

**VOLTAGE AND FREQUENCY OPTIMIZATION OF INVERTER-BASED
MICROGRIDS CONSIDERING LOW INERTIA GRIDS**

BY
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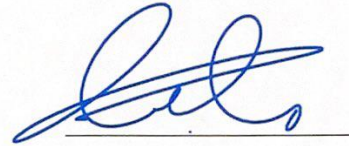


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“To my Inspiring Parent”

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LIST OF ABBREVIATIONS

AC	:	Alternating