of renewable, such as solar and wind, which alleviate dependence on fossil fuels, and therefore they also help to decrease operating expenses. Moreover, intelligent control systems manage loads, enhance energy efficiency, and minimize electrical losses. Microgrids also play a role in enhanced power quality and rapidity. The figure1.18 shows a application Microgrid in hospitals.

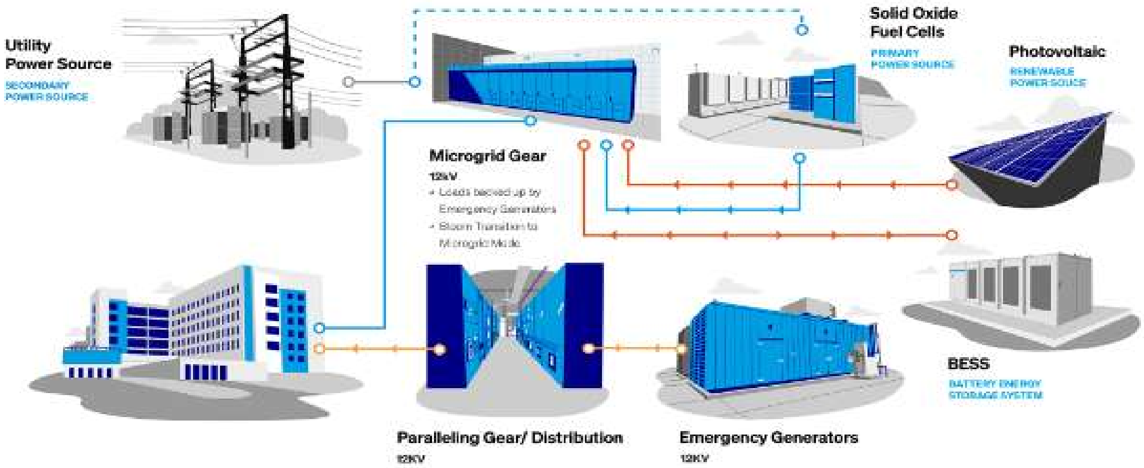


Figure I.17: Application Microgrid in hospitals

I.7.2 Industrial and Commercial Facilities

Industrial and commercial facilities frequently use microgrids to ensure a reliable power supply and minimize the impact of grid disruptions on critical operations. Microgrids provide businesses with greater control over their energy supply, reducing the risk of downtime, productivity losses, and revenue impacts associated with power outages [33].

I.7.3 Military Installations

Military bases and installations use microgrids to improve energy security and operational readiness. Self-sufficient energy systems reduce dependence on vulnerable external power sources, improve mission readiness, and enhance overall resilience in challenging environments [33].

Figure I.18: Application Microgrid in Military Installations

I.7.4 Electric vehicles

Microgrids are utilized in the electric vehicle space for effective and sustainable vehicle charging. They offer intelligent charging stations that utilize renewable energy from sources like solar and wind power. This method lessens the burden on the regular electric grid and lowers greenhouse gas emissions. They also make it possible to manipulate energy supply during peak times using storage systems such as batteries, which helps to maintain a stable electricity supply. In addition, microgrids facilitate V2G (Vehicle to Grid) technologies, where electric vehicles can discharge power into the grid, thus improving the effectiveness of energy distribution. This is particularly useful for smart cities, large parking areas, as well as transit companies, speeding up the delivery of sustainable electric mobility. Electric vehicles are one of the main application areas of microgrid systems.

Figure I.19: Electrics vehicles and Microgrid

I.8 Bella Colla Microgrid

The Bella Coola microgrid system is not connected to the bulk power system. This microgrid is comprised of two generating plants and two communities. The Ah Sin Heek (ASK) generating station has six to eight diesel generators ranging in size from 300 to 2500 KVA. Two of these diesels are manual start. Clayton Falls is a run-of-river hydro-electric plant with two generators having ratings of 720 and 1400 kVA. A single 25 kV feeder connects the two generating stations with the community of Bella Coola tapped from this circuit. The community of Hagensborg is tapped from a second feeder which is fed from the ASK station. Bella Coola and Hagensborg have winter/summer peaks of 2.1/1.5 MW and 2.6/1.7 MW, respectively [34].

The Microgrid control system is composed of a central controller, local controllers, a communication network, and a local HMI for manual operation and monitoring. Each DER will include local control loops that regulate real and reactive powers, or alternatively, frequency and voltage at given reference points. Additional universal relays are added to the control system of diesel and hydro-electric machines to provide additional automations and controls needed. One of the main reasons of such decision is that the original control system is old and only accepts the reference points through motorized operated potentiometer controllable only by raise and low commands. To solve this issue, PID controller is added to universal relays. One PID controller in cascade is assigned for each diesel generator. The PID controller receives the power reference command from supervisory controller, and by getting the actual power as a feedback, it controls the output power of the diesel generator [34].

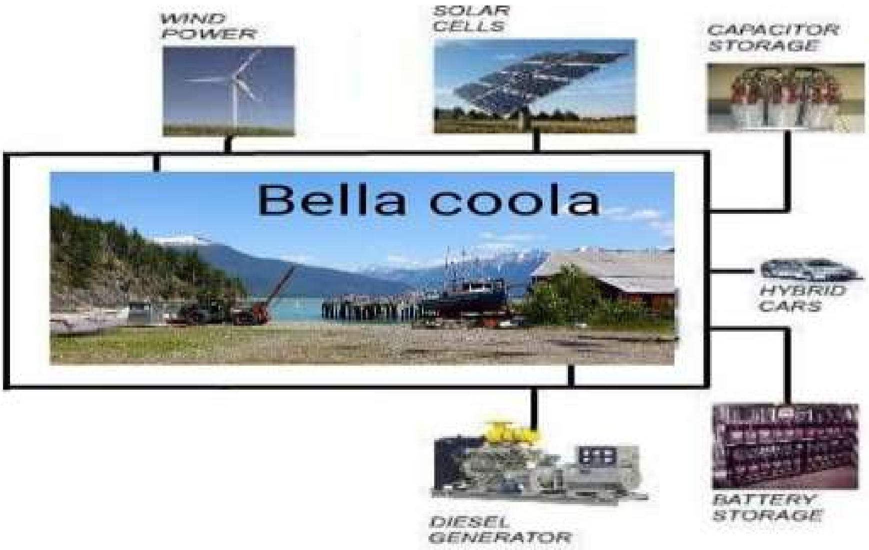


Figure I.20: Bella Coola Microgird System [34]

I.9 Challenges of the Microgrid

While microgrids offer numerous advantages, you'll want to avoid the potential disadvantages and challenges associated with their implementation. These may include [35]:

I.9.1 Initial Investment Costs

The upfront capital costs of designing, installing, and integrating a microgrid can be significant. Microgrids require the installation of distributed generation sources, energy storage systems, control systems, and specialized infrastructure. The initial investment can be a barrier for some organizations, especially smaller businesses or communities with limited financial resources [35].

I.9.2 Complex Planning and Design

Designing a microgrid involves careful consideration of load profiles, generation capacities, energy storage requirements, and control systems. It requires expertise in electrical engineering, energy management, and grid integration. The complexity of the planning and design process can pose challenges, especially for organizations lacking specialized knowledge or resources [35].

I.9.3 Maintenance and Operational Complexity

Microgrids involve multiple components, including generators, renewable energy systems, energy storage systems, and control systems. Ensuring the proper maintenance, operation, and coordination of these components can be complex. Organizations need to have skilled personnel or access to experienced service providers to manage and maintain the microgrid infrastructure effectively [35].

I.9.4 Grid Interconnection and Regulatory Hurdles

Connecting a microgrid to the main grid or ensuring compatibility with existing grid infrastructure may involve regulatory hurdles and interconnection challenges. Depending on the jurisdiction, regulatory frameworks, utility requirements, and grid codes can pose obstacles to microgrid deployment. Resolving interconnection issues and navigating regulatory processes can cost time and money [35].

I.9.5 Dependency on Fuel Availability

Fuel supply disruptions or fuel price fluctuations can affect a microgrid that relies on traditional fossil fuel generators for backup power or primary generation ensuring a reliable and consistent fuel supply another challenge with microgrid systems is the lack of consumer awareness about these systems or how they operate. This lack of awareness can slow the implementation of microgrids.periods can pose a challenge, especially in remote areas or during emergencies [36].

I.9.6 Scalability and Flexibility Limitations

Some microgrids face limitations in scalability and flexibility. The integration of additional generation capacity or the expansion of the microgrid network may require significant modifications to the existing infrastructure or grid configuration. The flexibility to adapt to changing energy demands, technology advancements, or evolving regulatory requirements should be carefully considered during the planning phase [35].

I.9.10 Energy Management Complexity

Optimizing energy management within a microgrid can pose a challenge. Balancing the generation, storage, and consumption of electricity in real-time to ensure grid stability, reliability, and cost-effectiveness requires sophisticated control systems and advanced algorithms. Achieving optimal energy management and addressing dynamic load fluctuations can be complex, particularly for larger and more interconnected microgrids [35].

I.9.11 Limited Economies of Scale

Localized areas or specific facilities are typically served by microgrids, which may limit the economies of scale that can be achieved compared to large, centralized power systems. The relatively smaller scale of microgrids may result in higher costs per unit of energy generated or stored, making it less cost-competitive compared to grid-scale alternatives for some applications [35].

I.10 The Problems Exist in the Microgrid

Microgrid systems suffer from several electrical problems that affect their stability and performance, and frequency instability (fluctuation of frequency) is one of the most prominent challenges. The grid frequency depends on the balance between generation and consumption, and any imbalance in this balance leads to changes that may cause protection systems to operate or even load shedding. The problem becomes more complicated when microgrids are operated in island mode, where reliance on renewable energy sources is high, and these sources are inherently unstable, and the electronic inverters used in the grid do not have sufficient inertia to maintain the frequency when load or generation disturbances occur. In addition, there is the problem of voltage fluctuations resulting from sudden changes in demand or production, which may affect the performance of electrical equipment and increase grid losses. Low power factor is another challenge, as inductive loads such as motors and transformers lead to increased inefficient currents, which increases electrical losses. In addition, harmonic distortion resulting from the use of electronic devices disturbs the sine waveform of voltage and current, which may lead to abnormal heating of equipment and reduce its lifespan. Phase imbalance is also a common problem, especially when the loads are not evenly distributed across the three phases, which leads to high currents flowing in the neutral line and affecting the performance of transformers and generators. The problem of reverse power flow, which occurs when renewable energy production is higher than demand, cannot be ignored, which can lead to unwanted voltage spikes and grid instability. Finally, surge currents represent an additional challenge when operating large loads, as they lead to sudden voltage drops, which can cause unstable operation of sensitive devices. All these issues make it necessary to look for advanced solutions to ensure the stability and efficiency of microgrid systems.

I.11 Protection of Microgrid

Power flow in a conventional distribution network is unidirectional. However, with the integration of DERs the power flow in the distribution systems can be bi-directional. Faults current path may change depending upon the location of the fault. Constant relay settings may be invalid in case of microgrids (especially for the microgrids with an inverter based DGs). Hence, the conventional protection schemes are not valid in the case of microgrids. Microgrids with the ability to operate both in grid connected and islanded mode impose more challenges, and hence, more sophisticated protection schemes are needed for the successful operation of a microgrid [37].

Protection issues (e.g. bidirectional flow, fault current path, relay settings, short circuit capacity) of microgrids have been discussed in literature where several protection schemes have been proposed. In the case of an inverter based DG fault current is limited . Conventional relay systems are not suitable in case of inverter based DGs. Protection strategies can be based on communication, time grading, and other techniques. Time grading technique is used when the primary relay fails to operate during the occurrence of a fault. In such cases, backup relays operate after a specific time delay defined in the settings of the relay. Usually, the network is divided into zones, with each zone having its own protection relay system. Protection scheme for radial distribution systems was presented [38]. A protection scheme that uses microprocessors for the protection of microgrids operating in either grid connected or islanded mode was also presented [39], Adding communication can help improve the level of protection of microgrids hut at the expense of additional cost. In this type of protections system, the circuit breakers and protection relays are connected with a central control unit via a communication network. Optical ethernet communication network which connects the relay devices with the protection and control unit was proposed [40]. Flywheel inverter system was proposed to increase the fault current so that the relays can detect and can clear the fault. Use c of fault current limiters is proposed in [41], where these limiters are used in combination with over-current relays to solve the protection issue [42]. A protection scheme was proposed for inverter based DGs in which differential relay measures the difference in the current between two points [43]. Differential protection is one of the most reliable protection schemes for the protection of microgrids (in both grid-connected and islanded mode). Different protection scheme incorporated with digital communication relays was proposed [44]. Another protection scheme based on communication is the wide area protection (WAP). Protection strategy based on WAP was proposed [45]. Most of the faults in the system are temporary and are automatically removed. Auto reclosing relays give the best protection against such faults. At the time the relay senses the fault, it sends the signal to the circuit breaker to trip. After few milliseconds (or nanoseconds) the relay closes the circuit automatically to check whether it was a temporary fault or not. If yes, the network continues to operate in normal mode. If no, the reclosure relay trips, senses it as the permanent fault and opens the circuit permanently. Adaptive differential over current protection was proposed in which the numerical directional over current relays with directional interlocking capability was used for the protection of radial networks [46].

I.12 Conclusion

In this chapter, we presented a comprehensive study on the microgrid, which included its definitions and components, as it was found that allows it to operate independently or in integration with the main network or in integration with the main network. We also reviewed the energy sources used, such as solar energy and wind energy, with diesel serving as a reserve source to ensure supply continuity. We discussed the importance of storing energy in enhancing system stability and improving its efficiency. In addition, we discussed the challenges associated with microgrids and their characteristics that make it an effective solution, especially in remote areas. Since Bella Colla is the subject of our study, we will move in the next chapter to the modeling of the microgrid system in it, as we will depend on mathematical methods and modeling techniques to analyze its performance and study the factors that affect its operation, with the aim of improving its efficiency and ensuring its reliability.

II.1 Introduction

Modeling is the primary mechanism that drives the analysis and the study of microgrids. It becomes a possibility for the efficient and stable operation of these to make use of modeling of their different parts. The wind and solar energy systems depend solely on those. These are renewable; it is their inherent feature to be non-consistent in their natures that is why the systems need to develop control strategies in order to balance energy production and consumption. For backup, a diesel engine becomes the integral part to cover the anticipated deficit in the renewable energy production, particularly in the times of high load. Typically, the absence of the main power line in a microgrid implies that energy storage is crucial for ensuring the continuous availability of electric power. Taking electric vehicles into account, it is necessary to support operation by storage. Also, during microgrid operation, the storage of electric supply with batteries would ensure the continuous availability of electricity and hence support the operation of electrical loads, especially electric vehicles. In this chapter, we will focus on modeling these fundamental elements, wind energy, solar energy, diesel engine, and energy storage systems, to study how to achieve efficient and sustainable operation of microgrids in an off-grid environment.

II.2 Modeling of Bella Coola Microgrid

As part of this work, we modeled the Bella Coola Microgrid, an isolated grid for the production and distribution of electrical energy. This grid relies on an integrated mix of renewable and conventional energy sources to ensure energy demand is met while meeting sustainability and reliability standards. This grid consists of several production sources, including solar (photovoltaic), wind turbine, and hydropower, in addition to diesel generators, which are used as a backup solution in emergencies or when renewable energy production is low. To achieve greater stability in power management within the grid, various energy storage systems were integrated to play a pivotal role in storing excess energy and reusing it when needed. A hydrogen energy storage system was adopted, which allows excess electrical energy to be converted into hydrogen gas through electrolysis, then stored and reconverted to electrical energy using fuel cells when needed. In addition, a pumped hydro storage system was used, which relies on exploiting excess energy to pump water into an overhead reservoir and then recovering it to produce electricity via turbines during peak periods or when energy production is in short supply. Other storage systems, such as batteries, were also employed to store energy in the short term and improve grid dynamics.

This modeling aims to study the performance of the Bella Coola Microgrid, as shown in the figureII.1.

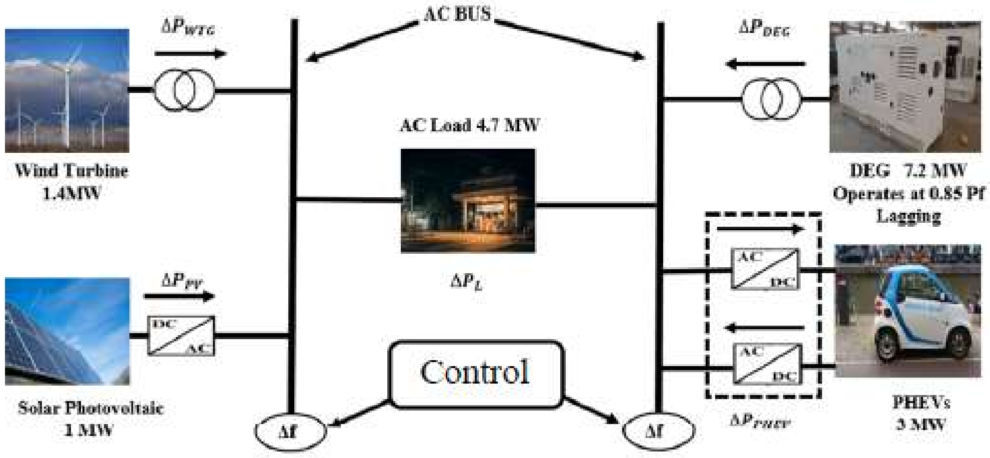


Figure II.1: Structure overview on proposed isolated microgrid system Bella Coola

II.3 Modelling of Energy Resources

This chapter 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 [47]. The significance of this chapter 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 [48]. The islanded microgrid operation serves as a pivotal juncture in the chapter, with accompanying Figure II.1illustrating 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 [49].

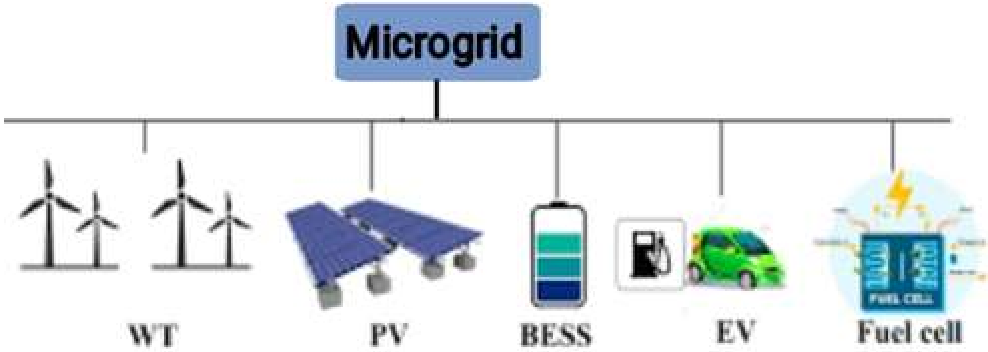


Figure II.2: Distributed energy resources and microgrid

II.4 Renewable Energy Sources Modeling (RES)

Renewable energy sources (RES) play a vital role in achieving sustainability and reducing dependence on fossil fuels. The goal of modeling these sources is to develop accurate mathematical models and simulation representations that help in analyzing their performance and integration with electrical grids. These models include solar and wind power plants, where the impact of environmental variables on energy production and efficiency is evaluated. Through accurate modeling, operation and control strategies can be optimized, contributing to the enhanced stability and safety of modern energy systems. Below we will review these models in detail, focusing on the influencing factors and different analysis methods.

II.4.1 Photovoltaic Cells

A photovoltaic cell is an electronic device that converts light energy from the sun directly into electrical energy using the photovoltaic effect. They are primarily composed of semiconductor materials such as silicon, where sunlight excites electrons within the material, generating a direct electric current. These cells are used in solar panels to produce electricity in a clean and sustainable way, helping to reduce dependence on conventional energy sources. Despite their significant benefits, such as reduced pollution and lower operating costs, their efficiency is affected by the amount of sunlight available, and their initial cost can be high.

II.4.1.1 Modeling of the Solar Cell

Ideally, a PV cell is modeled by a current generator with a diode in parallel. In this configuration, the current injected by the source is representative of the energetic sunshine (also called irradiance) and of the PV cell surface. The current voltage property I (V) of the diode is non-linear and gives a fairly accurate account of the I (V) behavior of the cells [50].

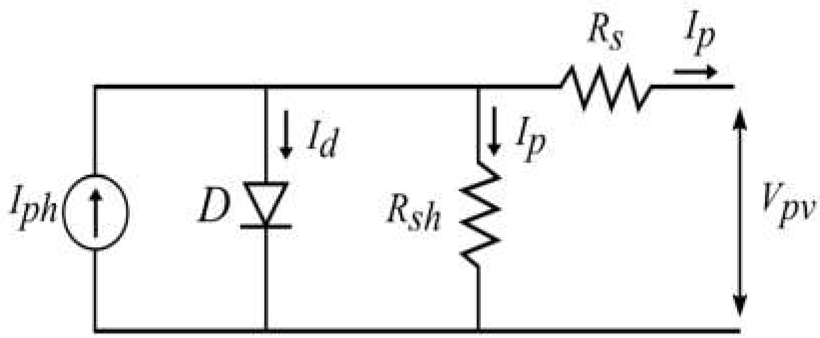


Figure II.3: Equivalent diagram of a PV cell

Two resistors are added to the model. One in series R_s and the other in parallel (R_{Sh}). Resistance R_s characterizes the voltage drops due to the connection contacts between the different cells while resistance RSh characterizes the leakage current in the diode [10]. The equivalent electrical model of a PV cell is given in Figure II.3.

The mathematical model which governs the diagram of Figure II.3is indicated in the equation$(II.1)$[4].

$$\mathrm{I_{pv}} = I_{ph} - I_s\left(e^{\frac{Q(V_{pv}+R_S.I_{PV}}{n.K.T}-1}\right) - \frac{V_{pv} + R_s.I_{pv}}{R_{sh}} \qquad (II.1)$$

With:

I_{ph} The photocurrent (A)

$\mathrm{I_{pv}}$ Current delivered by the cell (A)

V_{pv} Voltage generated by the cell (V)

I_s Diode saturation current (A)

T Cell temperature (K)

n Cell ideality factor (n between 1 and 2)

K Boltzmann constant, K = 1.38 × 10−23 (J/K)

Q Charge of an electron, Q = 1.16 × 10−19 (C)

The current-voltage I (V) and power-voltage P (V) characteristic curves of PV cell obtained are shown in Figure II.4.

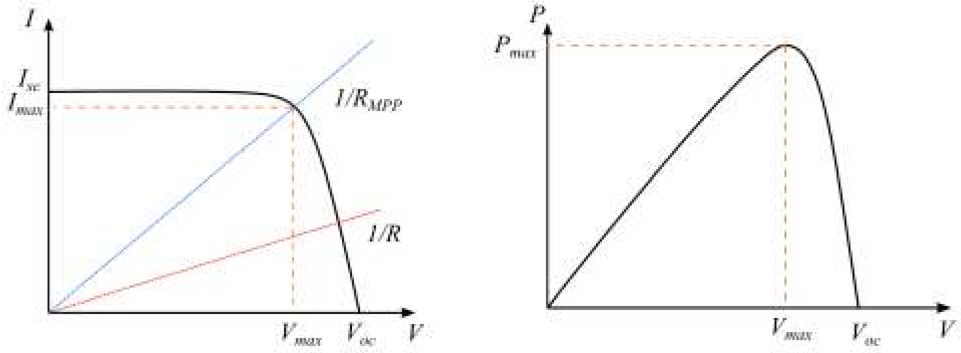


Figure II.4: I (V) and P (V) characteristic curves of a PV cell

Thus, the mathematical model of the PV modulus can be obtained by considering the following equations: [51]

$$I_{mpv} = N_p \times \text{Ipv} \quad (\text{II. }2)$$

$$V_{mpv} = N_S \times \text{Vpv} \quad (\text{II. }3)$$

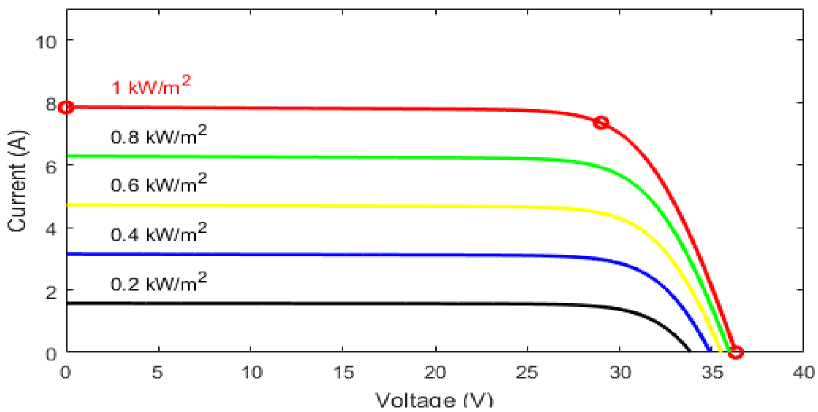
I_{mpv} PV module current (A)

V_{mpv} PV module voltage (V)

N_S Number of PV cells connected in series.

N_p Number of PV cells connected in parallel.

To develop the modelling and carry out the simulation of a solar panel model, the Module type: 1Soltech 1STH-215-P is one of the types to be used in our experiment by using MATLAB. However, if the light shines brightly enough, the temperature of the cells will rise above 25°C. For various irradiances and temperatures, I_V and P_V curves were simulated [52].which gives us this result from the simulation shown in Figures [II.5 to II.8].



FigureII.5: characteristics, varying irradiance at constant temperature

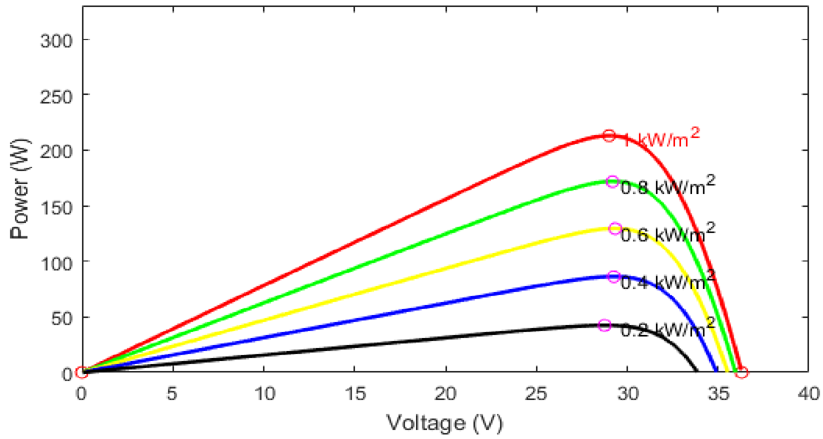


Figure II.6: 7-P–V characteristics, varying solar radiation at constant temperature

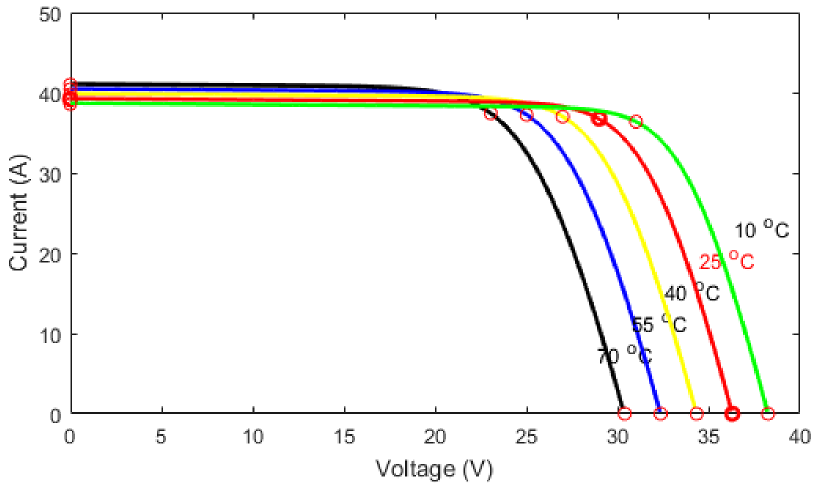


Figure II.7: characteristics, varying temperature at constant solar radiation

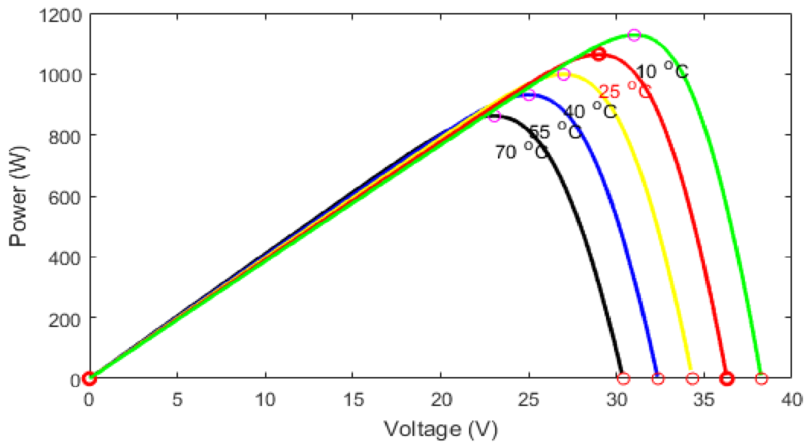


Figure II.8: P–V characteristics, the varying temperature at constant solar radiation

II.4.1.2 Mathematical Modelling

Design and installation of PV generator performance under natural irradiation is a crucial challenge to cope with PV power generating integration in microgrids. The equation (II.7) represented the PV power output per unit area from a PV generator with a fixed orientation [53].

$$P_{PV} = \eta_{PV}(t) \cdot A_{PV} \cdot I_r(t) \qquad (II.4)$$

Where:

ηpv The module's power conversion efficiency (power output from the system divided by power input from the sun)

A_{PV} ($m2$) The surface area of PV panels

Ir ($W\backslash m2$) The solar irradiations.

The efficiency of a PV generator can be determined by the following formula:

$$\eta_{PV} = \eta_r . \eta_{pc}\left(1 - \beta(T_c - NOCT)\right) \qquad (II.5)$$

The reference module efficiency η_r is determined by the cell material. With 13% efficiency, polycrystalline silicon technology was utilized. β is the temperature coefficient of the generator, ranging from 0:004 to 0:006 (°C). The cell temperature (**°C**) is denoted byT_c. The following equation (II. 6) can be used to predict a PV module of polycrystalline silicon solar cells based on the ambient temperature T (**°C**) and sun irradiation Ir.

$$T_c = 30 + 0.017(I_r(t) - 300) + 1.14(T(t) - 25) \qquad (II.6)$$

Using the above concept, the photovoltaic output model may be stated as

$$P_{PV} = \eta_{PV}(t) \cdot A_{PV} \cdot I_r(t)\left(1 - 0.0035(T(t) - 25)\right) \qquad (II.7)$$

The output power (in watts) of the studied PV system is determined by

$$P_{PV} = \eta . S . \Phi\left(1 - 0{,}0035(T_a - 25)\right) \qquad (II.8)$$

Where η ranging from 9% to 12% is the conversion efficiency of the PV array, S (= 4084 m^2) is the measured area of the PV array, Φ (= 1 kW/m^2) is the solar radiation, and Ta is the ambient temperature in degree Celsius. The value of PPV depends on Ta and Φbecause η and S are constant. In this work, Ta is kept at 25 $\circ C$ and PPV is linearly varied with Φ only. [53]

The characteristic of a PV system is illustrated in [8]. Large PV system generates dc voltage that is converted into ac using a dc-ac converter. A PV array should operate near the peak point of the V−P curve to extract maximum power under a given irradiance and cell-surface temperature. Power output (in Watts) of a PV array that varies with irradiance and cell-surface temperature is illustrated in [54].

II.4.2 Wind Turbine Modeling

Wind turbine modeling requires the modeling of the wind, the aerodynamic behavior of the blades, the electric generator, the power converter and the system.

This chapter is composed of three parts:

- A first part is devoted to the modeling of the mechanical part of the wind turbine, where the wind model and its evolution will be studied in detail,
- The second part is devoted to the modeling of the permanent magnet synchronous machine, and we will end this part with a simulation of these configurations in generator operation.
- In the third and final part we will present the modeling of the associated converter.

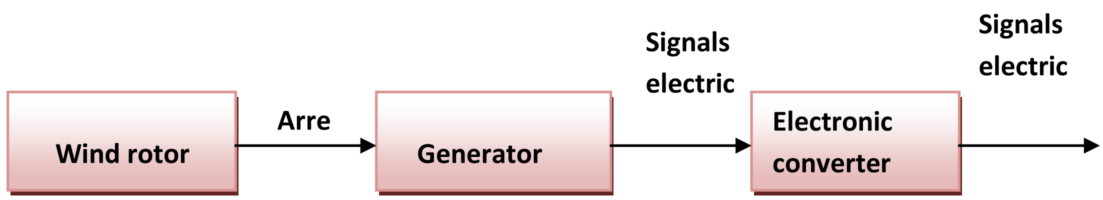


Figure II.9: Wind conversion system structure

II.4.2.1 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 [55].

The base wind-speed component can be expressed by [55]

$$V_{WB} = K_B \tag{II.9}$$

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

$$V_{WG} = \begin{cases} 0, & t < T_{1G} \\ V_{COS}, & T_{1G} < t < T_{1G} + T_G \\ 0, & T_{1G} + T_G < t \end{cases} \tag{II.10}$$

$$V_{cos} = \frac{MAXG}{2}\left[1 - \left[\cos 2\pi\left(\frac{t}{T_G}\right) - \left(\frac{T_{1G}}{T_G}\right)\right]\right] \tag{II.11}$$

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:

$$V_{WR} = \begin{cases} 0\,, & t < T_{1R} \\ V_{ramp}\,, & T_{1R} < t < T_{2R} \\ 0, & T_{2R} < t \end{cases} \qquad (II.12)$$

$$V_{ramp} = (MAXR)\frac{1-(t-T_{2R})}{T_{1R}-T_{2R}} \qquad (II.13)$$

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 < 25 1s during the simulations. The noise wind-speed component can be expressed by:

$$V_{wN} = 2\sum_{i=1}^{N} \sqrt{s_v(w_i)\Delta w}\, cos(w_i t + \varphi i) \qquad (II.14)$$

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

$$S_v(w_i) = \frac{2k_N F^2 |w_i|}{\pi^2[1+(Fw_i/\mu\pi)^2]^{4/3}} \qquad (II.15)$$

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:

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \qquad (II.16)$$

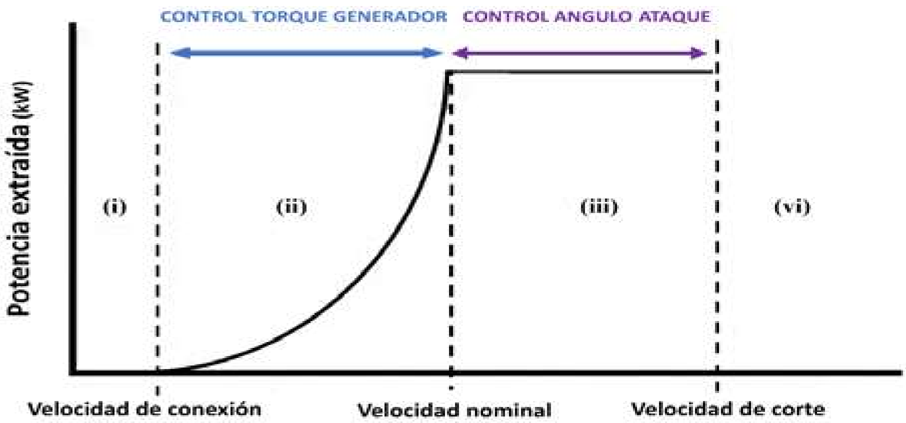


Figure II.10: Characteristic curve of output mechanical power versus wind speed of the studied WTGs

II.4.2.2 Mathematical model

The kinetic energy of large air masses that move across the earth's surface is transformed into mechanical energy using a wind turbine in the wind generation system.

The wind turbine rotates thanks to the kinetic energy received by the blades. Also, the generator rotates in the same direction and is directly or indirectly connected with the turbine by a gearbox. The generator, therefore, generates electricity according to the Faraday law.

The overall principle is that the kinetic energy becomes mechanical energy, and mechanical energy is finally turned into electrical power (Pwt).

The WTG is characterized by non-dimensional curves of power coefficient Cp as a function of both tip speed ratio λ and blade pitch angle β. The tip speed ratio, which is defined as the ratio of the speed at the blade tip to the wind speed [53] can be expressed by

$$\lambda = \frac{R_{blade}}{\omega_{blade}} \quad \text{(II.17)}$$

Where

R_{blade} The radius of blades (23.5 m)

ω_{blade} The blade rotational speed (3.14 rad/s)

The wind turbine must be designed to withstand large forces during storms because the force extracted on the rotor is proportional to the square of the wind speed. The majority of modern designs are three-bladed horizontal-axis rotors, which provide a good value of peak Cp [56].

The power coefficient Cp indicates how much energy is extracted from the wind by the turbine. It varies depending on the rotor design and the relative speed of the rotor and the wind (known as the tip speed ratio), with a maximum practical value of about 0.4 [56]. The power coefficient Cp is determined by the tip speed ratio and pitch angle, both of which will be investigated further. Blade element theory [57], must be used to calculate the performance coefficient. Because this requires aerodynamics knowledge and the computations are quite complex, numerical approximations have been developed. [57].

The expression for approximating Cp as a function of λ and β is given by

$$Cp = (0.44 - 0.0167\beta).\left[\frac{\pi(\lambda-3)}{15-0,3\beta}\right] - 0,0184(\lambda-3)\beta \quad \text{(II.18)}$$

The governing equations representing mechanical power output from the wind turbine may be given by

$$Pw = \frac{1}{2} \cdot \rho \cdot A_r \cdot C_P V_w^3 \quad \text{(II.19)}$$

Where

P Power (W)

Cp Power coefficient

Vw Wind velocity (m/s)

Ar Swept area of rotor disc (1735 $m2$)

ρ Density of air (1.225 *kg/m*3)

II.4.3 Hydroelectric Power

Hydroelectric power is one of the most important sources of electricity production in the Bella Coola region, especially given the abundance of rivers and water flowing from the surrounding mountains. This has allowed the power of flowing water to be harnessed to generate energy in a natural, clean, and environmentally friendly way. The idea of generating electricity in Bella Coola is based on building hydroelectric power stations near rivers. Large quantities of water are stored behind dams. When electricity is needed, the gates are opened, allowing the water to flow rapidly toward turbines. These turbines resemble a large fan, and when the moved by the force of the water, they spin generators that convert this movement into electrical energy. The electricity is then transmitted to special stations to increase the voltage so that it can be easily distributed to homes and public facilities in Bella Coola. This method is environmentally friendly and does not pollute the air. Furthermore, the region's abundant rainfall and constant water availability ensure continuous electricity production throughout the year without interruption.

Hydroelectric power in Bella Coola has thus become a successful example of harnessing nature to serve humanity, providing clean, renewable energy that preserves the environment and meets the needs of the population in a sustainable manner.

II.4.3.1 Hydroelectric Mathematical Modelling

The output power of a single micro-hydro turbine is given by; [58]

$$P_{MHP} = \eta\, 9.81\ Q\ h \qquad (II.20)$$

P_{MHP}Output power of the micro-hydro in the current time step [kW]

η Hydro turbine efficiency

Q water flow rate [m3/s]

h Net available water head [m]

According to, the output power of run of the river that operates with low and medium heads can be calculated as;

$$P(h,q) = \eta(q).h.q \qquad (II.21)$$

$P(h,q)$Hydropower output with current head and flow rate [kW]

$\eta(q)$ Turbine efficiency at the current flow rate

Where $q = \sqrt{h}$ $(II.22)$

Equation (5) applies to ROR with a low head, and the head is the square of the flow rate

Where $h = q^2$ (II.23)

Equation (II.23) is very important since we only know the flow rate from the historical date to be provided by Anambra Imo River Basin.

Substituting equation (II.22) to equation (II.23)

$$P(h,q) = \eta(q).q^3 \quad (II.24)$$

$$P(h,q)(t) = \eta(q).q^3(t) \quad (II.25)$$

II.5 Modeling of Conventional Sources

II.5.1 Diesel Generator

Diesel engines are internal combustion diesel engines that convert chemical energy into mechanical energy. This process moves pistons up and down inside cylinders, which then creates motion that is converted into electricity [59].

To get a diesel engine up and running, the process begins with the starter motor cranking the engine, which in turn rotates the crankshaft. This movement causes the pistons to move up and down within the cylinders. As the piston ascends, it compresses the air inside the cylinder, significantly increasing its temperature. At the peak of this compression stroke, diesel fuel is injected into the hot, compressed air [59].

The high temperature causes the diesel to ignite spontaneously, creating a small explosion that forces the piston back down. This cycle repeats rapidly, powering the engine. Diesel engines rely on this compression ignition process [59].

The Diesel Engine Generator is integrated as a secondary source that enhances renewable sources when a sudden change occurs in wind speed and solar radiation. One of the most utilities of the use of microgrid is to reduce the energy cost and the greenhouse emissions. [60].

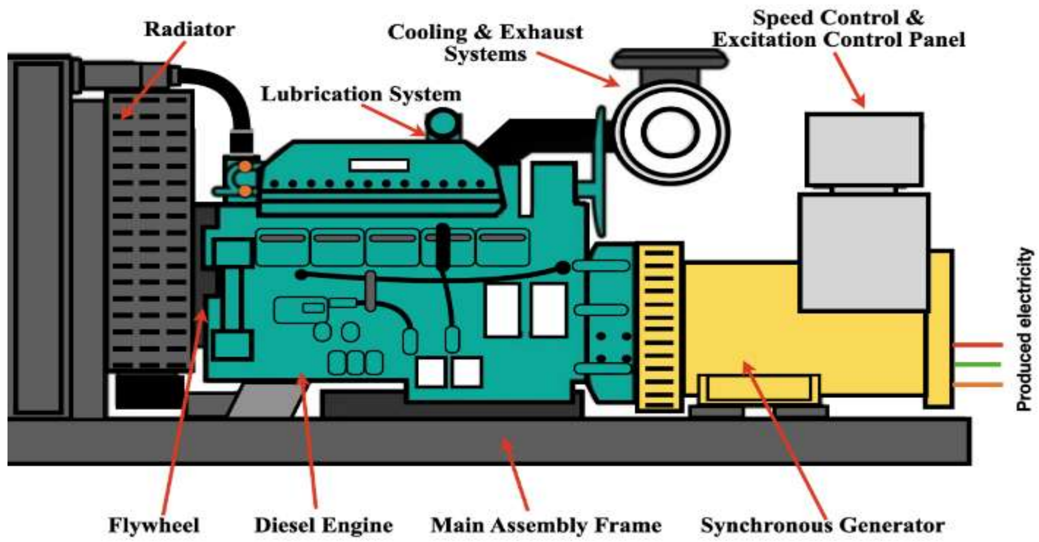
II.5.1.1 Components of the Diesel Generator

A diesel engine consists of various components, including essential electrical parts that ensure startup and power generation.

a. Starter Motor: Draws power from the battery to initiate engine operation by rotating the crankshaft.

b. Alternator (Dynamo): Converts the engine's mechanical energy into electrical energy to charge the battery and power electrical systems.

c. Battery: Supplies the initial power for the starter motor and supports other electrical components.



FigureII.11: The components of the Diesel Generator

II.5.1.2 Mathematical Model of a Diesel Engine System in a Microgrid

In a microgrid, a diesel engine is typically used as a Diesel Generator (DG) to supply electrical power. The mathematical model of a diesel engine system in a microgrid consists of mechanical, electrical, and control system equations to describe its operation and interaction with other components like loads, renewable energy sources, and energy storage systems.

a. Fuel Consumption Model

The fuel consumption rate is given by:

$$\dot{m_{fuel}} = \frac{P_{mech}}{\eta_{fue}.LHV} \tag{II.26}$$

m_{fuel} Fuel mass flow rate (kg/s)

P_{mech} Mechanical power output of the engine (W)

η_{fue} Engine fuel efficiency

LHV Lower heating value of diesel fuel (J/kg)

b. Engine Speed and Torque Dynamics

The mechanical torque produced by the diesel engine is:

$$T_{eng} = \frac{P_{mech}}{\omega} \tag{II. 27}$$

T_{eng} Engine torque (Nm)

ω Angular speed of the engine (rad/s)

The engine rotational dynamics are given by:

$$J\frac{d\omega}{dt} = T_{eng-} - T_{load} \tag{II.28}$$

J Moment of inertia (kg·m²)

T_{load} Load torque applied by the generator (Nm)

c. Generator Voltage Equations

For a synchronous generator, the electrical model is given by:

$$V = E - I(R + jX_s) \qquad (II.29)$$

V Terminal voltage

E Internal induced voltage

I Output current

R Stator resistance

X_s Synchronous reactance

The dynamic model of a DEG for small signal analysis is expressed by Equation (II.30) [61]

$$\frac{d\Delta P_{DEG}}{dt} = \frac{K_{DEG}\Delta P_C}{T_{DEG}} - \frac{K_{DEG}\Delta F}{RT_{DEG}} - \frac{\Delta P_{DEG}}{T_{DEG}} \qquad (II.30)$$

Where

T_{DEG} Respectively the DEG time constant

K_{DEG} Respectively the DEG gain

R The speed drop coefficient

ΔP_{DEG} The changes in DEG power

ΔP_C The changes in the control signal applied to the DEG

ΔF The frequency changes

II.5.2 Modeling of Fuel Cell System

Fuel cell is a device that converts chemical energy from fuel into electricity. Electricity was form through a chemical reaction of positive charged hydrogen ions with oxygen or other oxidizing agent [62].

Fuel cells have variety of different types as shown in Figure II.12. Each of it consist of an anode, a cathode and electrolyte which allow positive charged hydrogen ions to move between the two sides of fuel cell. To generate positive hydrogen ions and electrons, each anode and cathode contains catalysts which caused the fuel to oxidize. After the oxidation reactions, the hydrogen ions are drawn to the electrolyte. Simultaneously, through an external circuit, electrons are also drawn from the anode to the cathode. This helps produced direct current electricity. Hydrogen ion, electrons, and oxygen react with each other at the cathode to form water [63].

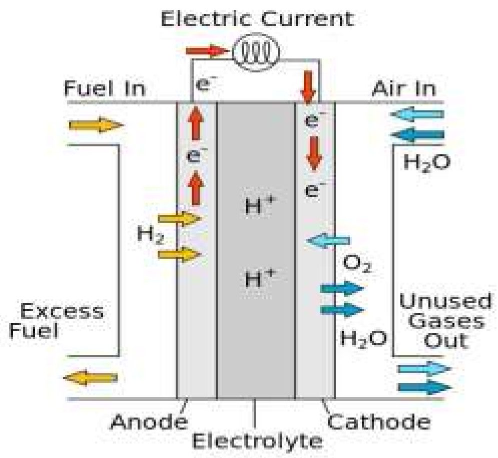


Figure II.12: Construction of fuel cell [17]

The two half reactions occur in the fuel cell are:

At anode:

$$H_2(g) \rightarrow 2H^+ + 2e^- \quad \text{(II.31)}$$

At cathode:

$$\frac{1}{2}O_2(g) + 2H^+ + 2e^- \rightarrow H_2O \quad \text{(II. 32)}$$

Overall reaction:

$$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O \quad \text{(II. 33)}$$

The fuel cells generate direct current. According to the power rating, there are numerous way of a fuel cells was chosen. 1KW fuel cells has the output voltage range 25-50V while 30KW and above of fuel cells can have output voltage range 200-400V. [64].

The drawing for the circuit is using simplified model as shown in Figure 6. The simplified model corresponds to a particular fuel cell stack operating at nominal conditions of temperature and pressure. [65].

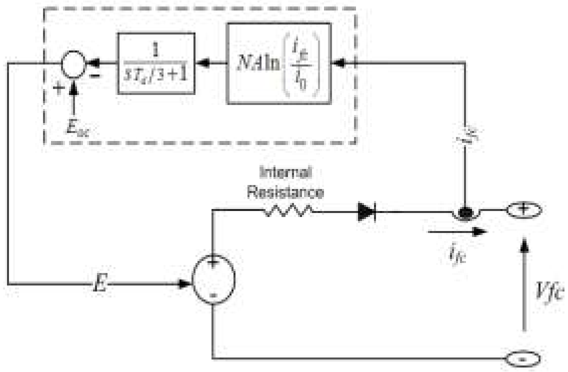


Figure II.13: Simplifie model

$$E = E_{oc} - \frac{1}{s\frac{T_d}{3} + 1} N.A.\ln\left(\frac{i_{fc}}{i_0}\right) \quad \text{(II. 34)}$$

E Open Circuit Voltage

A constant related to the exchange current density

i_0 The reference exchange current density

i_{fc} The fuel cell current.

$$V_{ohm} = R_{int} i_{fc} \tag{II.35}$$

V_{ohm} Ohmic Voltage Drop

R_{int} Internal resistance

$$V_{fc} = E - V_{ohm} \tag{II.36}$$

$$V_{fc} = E_{oc} - \frac{1}{s\frac{T_d}{3}+1} N.A.\ln\left(\frac{i_{fc}}{i_0}\right) - R_{int} i_{fc} \tag{II.37}$$

The dynamic model of a fuel cell for small signal analysis is expressed by Equation (II.38) [63]

$$\frac{d\Delta P_{FC}}{dt} = \frac{K_{FC}\Delta P_{AE}}{T_{FC}} - \frac{\Delta P_{FC}}{T_{FC}} \tag{II.38}$$

Where

T_{FC} Respectively the FC time constant

K_{FC} Respectively the FC gain

ΔP_{FC} The changes in FC output electrical power

II.6 Model of the Plug-in Hybrid Electric Vehicles (PHEV)

Electric vehicles are considered an important element in this work as they serve two functions: acting as a load and serving as a source for energy storage and load financing in case renewable energy sources fail .They represent an alternative for energy storage to meet needs in controlling frequency deviations in the microgrid.

The energy present in electric vehicles can be expressed based on frequency deviation as [66]:

$$\Delta P_{PHEV} = \begin{cases} -\Delta P_{MAX}, U_C < -\Delta P_{MAX} \\ -\Delta P_{MAX}, U_C > -\Delta P_{MAX} \\ U_C, | U_C | \leq \Delta P_{MAX} \end{cases} \tag{II.39}$$

Where U_C is the output signal determines whether the ΔP_{PHEV} will be employed for either charging or discharging purposes [66]; P_{max} is the maximum power that can be obtained from an individual electric vehicle.

The battery's state of charge (SOC) influences the value of *KEV* Figure II.14 depicting the relationship between K_{EV} and SOC for PHEV [67, 68].

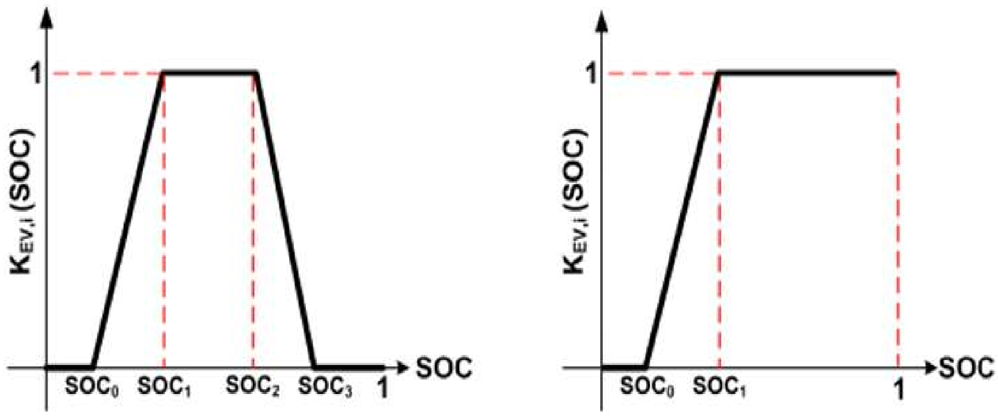


Figure II.14: Representing the charging and discharging PHEV

II.7 Energy Storage System in Bella Colla

In the Bella Coola region, which relies on microgrids to provide electricity, energy storage plays a vital role in ensuring grid stability and efficiency. Given the intermittent nature of renewable energy sources such as solar and wind, storage systems help balance supply and demand, ensuring energy availability even during times of low production. Energy storage technologies are diverse and include electric batteries such as lithium-ion batteries, pumped hydroelectric storage, and hydrogen storage systems. In this work, we will expand on these types of storage systems used in the Bella Coola region and their impact on the performance and sustainability of the microgrid.

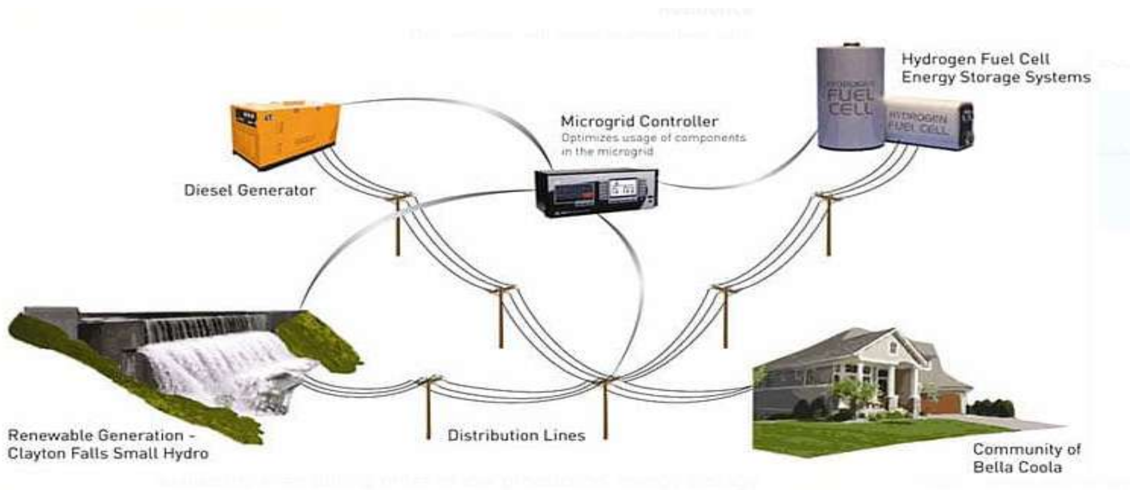


Figure II.15: storage energy systéme in Bella Coola

II.7.1 Battery Energy Storage Systéme (BESS)

II.7.1.1 Structure and Mechanism of Charging and Discharging

Structure and Charge/Discharge Process

In terms of structure, the cell (storage) consists of the following basic elements [69]:

a. Positive Electrode: It is often made of metal oxide or oxygen, and it gives electrons to the external circuit.

b. Negative Electrode: It is usually made of metal or hydrogen, and it receives electrons from the external circuit.

c. The Electrolyte is the medium that allows the internal transfer of ions between the two electrodes.

d. The Separator is an electrical insulator that allows the passage of ions without electrons, as in super-capacitors.

e. The Collector: It is used to collect current along the negative and positive electrodes. Copper is usually used to connect the anode to the outside and aluminum to connect the cathode.

The principle of operation of the battery depends on the external movement of electrons through the source (or load) and on the internal movement of ions within the electrolyte [70].

The cell is charged by connecting it to a direct current source called the charger, where the positive pole of the charger is connected to the positive pole of the battery and the negative pole of the charger is connected to the negative pole of the battery.

Figure II.16 shows the movement of charges during the charging process, as electrons move from the positive pole of the battery through the external circuit to the negative pole of the battery, positive charges move from the negative pole to the positive pole through the electrolyte until the charge is complete [69].

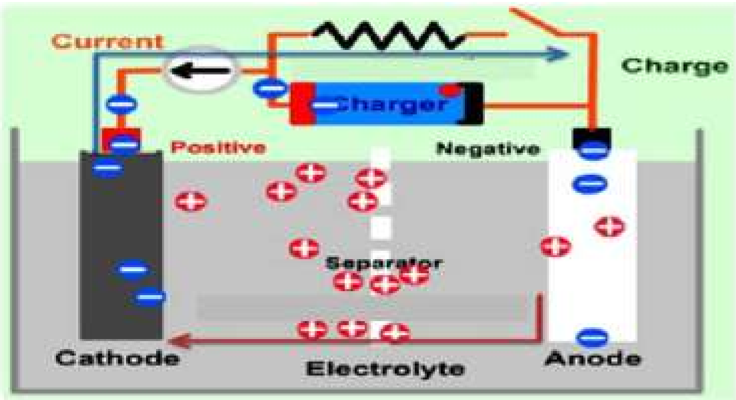


Figure II.16: The movement of shipments during the shipping process

To discharge the battery, the charger circuit is disconnected and a discharge resistance load is connected to the battery terminals. Figure II.17 shows the movement of charges during the discharge process. When the discharge process begins, oxidation reactions occur on the negative pole, which leads to the loss of electrons from this pole.

The electrons resulting from the oxidation exit the negative pole through the external circuit (load) of the battery until they reach the positive pole and participate in the reduction reactions on it. The movement of ions inside the electrolyte is complementary to the movement of electrons, but its details depend on the materials that make up the electrolyte and the poles [69].

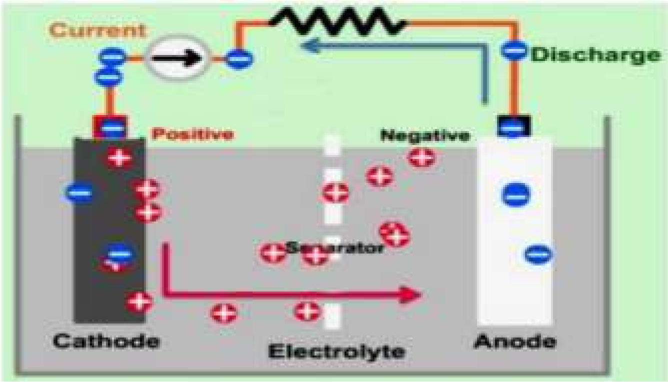


Figure II.17: The movement of shipments during the discharge process

II.7.1.2 Mathematical Modeling of the Battery

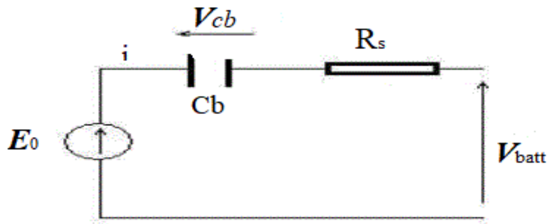


Figure II.18: Simple equivalent circuit of the battery [71]

C_{bat} The nominal capacity of the battery Q_c is the amount of charge missing compared to C_{bat}.E_0Is the voltage source and R_s is the series resistance [72].

So we have:

$$V_{bat} = E_0 - R_s * i - V_{cbat} \qquad (II.40)$$

The battery's state of charge (SOC) is also defined by:

$$SOC = 1 - \frac{Q_d}{C_{bat}} \qquad (II.41)$$

Charging:

$$C(t+1) = C(t) - \Delta t\, P_t^{B,c} \mu_c \qquad (II.42)$$

Dischargind : $C(t+1) = C(t) - \frac{\Delta t P_t^{B,c}}{\mu_d}$ (II. 43)

$$0 \leq P_t^{B,c} \leq P_t^{c,max} \qquad (II.44)$$

$0 \leq P_t^{B,d} \leq P_t^{d,max}$ (II.45)

$C(t)_{min} \leq C(t) \leq C(t)_{max}$ (II.46)

Where:

$C(t)$ The battery capacity at time t

$P_t^{B,c}$The battery charging power

$P_t^{B,d}$The battery discharging power

$P_t^{c,max}$ The maximum value of $P_t^{B,c}$

$P_t^{d,max}$ Denotes the maximum value of $P_t^{B,d}$

The variation of the BESS powers for small signal analysis is expressed by Equation (II.47) [73]

$$\frac{d\Delta P_{BESS}}{dt} = \frac{k_{BESS}\Delta U_{BESS}}{T_{BESS}} - \frac{\Delta P_{BESS}}{T_{BESS}} \quad \text{(II.47)}$$

Where

T_{BESS} Respectively the BESS time constant

k_{BESS} Respectively the BESS gain

$d\Delta P_{BESS}$ The changes in BESS power

ΔU_{BESS} The changes in the control signal applied to BESS respectively

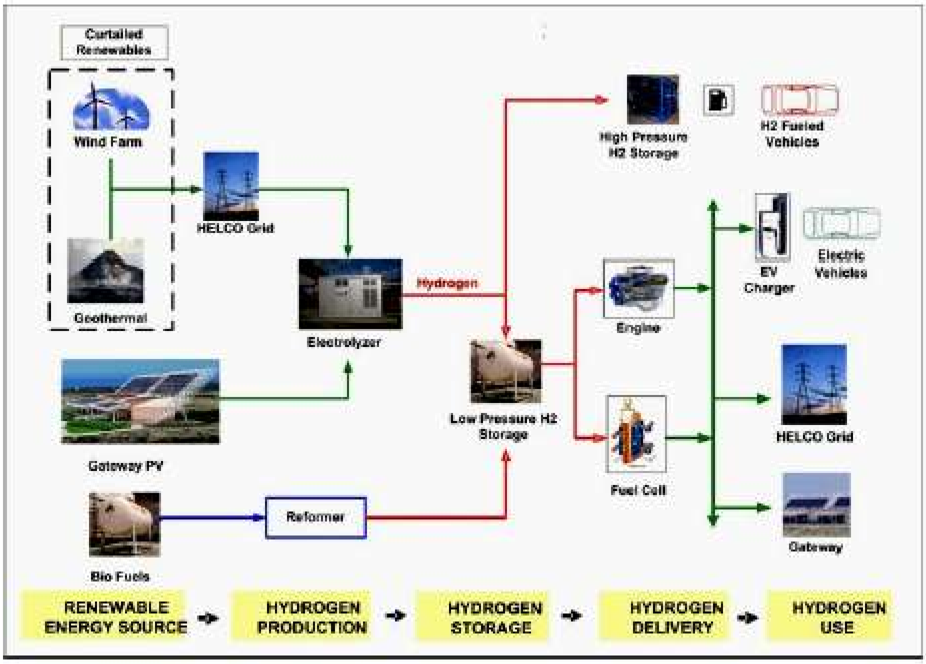
II.7.2Hydrogen Energy Storage

Bella Coola designs, assembles, installs, and operates hydrogen storage systems that optimize the use of renewable energy sources. Using electrolyser to generate hydrogen from surplus electrical power; the hydrogen is compressed and stored as a high-pressure gas. On demand, the compressed hydrogen can be passed through fuel cells to regenerate electrical power or used to power hydrogen-powered vehicles [74].

British Columbia designed, built, installed, and operated a hydrogen energy storage system in Bella Coola. The Hydrogen Assisted Renewable Power (HARP) project uses an electrolyzer to generate hydrogen from a renewable energy source. The system compresses and stores the hydrogen at a pressure of 200 bar (20 MPa). PEM fuel cells are used to convert the hydrogen into 100 kW of electricity during peak demand periods. The pilot project uses a microgrid control system to balance the electrical load between the renewable energy source, diesel generation, and power provided by the fuel cells [73].

Hydrogen is the universal and eternal fuel that will not run out over the ages. It is the fuel that does not produce any polluting or harmful emissions when burned. It also has the highest calorific value per unit mass among all energy carriers available on Earth [74], and its flame temperature is very high (above (2200)). In addition to the above advantages, hydrogen serves as an excellent medium for storing electrical energy, which is the subject of our research in this chapter. Before we discuss this, it is necessary to first identify the physical and chemical properties of hydrogen [64].

There are several methods to produce hydrogen, one of which is the electrolysis of water, which is an old electrochemical method that decomposes water into two compounds, hydrogen and oxygen, using direct current. To obtain hydrogen, renewable energy must be exploited, as shown in the figureII.19.



FigureII.19: Hydrogen production using renewable energy

II.7.2.1 The Water Electrolyzer

Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production [75].

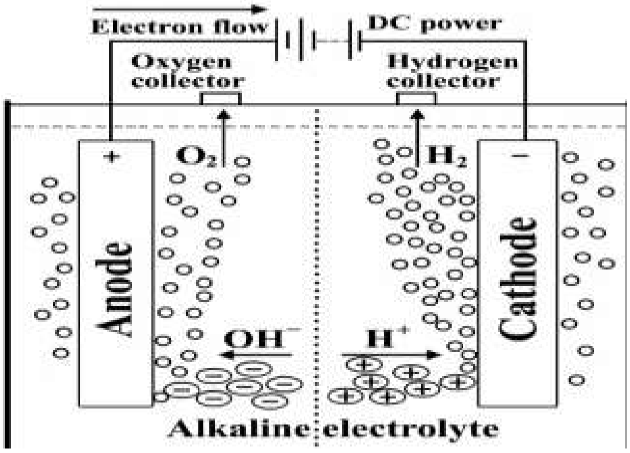


Figure II.20: water electrolysis system

The Aqua electrolyser (AE) provides the hydrogen needed for feeding the fuel cell element. Electrolyser power is provided by part of the WTG power $(1 - k_a)\Delta P_{WTG}$. The dynamic model of an AE for small signal analysis is expressed by Equation (II.48) [63]

$$\frac{d\Delta P_{AE}}{dt} = \frac{k_{AE}(1-k_a)\Delta P_{WTG}}{T_{AE}} - \frac{\Delta P_{AR}}{T_{AE}} \quad \text{(II.48)}$$

Where

T_{AE} Respectively AE time constant

k_{AE} Respectively AE gain

ΔP_{AE} Changes in AE hydrogen production

II.7.2.2 Faraday's Law

The amount of substance that is formed at an electrode during electrolysis is proportional to [76]:

- The amount of time where a constant current to passes
- The amount of charge, in coulombs, that passes through the electrolyte (strength of electric current)
- The relationship between the current and time is:

$$Q = I * t \quad \text{(II.49)}$$

Q Charge (coulombs, C)

I Current (amperes, A)

t Time (seconds)

The amount or the quantity of electricity can also be expressed by the faraday (F) unit

One faraday is the amount of electric charge carried by 1 mole of electrons or 1 mole of singly charged ions

Thus, the relationship between the Faraday constant and the Avogadro constant (L) is:

$$F = L * e \quad \text{(II.50)}$$

F Faradays constant (96 500 C mol^{-1})

L Avogadro constant (6.02 x 10^{23} mol^{-1})

e Charge on an electron

II.7.3Pumped Hydroelectric Energy Storage

Pumped Hydroelectric Energy Storage (PHES) systems utilize gravity to generate power. The potential energy stored in water generates electrical energy when it falls from an upper basin to a lower basin and stores energy when it rises back up. These systems are simply pump-generating centers used for high-energy applications (a few MW or hundreds of GWh) [71].

II.7.3.1 Principle of Pumped Hydro Storage

The work done by a mass of 1 ton falling a distance is given by the following equation:

$$W = \frac{m.g.h}{3600} \quad \text{(II.51)}$$

Where:

g Gravity.

According to this equation, a mass of 1 ton falling a distance of 100 produces only 0.272 kWh of work [77]. Therefore, a large mass of water must be used to achieve high power output for only one hour, and such a large mass can only be found in large dams (barrages). This type of dam collects water in large basins on high slopes, and the energy produced from these dams is used to meet the needs of the electrical grid. Some of this energy can be used during peak hours.

II.7.3.2 Process of Energy Storage Pumped-Hydro

If we want to store electrical energy, water must be used in both directions (see Figure II.20), from and to the two basins, periodically via the hydroponic feeder, which becomes a pump when the water is lifted.

The general principle of operation of this system is well-known and depends on energy demand. During times of high energy demand, such as peak times, water flows from the upper basin to the lower basin, passing through a turbine to generate electrical energy. The energy is then injected into the grid via a transformer and transmission lines. During times of low energy demand (i.e., there is a surplus of generated energy, such as midnight), water is lifted from the lower basin to the upper basin using pumps powered by motors powered by the grid or renewable energy sources [78].

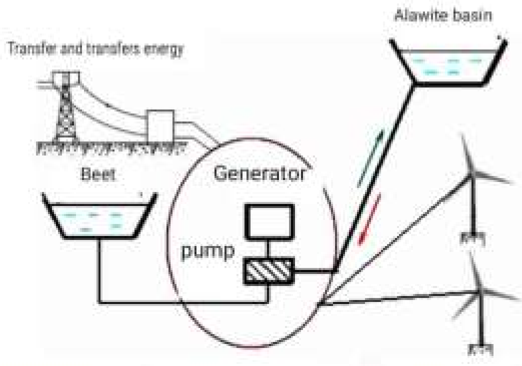


Figure II.21: Schematique of a connacted water storage systéme for renewable energy sources

II.8 Droop Characteristic

Droop control method is one of the techniques to control the frequency deviations of the MG. Generally, a reference frequency is set as a small percentage of the actual frequency of the system. As the load increases, the actual frequency of the plant decreases which is caused by the reduced power generation. Hence, the difference between the reference frequency and the actual frequency increases the working fuel input to the plant to generate more power to meet the load. Briefly, the power generation of a system should change in proportion to the frequency deviations. This is executed by the droop constant R [32].

$$\Delta f = f - f_0 \quad (II.52)$$

$$\Delta P = P - P_0 \quad (II.53)$$

The slope of the power-frequency relationship is a unique characteristic of each generator and is referred to as the speed regulation or droop (R), and is defined as follows [79]:

$$R\% = \frac{w_{NL} - w_{FL}}{w_0} \times 100 \quad (II.54)$$

Where:

w_{NL} The no-load steady-state speed

w_{FL} The full load steady-state speed

w_0 The rated speed. Under the frequency droop paradigm

The load shift can be tracked by the interconnected generating units with different droop characteristics to restore the nominal system frequency. The governors increase the outputs when the networks load changes, causing the units to slow down and the governors to increase the outputs until they achieve a new common operating frequency. The amount of power produced by each generating unit to adjust for network load changes is determined by the unit’s droop characteristic [78].

II.9 Droop Control

The frequency and voltage droop control is considered by the f (P) and V(Q) characteristics. The control behavior is defined by the parameters for active and reactive power as well as the frequency and voltage (P_0, f_0), but also by the frequency droop factor k_f.[80]

The frequency set pointf_{set}resp is defined by

$$f_{set} = f_0 - \frac{1}{k_f} \cdot \frac{1}{1+sT_{kf}} \cdot (P-P_0) \qquad (II.55)$$

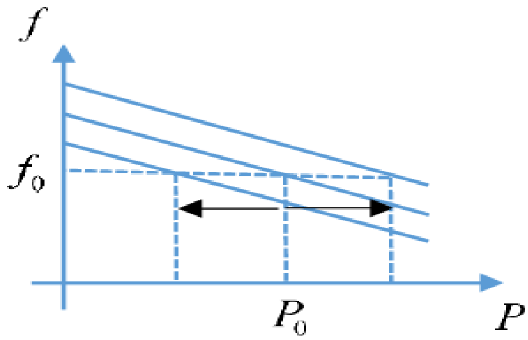


Figure II.22: Drop frequency control

II.10 Generation-Load Model

For the purposes of analysis in the presence of load disturbances, a simple, low-order linearized model is commonly used. The overall generation-load dynamic relationship between the incremental mismatch power ($\Delta P_m - \Delta P_L$) and the frequency deviation (Δf) can be expressed as (II.56)

$$\Delta P_m(t) - \Delta P_L(t) = M\frac{d\Delta f(t)}{dt} + D\,\Delta f(t) \qquad (II.56)$$

Where:

ΔP_m The mechanical power change

ΔP_L The load change

M The inertia constant

D The load damping coefficient

Using the Laplace transform can be written as

$$\Delta P_m(s) - \Delta P_L(s) = Ds\Delta f(s) + D\Delta f(s) \qquad (II.57)$$

Equation (II.57) is represented in the right-hand side of the frequency response model [78]

II.11Conclusion

In this chapter, we developed accurate mathematical models of microgrid components, including renewable energy sources such as wind, solar and hydroelectric, along with diesel engines, which contribute to the continuity of power supply when production fluctuations occur. We also discussed storage systems and their role in balancing production and consumption, which helps stabilize the grid and improve its performance.

Based on these models, in the next chapter we will move to the simulation phase, where we will work on addressing frequency fluctuations using PID control supported by ant colony optimization technology, which allows for intelligent and effective parameter tuning, which contributes to enhancing the stability and efficiency of microgrid operation.

III.1 Introduction

With the significant expansion of the use of renewable energy sources within microgrids, frequency fluctuations have become one of the most prominent challenges threatening the stability of these systems. These fluctuations are often caused by sudden changes in loads or power production, and can lead to quality of service problems or even grid disruptions. To address these types of problems; the PID controller is a popular solution due to its simplicity and effectiveness. However, its effectiveness remains highly dependent on the selection of appropriate parameters. In this chapter, the Ant Colony Algorithm will be used as a smart method for optimally tuning these parameters. We will discuss how to design a PID controller, explain how to apply ACO to its tuning, and present and analyze simulation results. To highlight the role of ACO in solving the frequency fluctuation problem, we will compare it with other algorithms in different scenarios.

III.2 Thesis objective

Frequency fluctuation is a fundamental challenge in modern energy systems, especially in microgrid systems that rely heavily on renewable energy sources, which are characterized by their volatile and unstable nature. In this context, maintaining the system frequency at the reference value (50 Hz) is essential to ensure grid stability and safe operation of various electrical devices.

Based on this problem, this thesis aims to address the problem of frequency fluctuation in microgrid systems by developing an effective control strategy that minimizes frequency deviation. To achieve this, a PID controller was adopted due to its simplicity and effectiveness, and an Ant Colony Optimization algorithm was employed to optimally tune the controller parameters.

The problem is how to tune the parameters of the PID controllers using the multi objective ant colony optimization as indicated in Figure III.1. [81]

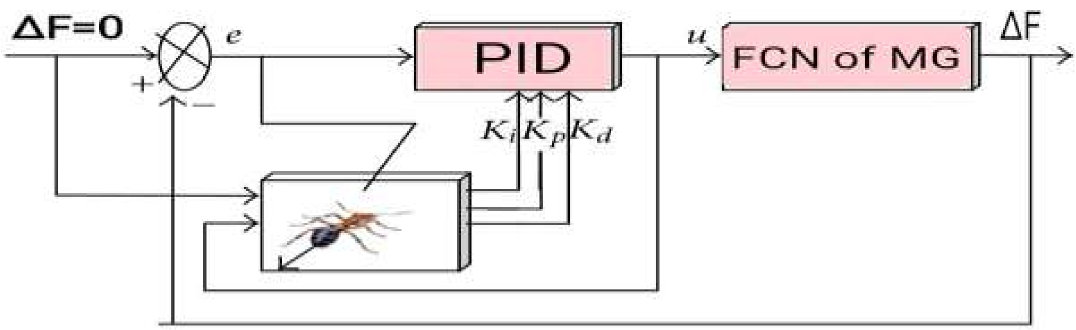


Figure III.1: PID control system with Ants colony algorithm

III.3 Small Signals Model of Microgrid system

In order to analyze small signals to verify the reliability and stability of frequency deviation for the microgrid system, models can be designed. These models can include PV, WTG, DEG and PHEV, which can be modeled by the first-order transfer function., the energy balance equation for the energy released by the microgrid can be written as [82, 83]:

$$P_S = P_{PV} + P_{WTG} + P_{DEG} - P_{PHEV} \quad \text{(III. 1)}$$

where *PS* is the total average power generation. The generation-load balance equation is:

$$\Delta_{PL} = \Delta_{PPV} + \Delta_{PWTG} + \Delta_{PDEG} - \Delta_{PPHEV} \quad \text{(III. 2)}$$

From (III. 2)we infer that variations in power generation have a significant impact on frequency deviation in the system. Therefore, frequency deviation Δf can be expressed from [25, 26]:

$$\mathrm{TF_S} = \frac{\Delta F}{\Delta P_L} = \frac{1}{K_S(1+S.T_S)} = \frac{1}{M.S+D} \quad \text{(III. 3)}$$

Where:

M, *D* The equivalent inertia constant and damping constant, respectively

Δf The frequency deviation

K_S The gain constant of the microgrid

T_S The time constant

TFS The transfer function of the microgrid

S is The Laplace variable

The Frequency deviation of the microgrid system can be expressed as:

$$\Delta F = \frac{1}{M.S+D}(\Delta_{PPV} + \Delta_{PWTG} + \Delta_{PDEG} - \Delta_{PPHEV}) \quad \text{(III. 4)}$$

In order to study the variations in frequency deviation, it is necessary to examine each element of the energy sources connected to the microgrid.

III.3.1 Linear model of PV

For frequency domain analysis, it is represented by a first-order lag transfer function model given as [84]:

$$G_{pv}(s) = \frac{\Delta P_{pv}}{\Delta\varphi} = \frac{K_{pv}}{1+ST_{pv}} \quad \text{(III. 5)}$$

III.3.2 Linear model of Wind

The Wind Turbine Generator output power changes according to the weather conditions. The transfer function of the WTG is represented in the first-order as given bellow [84].

$$Gwtg(s) = \frac{\Delta P_{wtg}}{\Delta P_{wt}} = \frac{K_{wtg}}{1 + ST_{wtg}} \qquad (III.6)$$

III.3.3 Linear model PHEV

Hybrid electric vehicles (HEVs) play an important role in modern energy systems by combining internal combustion engines with electric propulsion for improved efficiency and reduced emissions. Their integration with the power grid through vehicle-to-grid (V2G) technology allows them to support frequency stability by charging during low-demand periods and supplying energy when demand is high. This capability helps balance fluctuations in power generation and consumption, contributing to a more stable and reliable electrical grid. Additionally, HEVs reduce dependence on fossil fuels and promote the transition toward cleaner transportation solutions. Figure III.2

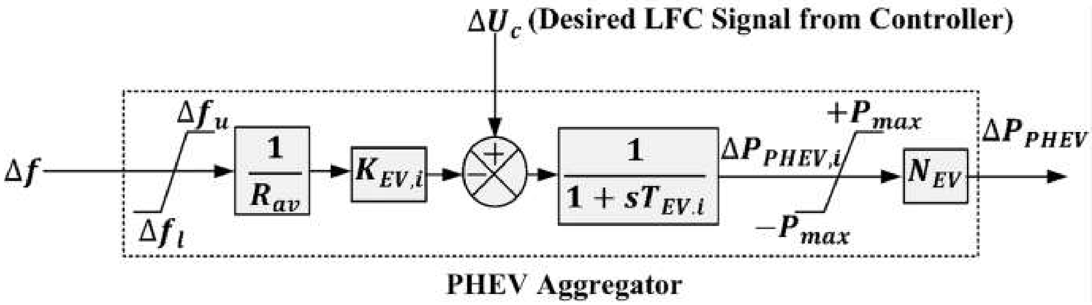


Figure III.2: PHEV Aggregator Model for Frequency Control Studies

Following analysis and simplification, the ultimate mathematical expression can be represented in the format of a first-order simplifier [5]:

$$\Delta P_{PHEV} = \frac{N_{EV}\left[\Delta U_c - \Delta f \cdot \frac{K_{EV}}{R_{av}}\right]}{1 + S \cdot T_{EV}} \qquad (III.7)$$

Where

ΔP_{PHEV} The energy generated by a single PHEV

N_{EV} The total number of electric vehicles

ΔU_c The controller's output signal

Δf The frequency deviation

K_{EV} The gain constant of the PHEV

R_{av} The droop characteristics of the PHEV

T_{EV} The battery time constant

III. 3.4 Linear model Diesel Generator

A diesel generator is a reliable power source that converts the chemical energy of diesel fuel into electrical energy through an internal combustion engine and an alternator. Diesel generators are commonly used for backup power and in off-grid applications, where they provide a stable power source and are known for their efficiency and durability. In microgrids, these generators help maintain frequency stability by quickly adjusting their output to keep pace with fluctuations in demand. Their ability to provide instant, continuous power makes them essential for critical facilities, remote areas, and hybrid power systems where renewable energy sources may be intermittent. The diesel generator's functionality can be described using a straightforward first-order transfer function (III.8).

$$G_{DEG}(s) = \frac{\Delta P_{DEG}}{\Delta U_{DEG}} = \frac{K_{DEG}}{1+S.T_{DEG}} \qquad \text{(III. 8)}$$

III.3.5 Models of different storage systems

The storage energy system is a significant device in the hybrid system, to store the fluctuation of generated power to release it to supply the connected load where there is an unbalance between generation and load. The transfer functions of the BESS can be, respectively, presented as first-orders given next [85,87-88, 89-90].

$$G_{BESS}(S) = \frac{\Delta P_{BESS}}{\Delta F} = \frac{K_{BESS}}{1+ST_{BESS}} \qquad \text{(III. 9)}$$

The transfer functions of the characteristic of aqua electrolyses function is expressed by Equation (III. 9)

$$\begin{cases} G_{AE}(S) = \frac{K_{AE}}{1+sT_{AE}} = \frac{\Delta P_{AE}(S)}{\Delta P_t(S)} \\ \Delta P_t(S) = (1-K_t)\Delta P_{WTG}(S), K_t = 0.6 \end{cases} \qquad \text{(III. 10)}$$

III.4 MATLAB/ Simulink Model of a Microgrid System

After writing the program and entering settings, we designed a microgrid system consisting of a combination of different energy sources, including solar panels (PV), wind power, plug-in hybrid electric vehicles (PHEV), and load. This system was built and simulated using MATLAB/Simulink to study the frequency behavior within the microgrid as shoxn in the Figure III.3.The main objective of this study is to control and adjust the frequency by addressing the problem of frequency fluctuations resulting from changes in loads and renewable energy sources. To achieve this goal, a PID controller was used to control the frequency, and the Ant Colony Optimization algorithm was used to optimally tune the controller parameters to improve system performance and stability.

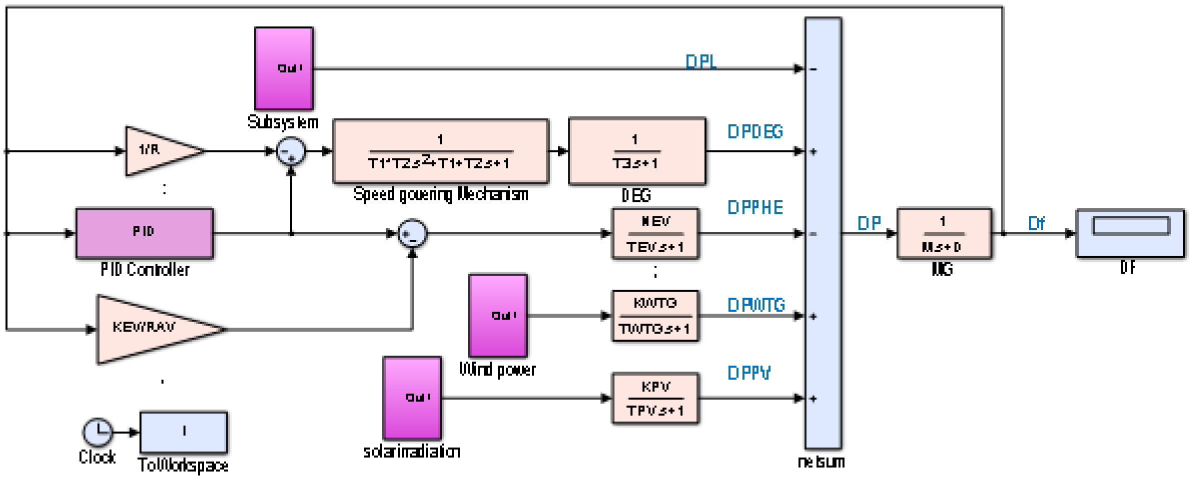


Figure III.3 : Bella colla Microgrid Model

III.5 PID controller structure

The Proportional Integral Derivative (PID) controller is the most commonly used controller in the process industries for closed-loop control. It can ensure excellent performance with a simple algorithm for a wide range of processes. It is worth noting that the cost-benefit ratio produced by the PID controller is difficult to achieve by other controllers. It has been discovered that the PID algorithm is used by 97 percent of regulatory controllers in the industry. The PID controller is also known as the Proportional (P), Integral (I), and Derivative (D) controllers (D). The desired closed-loop system performance can be attained by adjusting the controller parameters appropriately. This is referred to as controller tweaking. For tweaking the PID controller, hundreds of tools, approaches, and theories are available. However, determining ideal parameters for the PID controller remains problematic; in practice, control engineers continue to employ the trial-and-error method for tuning [91]. The mathematical form of the PID algorithm is represented.

$$G(s) = K_p + \frac{1}{S}K_i + SK_d \qquad \text{(III.11)}$$

- The K_p will reduce the rise time, but it will never eliminate the steady-state error.
- The K_i will eliminate the steady-state error, but it may make the transient response worse.
- The K_d will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response

The PID controller is implemented to improve the dynamic response in addition to reduce or eliminate the steady state error. To characterize the performance of the PID controller systems, we compute the indexes' performance of the transient response such as rise time (*tr*), overshoot (*Os*), settling time (*ts*)¨[81].

III.6 Tuning of PID Controllers

Tuning of PID controllers is a critical issue in control system design. In the PID controller design, several tasks have to be considered. The two main functions that should be focused on are either reference-signal tracking or disturbance rejection. However, in some cases, both of these tasks have to be considered simultaneously. Also, the controller should yield an acceptable level of the control signal not to harm the actuator. Moreover, the designed controller should perform well in the face of plant parameter uncertainties. That is, the controller should be robust. There have been various techniques applied for PID tuning, one of the earliest being the Ziegler Nichols technique. These techniques can be broadly classified as classical and computational or optimization techniques [92]

III.6.1 Classical Techniques

Classical techniques make certain assumptions about the plant and the desired output and try to obtain some features of the process analytically or graphically to decide the controller settings. These techniques are computationally swift and straightforward to implement and are suitable as a first iteration. But due to the assumptions made, the controller settings usually do not give the desired results directly, and further tuning is required [92].

III.6.2 Optimization Techniques

The goal of multi objective optimization problems is to find the best compromise between multiple and conflicting objectives. Considering all objectives in these problems, there will be more than one solution that optimizes simultaneously all the objectives and there is no distinct superiority between these solutions. Usually there is not a single best solution being better than the remainder with respect to every objective [93]. The basic step in applying optimization method is to choose the optimization criteria that are used to evaluate fitness. Since the PID controller has many indexes performance of the transient response, then we can combine them into one objective function composed of the weighted sum of objectives [94].

III.7 Ant Colony Optimization Technique

This algorithm is specifically used to find solutions to problems of different instances. Ants cooperate within the colony to find good solutions. Based on the similarity between the ant colony algorithm and ant colonies in nature, the ant algorithm is robust and adaptable and can be applied to different versions of the same problem as well as to different instances [95].

The basic idea of ACO was originally proposed by Dorigo in 1992 [96]. It is based on the behavior of foraging ants. Ants cooperate to find the shortest route to a food source. The route between ant nests and food may contain many intersections. Therefore, they need to decide which route to take at each intersection, striving to minimize the total distance. Ants communicate by releasing pheromones, which are chemicals released by organisms of the same species. The transmitter and receiver are compatible, thus serving as a means of communication between organisms of the same species as they travel to and from food sources [97]. Pheromones evaporate over time. Since traveling a short path takes less time, this results in more pheromones. On shorter paths, ants are more likely to travel a path with more pheromones [96]. Over time, they converge on the path with the shortest set of paths to food, as shown in Figure III.5 where red represents low pheromone amounts, orange represents medium amounts, and green represents high amounts [98]. . Ant colony optimization (ACO) [99, 100] is a recently developed metaheuristic approach for solving hard combinatorial optimization problems such as the travelling salesman problem TSP [101], quadratic assignment problem [102], graph coloring problems [103], hydroelectric generation scheduling problems [104], vehicle routing [105], sequential ordering, scheduling [26], and routing in Internet-like networks [107].

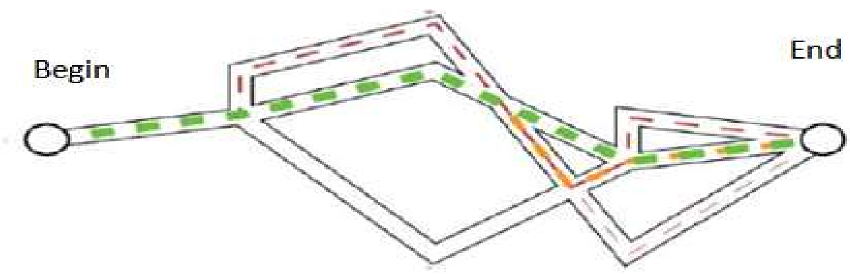


Figure III.4: The shortest path ants to find the pheromone [108]

Ant colony optimization algorithms are especially suited for finding solutions to difficult optimization problems. A colony of artificial ants cooperates to find good solutions, which are an emergent property of the ants' cooperative interaction. Based on their similarities with ant colonies in nature, ant algorithms are adaptive and robust and can be applied to different versions of the same problem as well as to different optimization problems [109].

In order to exploit the ACO algorithm, it would be better to represent our optimization problem by a direct way in the form of construction graph, where the ant select the optimum parametersK_p,K_i, and K_d. The graph shown in Figure III.6 illustrates the design PID problem using ant colony algorithm.In this study, each parameter of K_p, K_i, and K_d is coded by numbers, respectively. Therefore, only one node represents the optimum solution values of the parametersK_p,K_i, and K_d [81].

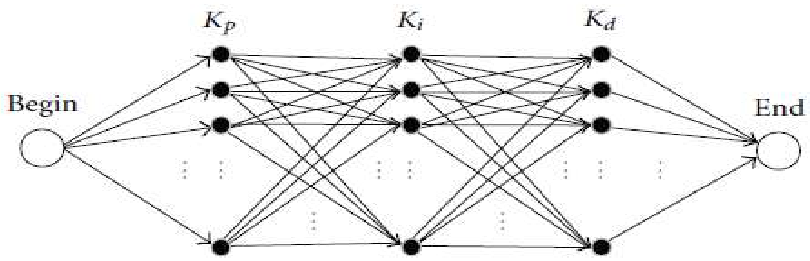


Figure III.5: Ant colony optimization graph

To learn more about the ant colony algorithm and how to adjust its PID prmeters ,we will explin this in detil nd step by step

Step1: Initialization

1.Defining the System to be controlled

The Transfer Function (TF) of the system to be tuned is defined.

2. Initializing the Ant Colony

Define the number of ants (num Ants), which represents the number of solutions to be explored in each iteration. Define the number of iterations (num Iterations), which determines how many rounds the algorithm will run to find optimal values. Set the initial pheromone levels, where all paths have the same probability at the start. And Initialize ACO parameters (α, β, ρ, Q)

Where:

α controls the influence of previous pheromones on new value selection.

β controls the influence of newly discovered values.

ρ Evaporation rate of pheromones

Q Reinforcement factor for successful solutions that improve system performance.

Define the Search Range for K_p, K_i, and K_d

Step2: Generating Initial Random Solutions

Different sets of values (K_p, K_i, K_d) are randomly generated within the defined limits. And each ant selects PID values randomly.

Step 3: Evaluating the Performance of Each Solution

Create a PID Controller for Each Ant; the controller is defined as a transfer function. Analyzing the Closed-Loop System Response, The feedback loop is closed between the controller and the system to obtain the actual response. And Calculi the Objective Function The Integral of Time-weighted Absolute Error (ITAE) to Evaluate Solution Quality

Step 4: Pheromone Update

Reducing the Influence of Old Pheromones (Evaporation), the pheromone level for all paths is reduced using an evaporation formula. Reinforcing Successful Paths (Pheromone Reinforcement), Solutions that resulted in better performance are reinforced by adding new pheromone amounts.

Step 5: Iterative Optimization

Selecting New Values for PID Parameters,Repeate the Process for a Certain Number of Iterations.

Step6: Extracting Results and Visualization

Printing the Best Discovered PID Values .At the end of the iterations, the optimal values found are printed.

After reviewing the steps of the ACO algorithm in tuning the PID parameters, the diagram below summarizes the entire process clearly.

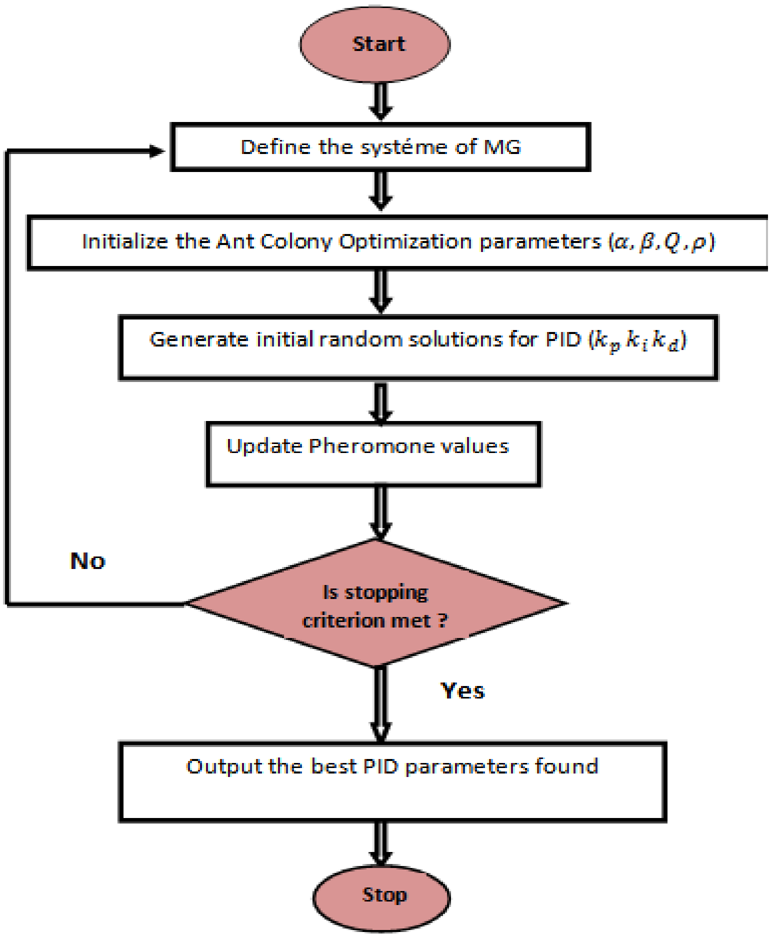


Figure III.6: Flowchart of PID Parameter optimization using ACO

III.8 Simulation Result

Our work on the graduation thesis and our topic in it, we worked in MATLEB 2008, and we used a time of **250s** and worked with these settings.

Table III.1: Optimized Controller Gains & System parameters

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

III.8.1 Graphic of ΔL Model

Load variations in microgrids significantly impact system stability and performance. As demand fluctuates due to varying consumption patterns, a balance between generation and load must be maintained to keep frequency within acceptable limits. Sudden increases in load can lead to frequency deviations, while decreased loads can lead to power surpluses and frequency spikes.

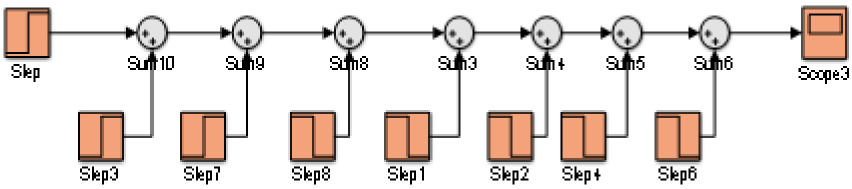


Figure III.7: Graphic of ΔL Model

After drawing Graphic of ΔL Model which consists of 8 steps, the result showed that the value of loed disturbance (ΔL) increases and then decreases gradually, as shown in Figure III.8

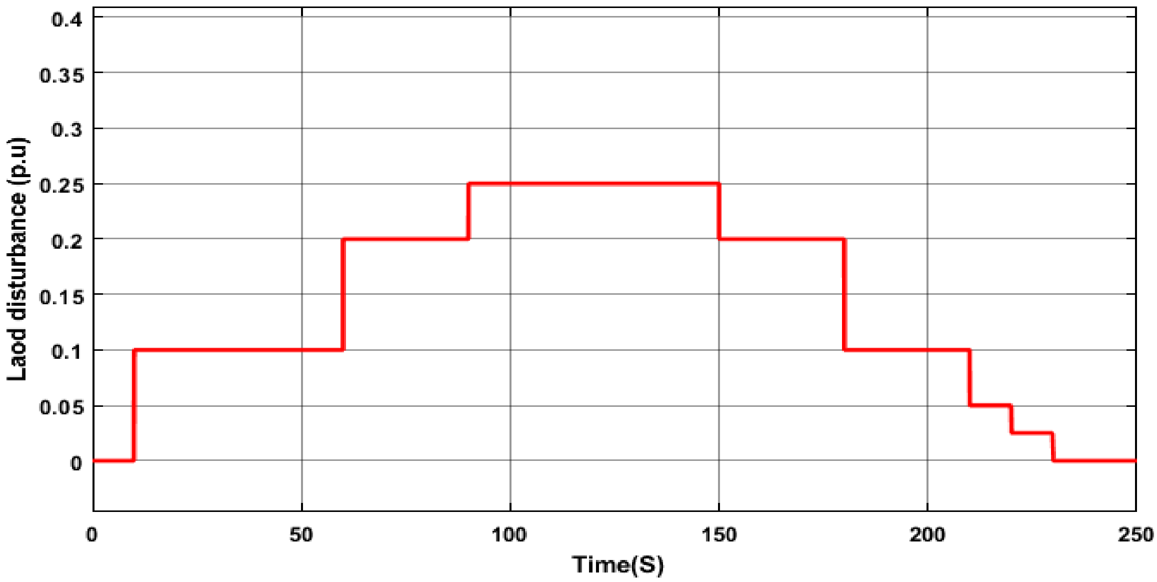


Figure III.8: Graphical Representation of External Impacts (ΔL) on Islanded Microgrid Stability

III.8.2 Graphic of PV Model

Photovoltaic systems rely on converting solar radiant energy into electrical energy through solar cells. Solar radiation and cell temperature are the most important factors affecting the power output of a solar system. In the context of frequency deviation analysis in power systems, the behavior of photovoltaic systems is represented through mathematical models that take into account changes in solar radiation and temperature and their impact on energy production. As shown in the Figure III.9.

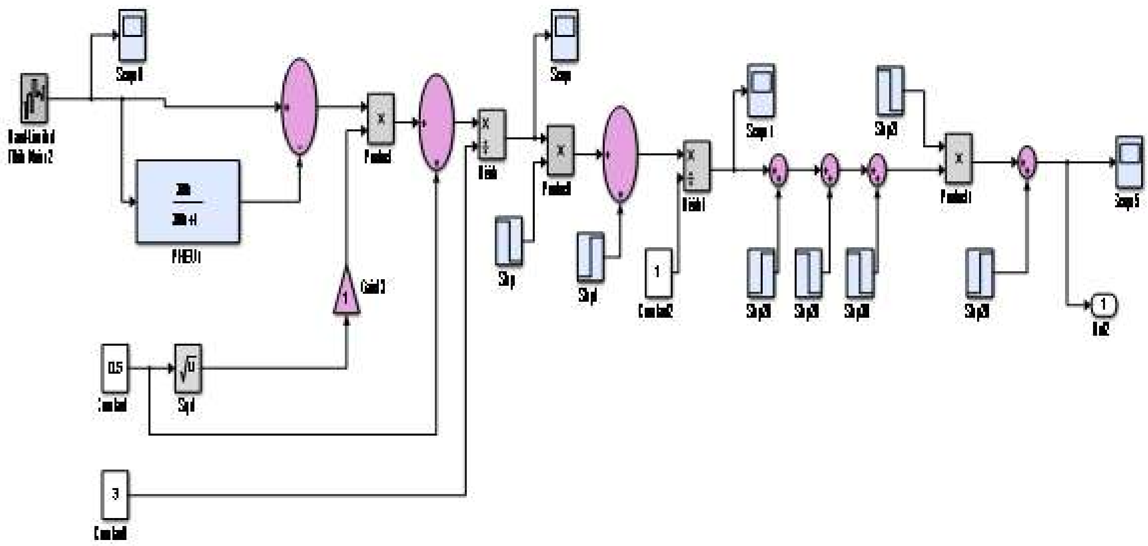


Figure III.9: Mathematical model for PV

Given the importance of analyzing the performance of electrical energy sources in microgrids, the photovoltaic power model diagram is an essential part of our study, as illustrated in the figure below.

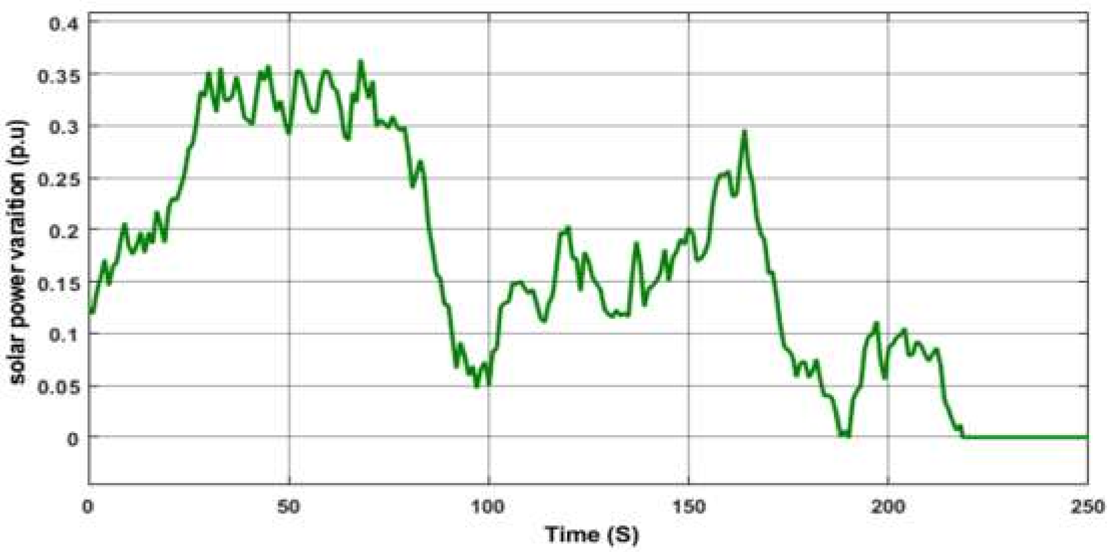


Figure III.10: Graphic of solar power variation

The curve represents the changes in photovoltaic power over time. We notice irregularity in the photovoltaic power values over time, which will affect the frequency curve in the final result, and then at 220 seconds it becomes zero.

III.8.3 Graphic of Wind Model

Wind turbines are used to harness the kinetic energy of the wind and convert it into mechanical energy, which is then converted into electrical energy by a generator. The power output of a turbine is affected by several factors, most notably wind speed, air density, and the characteristics of the turbine itself. For the purpose of analyzing frequency deviation in power systems, the behavior of wind turbines can be modeled in a similar manner, representing the variation in output power as a function of wind speed and other influencing factors using appropriate mathematical models, as shown in Figure III.11.

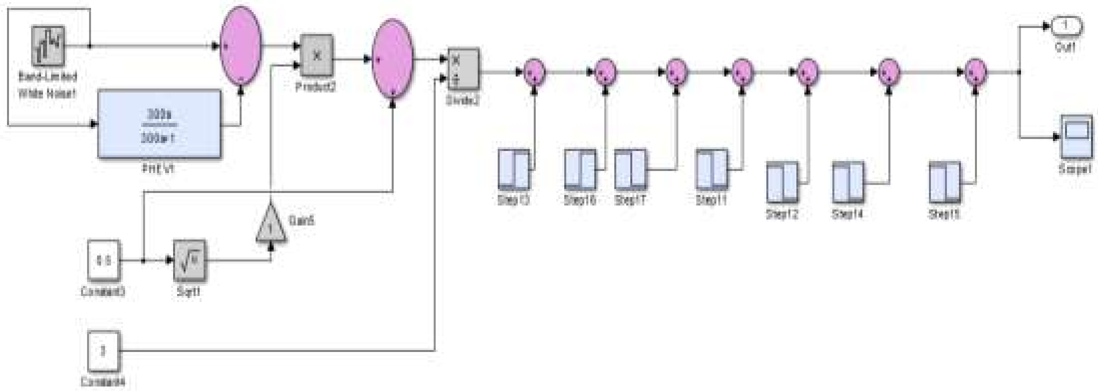


Figure III.11: Mathematical model for wind output power with random wind velocity pattern

The wind energy model diagram below is a key component of our analysis. It illustrates the structure and operation of wind turbines within the system, paving the way for a deeper understanding of their performance and impact on overall energy production.

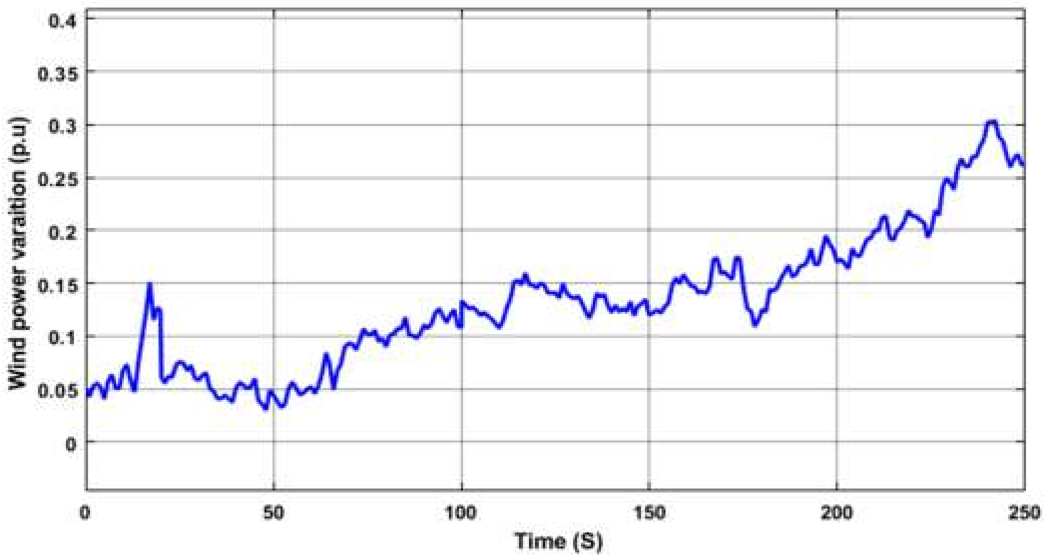


Figure III.12: Graphic of wind power variation

This graph illustrates changes in wind power production over time. The graph displays the fluctuations in wind power values over the observed period, which directly impacts the final frequency curve of the grid. The aim of analyzing these fluctuations is to understand their impact on frequency stability within the microgrid.

III.8.4 Tuning of PID Controller Using ACO Algorithm

To solve the frequency oscillation problem in the microgrid system, as mentioned earlier, we will use a PID controller. To adjust its parameters, we relied on the Ant Colony Algorithm. To study the impact of the ACO parameters on the tuning quality and efficiency of the controller, we proposed four different situations in which the basic values of the algorithm parameters, such as the number of ants, the evaporation factor, and the pheromone influence coefficients, were changed as shown in the table III.2. The goal of these situations was to analyze the sensitivity of the algorithm's performance to these parameters, and their reflection on the optimized PID parameters. Simulation results showed a clear impact of the ACO parameter selection.

Table III.2: The parameter of K_p K_i K_d in each scenario

	Num ants	**Num iteration**	α	β	Q	ρ	K_p	K_i	K_d
Scenario1	100	20	1	2	0.8	1.5	1.26	4.48	0.16
Scenario2	100	20	1.8	1.5	1.1	0.7	1	4	0.6
Scenario3	10	5	2	2	1	1	1.3	4.49	0.2
Scenario4	100	20	2	2	1	1	1.39	4.5	0.2

We noticed when increasing the number of ants in the algorithm, the research ability to explore multiple and varied solutions increases, allowing the discovery of more accurate and balanced values for the three transactions. This improves the performance of the control unit effectively and significantly reduces frequency fluctuations, even if this requires a longer mathematical time. The average evaporation rate of the Fairomon also played a pivotal role in the speed of the algorithm from the ineffective solutions, and pushing them towards searching for more suitable solutions to achieve frequency stability. The adjustment of this rate properly contributes to accelerating access to the perfect K_p, K_i and K_d values, thus reducing frequency oscillations and ensuring the speed of the system response. In addition, both Alpha and Beta transactions affect ants during the search; it helps to raise the value of alpha to enhance the exploitation of the previous performance paths, which contributes to accelerating the improvement of K_i and K_d values in order to support stability and reduce frequency fluctuations. While raising beta value enhances the aspect of the exploration based on the properties of the problem, which contributes to improving the system response and reducing oscillation to the lowest extent possible. In general, the ideal control of ACO algorithm represents a fundamental and essential.

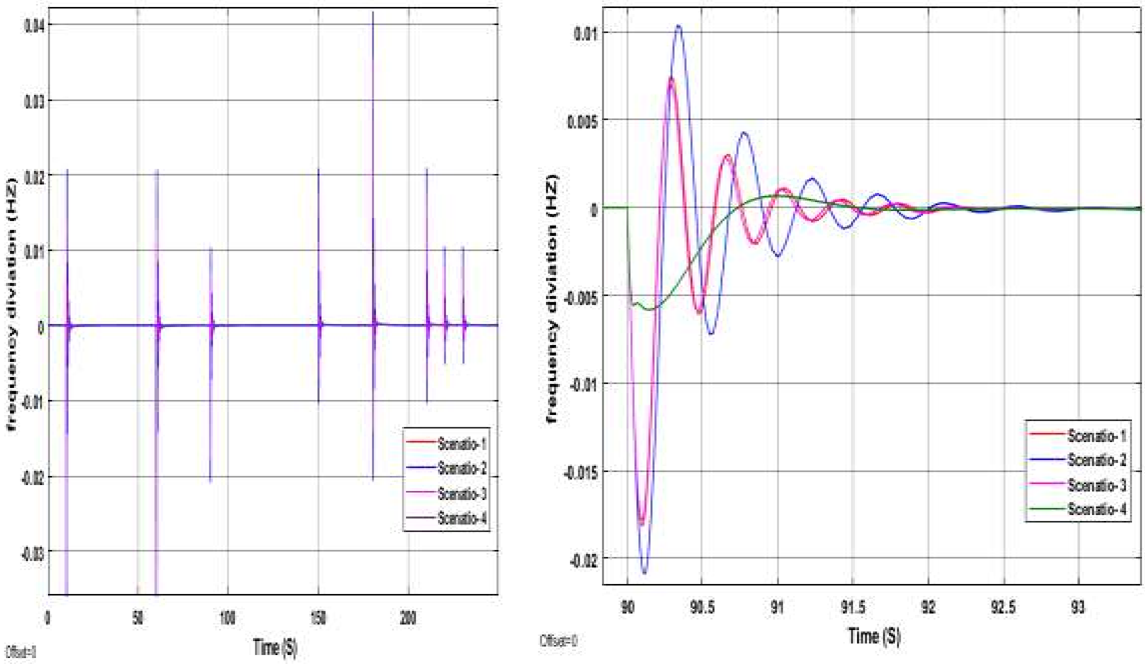


Figure III.13: (a) Simulation result deferent's scenarios with ACO **(b)** The zoom simulation

The results showed that situation4 performed better than the other scenarios. This tuning improved the system's response in terms of steady-state speed and reduced oscillations and overshoot, demonstrating a good balance between dynamic response and stability. In contrast, the other scenarios performed less effectively, either due to weaker response (as in scenario2) or relatively larger oscillations (as in scenario 1 and 3),as we show in Figure III.13.Therefore, scenario 4 can be considered optimal in terms of performance and frequency fluctuation control within a microgrid system.

III.9 Comparison between ACO, PSO and GA Algorithms

After determining the optimal tuning of the PID controller using the Ant Colony Optimization algorithm in scenario 4, which demonstrated excellent performance in reducing frequency fluctuations and improving system response, in this section we will compare the results of this scenario with those of the PID controller using other intelligent algorithms, namely Particle Swarm Optimization (PSO) [28] and Genetic Algorithm (GA) [29]. This comparison aims to highlight the effectiveness of the ACO algorithm and its role in improving system stability, and to achieve this we will analyze the frequency fluctuations in a microgrid system under four different scenarios to evaluate the system's performance under various operating conditions. The first scenario involves connecting loads, while the second scenario studies the impact of connecting loads to PV power. The third scenario involves combining loads to wind power. The fourth scenario involves combining two renewable sources,wind and PV without a load.Fainly, the fifth scenario combines both wind and solar power. This variety of scenarios aims to study the system's response to changes in energy sources and loads and their impact on frequency stability.

The results of the PID controller parameters for each of the algorithms are represented in the table.

Table III.3: The parameter of PID in deferent algorithm

	K_p	K_i	K_d
ACO	1.39	4.5	0.2
PSO	1	1.8895	0.2
GA	0.82617	4.5156	0.08295

In the first scenario, we will study the frequency behavior of a microgrid system as the load changes. The goal of this scenario is to analyze how the system responds to load fluctuations and evaluate the effectiveness of a PID controller tuned using the ant colony algorithm in maintaining frequency stability. It is also important to compare this with other algorithms.

When simulating the PID controller values for each algorithm in the microgrid systéme, we get the result show in the Figure III.14.

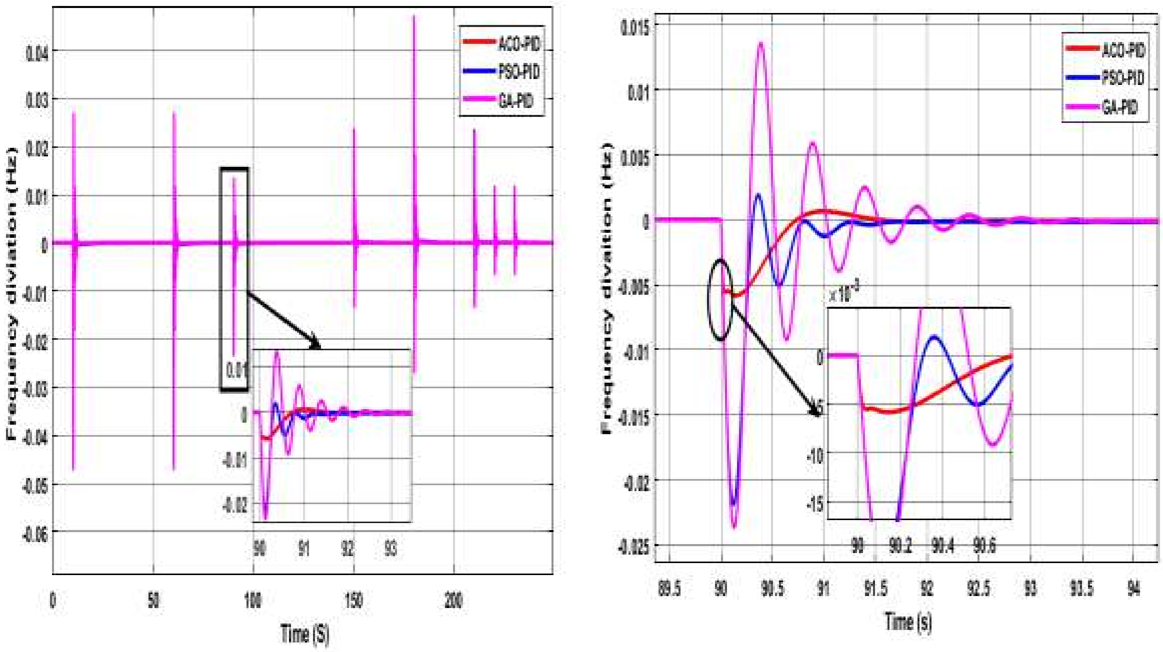


Figure III.14: Comparison between ACO, GA and PSO Simulation

Simulation results demonstrated the response of the Ant Colony Algorithm (ACO), Particle Swarm Algorithm (PSO), and Genetic Algorithm (GA) to a load disturbance of 0.20 p.u. The ACO algorithm performed extremely well across all parameters. It achieved the fastest response time of 91.48 seconds, demonstrating its high ability to quickly find optimal solutions. The response generated by the ACO also exhibited a high degree of stability after the disturbance, with the system returning to normal smoothly and without sharp fluctuations. Furthermore, the ACO demonstrated high accuracy in reaching the reference frequency value, with a very slight disturbance appearing at the end of the response but not significantly affecting overall performance, which is considered normal for systems. The PSO algorithm, on the other hand, achieved average performance. The response time was approximately 91.5 seconds, which is very close to that of the ACO. However, upon closer examination of the frequency behavior, it was found that the stability of the system with PSO was relatively lower, with more pronounced fluctuations than with the ACO. The accuracy in reaching the reference value was also not as high, as the system took a slightly longer time to fully stabilize. However, the PSO performance remained acceptable.In contrast, the genetic algorithm showed the poorest performance among the three algorithms. It recorded the longest response time of 93.1 seconds, indicating a slow convergence process toward the optimal solution. It was also observed that the system's behavior under the influence of the GA was characterized by greater oscillation and slower stability, with a less accurate response to reaching the reference frequency value.

From these results, it can be concluded that the Ant Colony Algorithm (ACO) is the most efficient at controlling frequency oscillations in a microgrid system under the influence of load disturbance. It outperformed in terms of speed, accuracy, and stability.

Scenaio II

In the scend scenario, we will study the frequency behavior of a microgrid system when the loads are connected solely to a solar PV source. The goal of this scenario is to understand how the system's frequency is affected by relying solely on solar power, especially since this source constantly changes depending on solar radiation intensity and weather conditions. This analysis will enable us to understand the challenges the system faces in maintaining frequency balance and stability in the absence of other energy sources, and how the system handles fluctuations resulting from this type of connection.

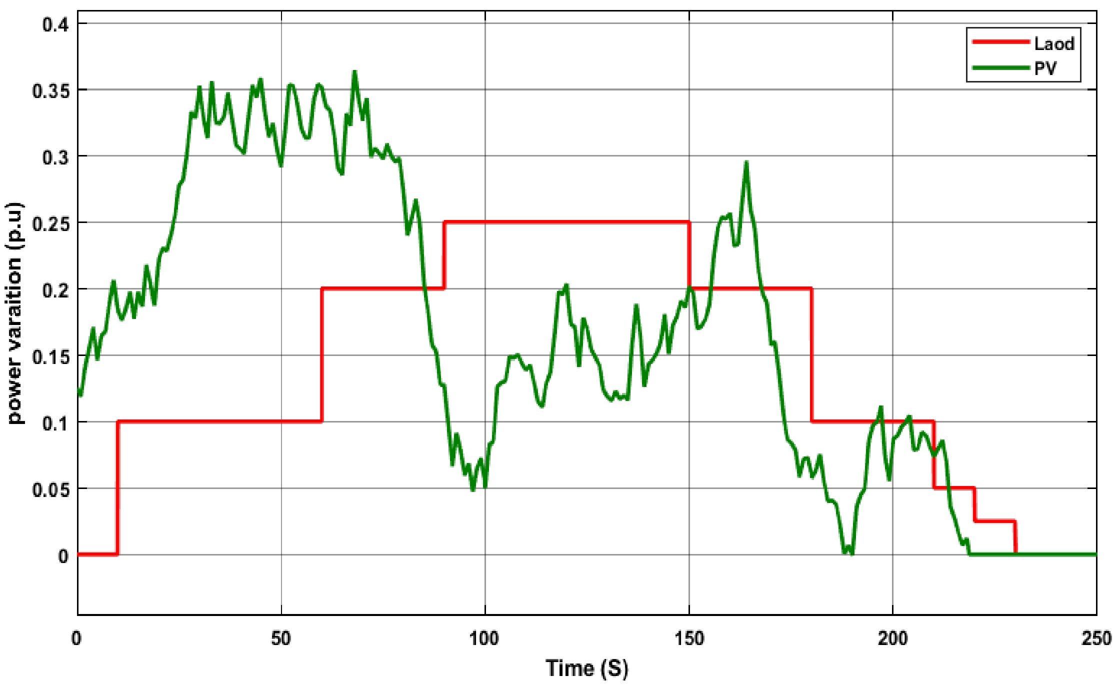


Figure III.15: Graphic of load and solar power variation

The curve shown below represents the results of the frequency diviation behavior when connecting the loads and Photovoltaic in Microgrid system

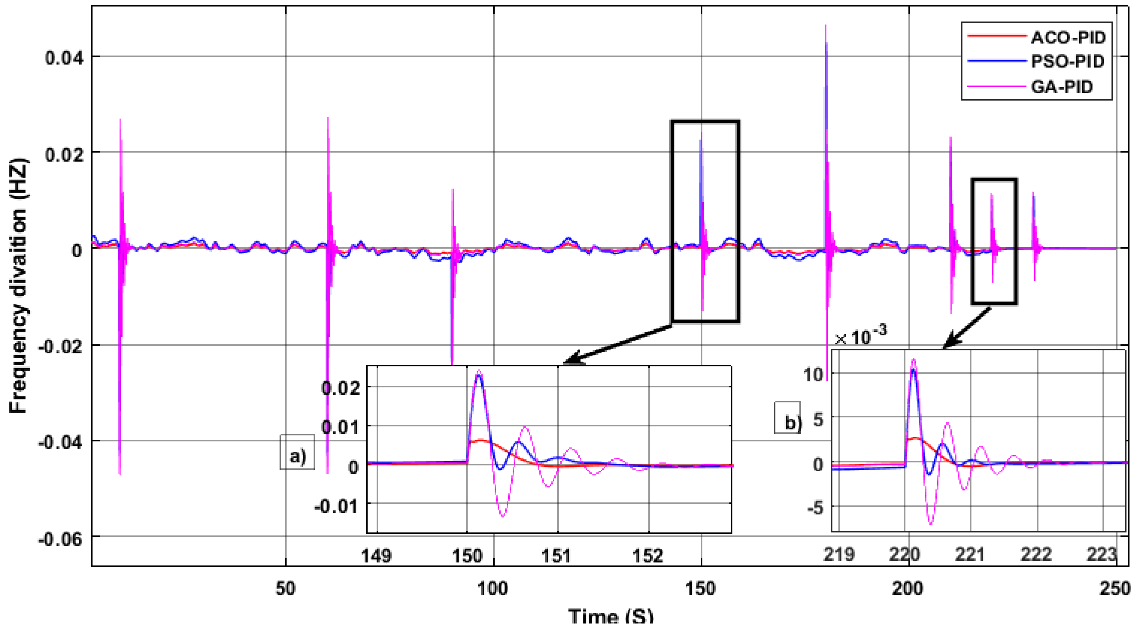


Figure III.16: simulation result of scenario II in each algorithm

When implementing the second scenario, connecting the loads to a solar-only power source, we observed that the system suffered from significant frequency fluctuations and instability compared to the case of connecting the loads alone without any renewable energy source. This is due to the unstable nature of solar energy, which is greatly affected by weather and radiation intensity changes. However, the ACO algorithm demonstrated outstanding performance in this scenario, noting its rapid response to sudden changes in power output, effectively reducing fluctuations and achieving good frequency stability compared to other algorithms used.

Scenario III

In the third scenario, the performance of the microgrid system was studied when the loads were connected to a wind energy source only, with the goal of understanding the impact of this type of renewable energy source on the frequency stability within the system. Wind energy, being dependent on variable natural conditions such as wind speed and direction, is an unstable source, making it important to study it to understand the operational challenges that the system may face. This scenario allows for a direct analysis of how the load interacts with wind energy and provides a basis for comparing performance with other scenarios that rely on different sources.

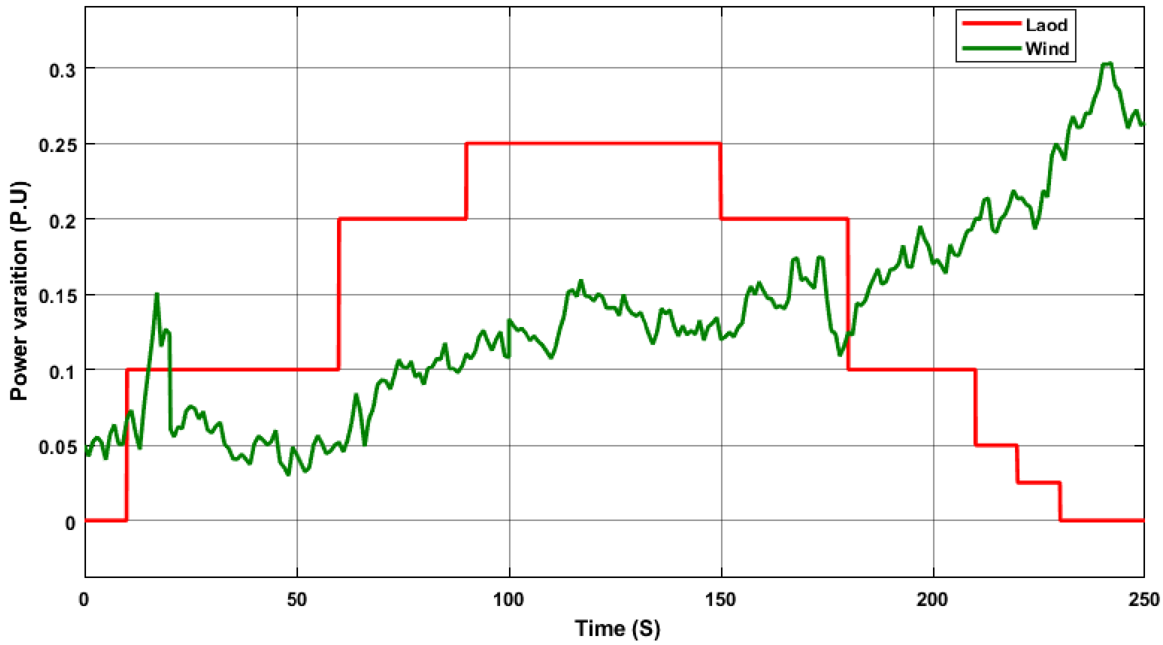


Figure III.17: Graphic of load and wind power variation

The curve below illustrates the frequency deviation behavior resulting from the connection of loads and wind within the microgrid system.

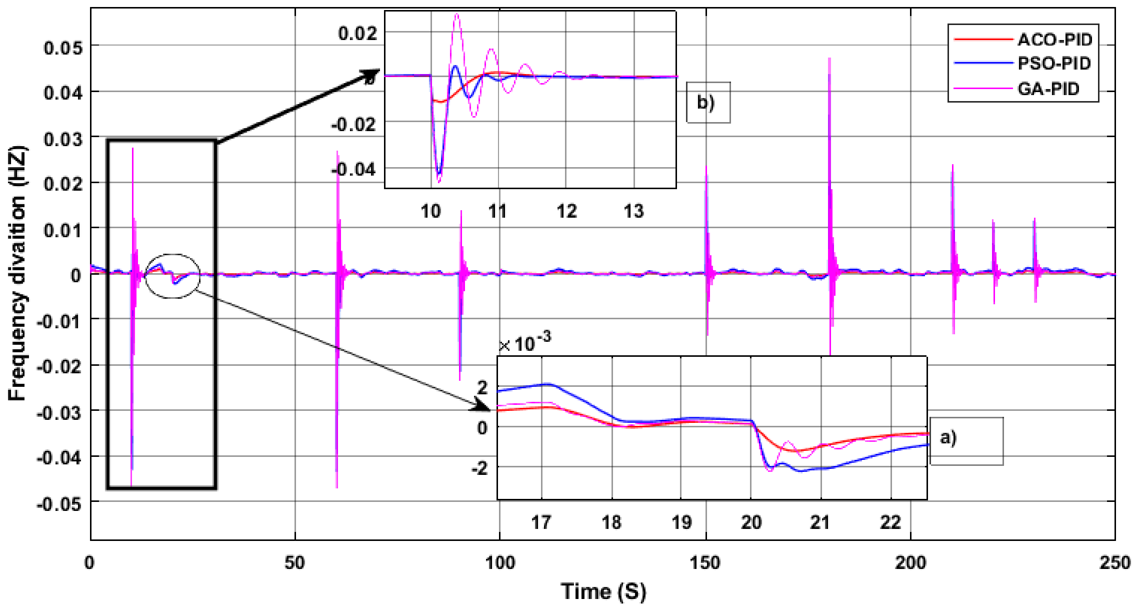


Figure III.18: simulation result of scenario III in each algorithm

When implementing the third scenario, which connects loads solely to the wind power source, we observed significant system frequency fluctuations, as well as poor stability compared to the case without any renewable source. This behavior is attributed to the volatile nature of wind power, which varies rapidly and irregularly depending on weather conditions. Despite these challenges, the Ant Colony Algorithm continued to deliver excellent performance, demonstrating rapid response to sudden changes, reducing fluctuations, and achieving better frequency stability compared to the PSO and GA algorithms. As shown in Figure III.18.

Scenario IV

In the fourth scenario, we studied a microgrid system in which only two renewable sources PV and wind were connected, with no connected loads. This scenario aims to understand how renewable energy sources interact with each other within the system. This scenario is important for understanding the challenges associated with integrating only renewable energy sources into a microgrid.

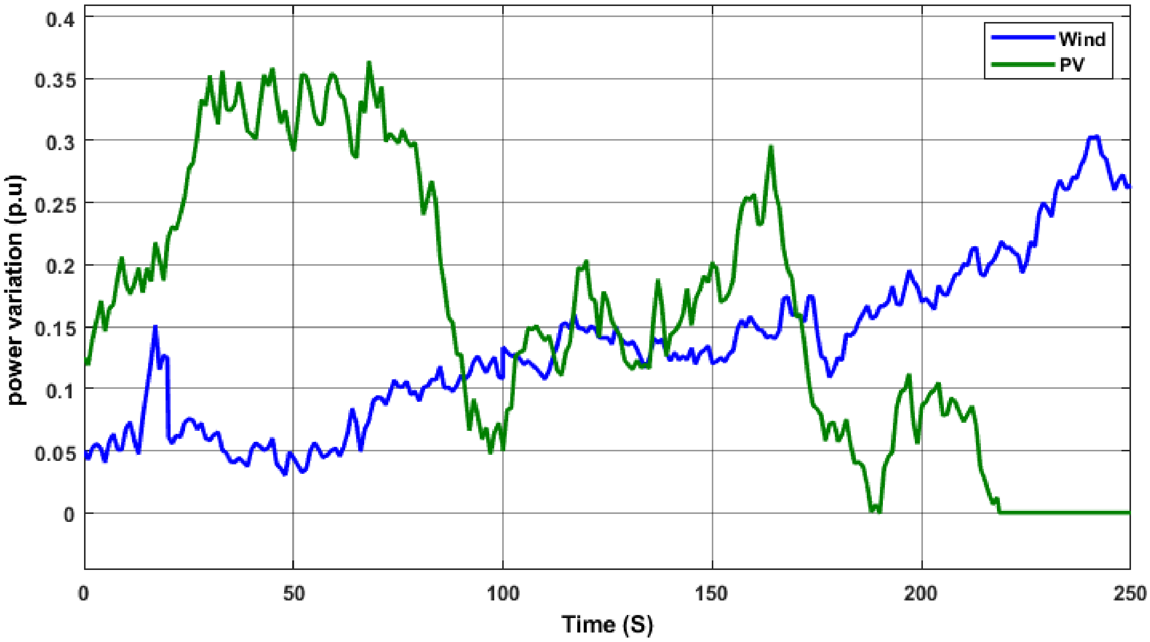


Figure III.19: Graphic of load and PV power variation

The curve shown below represents the results of the frequency diviation behavior when connecting the wind and Photovoltaic in Microgrid system

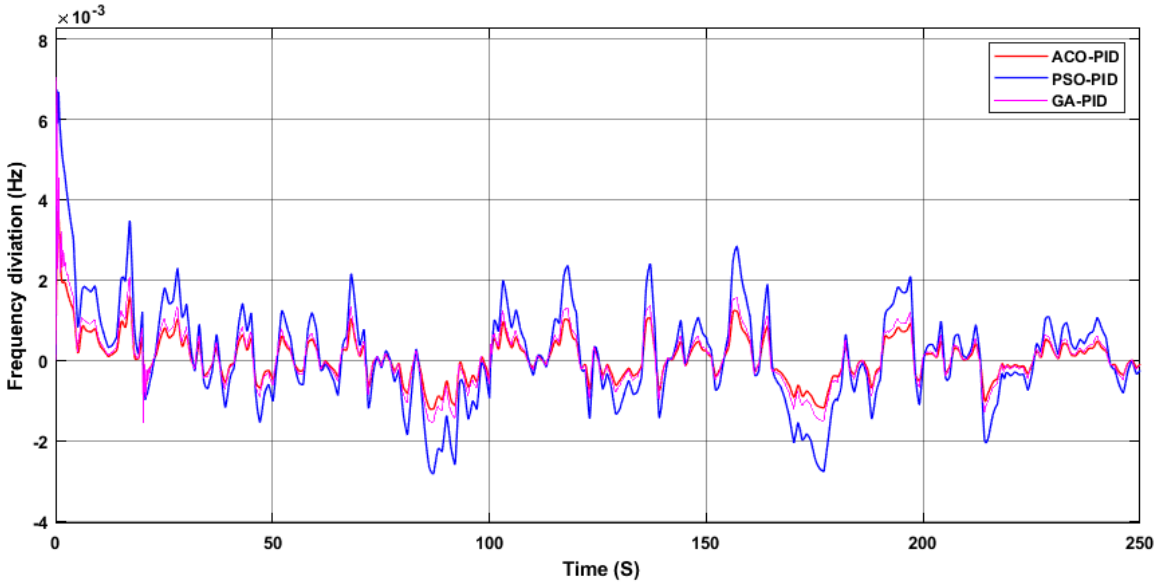


Figure III.20: simulation result of scenario IV in each algorithm

We observed that the system experienced significant frequency fluctuations, with significant instability, especially around the reference value 0. This behavior is attributed to the unstable nature of both sources. Despite these challenging conditions, the Ant Colony algorithm performed acceptability, managing to reduce the fluctuations to some extent and demonstrating a reasonable ability to improve frequency stability compared to other algorithms, even if its performance was not as robust as in the previous scenarios.

Scenario V

In the finale scenario, loads were connected to two renewable energy sources, solar PV and wind, in an integrated configuration within the microgrid system. This scenario represents the most realistic and complex case, as it involves the direct interaction between variable loads and two unstable sources in terms of production capacity. This scenario combines the effects of changes in consumption on the one hand, and natural fluctuations in production on the other, creating significant challenges for system stability, especially at the frequency level. This scenario aims to study how the system behaves under operating conditions close to reality, and the ability of the PID controller to maintain frequency stability.

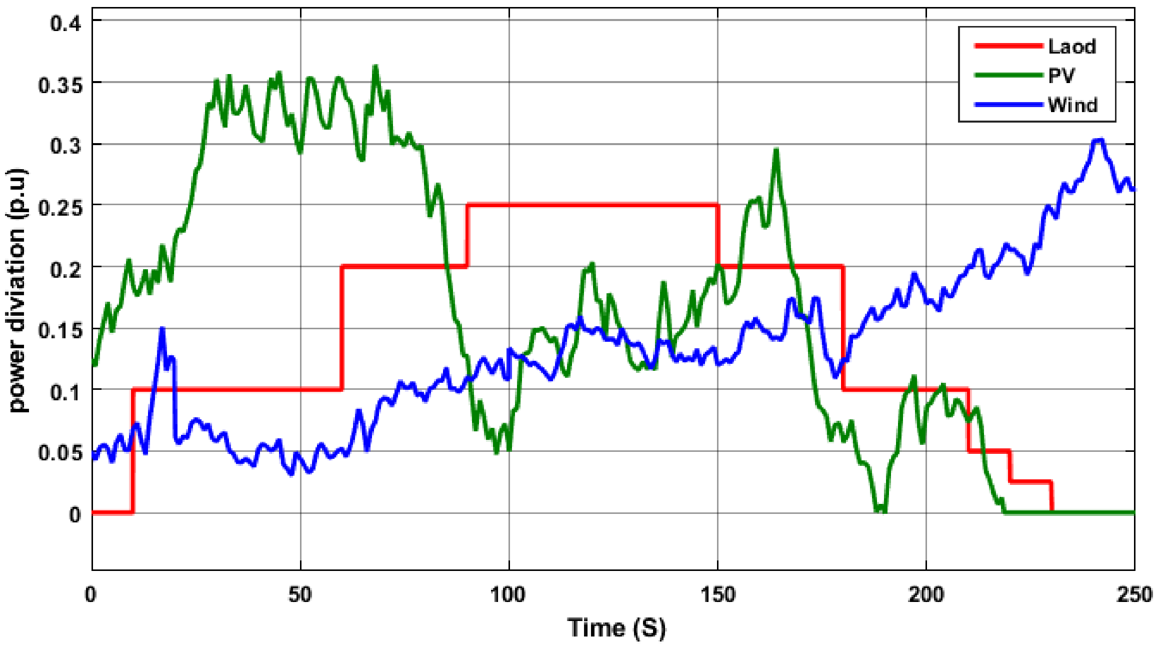


Figure III.21: Graphic of load, wind and PV power variation

The curve shown below represents the results of the frequency diviation behavior when connecting the loads, wind and photovoltaic in Microgrid system

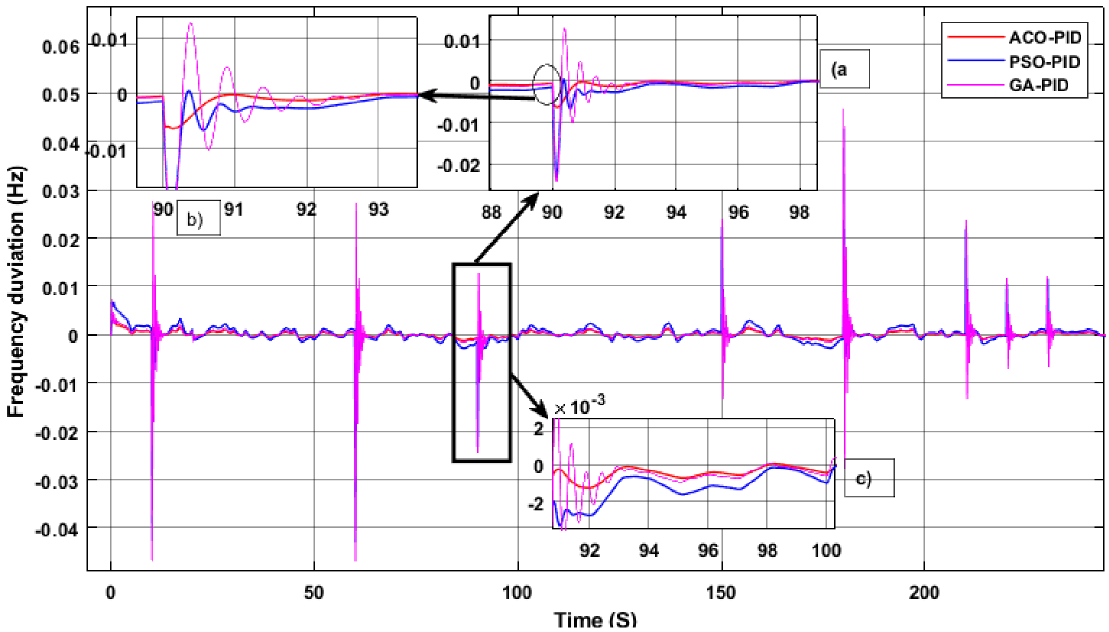


Figure III.22: simulation result of scenario V in each algorithm

We observed that the system had severe frequency fluctuations, and these fluctuations were much larger than we had seen in previous scenarios. This is because this scenario combines more than one renewable energy source wind and PV, both of which are known for their instability and loads with constantly changing power consumption. This combination of fluctuating production and variable demand made it very difficult to maintain frequency balance, as shown in Figure III.22.c.Despite these challenging and complex conditions, the Ant Colony algorithm once again demonstrated its ability to handle the challenges efficiently. It performed well and significantly mitigated the fluctuations while maintaining a fast system response. However, some other algorithms struggled to adapt to this situation, as shown in Figure III.22.a.

III.10 Conclusion

This chapter focused on addressing the frequency fluctuation problem in a microgrid system by adopting a PID controller tuned using the Ant Colony Algorithm, which has been considered an effective solution for improving frequency stability. To evaluate the effectiveness of this approach, its performance was compared with two other algorithms, PSO and GA, to determine the effectiveness of the ACO algorithm in improving system response and reducing fluctuations. The system was tested in various operating scenarios, including load connection and the integration of renewable energy sources such as solar and wind power, to study the impact of these factors on system dynamics and stability. These scenarios contributed to a deeper understanding of the impact of load changes and natural fluctuations in renewable energy sources on frequency stability within a microgrid system. To highlight the performance of the ACO algorithm in frequency control under these scenarios, the results showed that this algorithm performed superiorly in reducing frequency deviations compared to the PSO and GA algorithms. Its high ability to precisely and efficiently tune the PID controller parameters played a crucial role in achieving a rapid dynamic response and improving frequency stability under various operating conditions.

General Conclusion

In this work, we address a contemporary and promising topic in the field of energy which is the microgrid system, which is considered an effective solution for delivering electrical power to remote and isolated areas. We focused our study on the Bella Coola area, which is an ideal model due to its location far from the main electrical grid. This work consists of three chapters. In the first chapter, we discussed general concepts about the microgrid system, touching on its different types and basic components, in addition to its multiple applications in various fields, and the challenges it faces. To enhance the theoretical understanding of this system, we devoted the second chapter to modeling the microgrid system in the Bella Coola area, where we developed a nonlinear model for all the system components. In the third and final chapter, we focused on addressing the problem of frequency fluctuation within the microgrid system, using a PID controller supported by the Ant Colony Algorithm .

The study focused on the problem of frequency fluctuations resulting from load fluctuations and renewable energy sources, which directly impact the quality and stability of electrical power. To address this challenge, a classical PID controller was employed due to its effectiveness and simple structure, while improving its performance by relying on the Ant Colony Algorithm.

After a thorough study of the subject, we can say that this work has contributed to the following:

- It has given an overview of microgrids.
- It has presented a nonlinear modeling in Bella Coola microgrids.
- The microgrid scheme has been designed using the small signal model with a first-order transfer function.
- It has addressed the frequency fluctuation problem using PID with ACO.

Simulation results showed that combining the classical controller with the ACO algorithm significantly improved the system's dynamic response, with reduced oscillation rate and settling time, even under challenging operating conditions such as load fluctuations or unstable renewable energy sources. This demonstrates the ant colony algorithm's ability to adapt to complex environments.

In light of the results achieved, this study emphasizes the great potential of microgrids as sustainable future solutions for energy provision, especially in remote areas.

From this perspective, this thesis recommends intensifying scientific research efforts in this field, given its importance

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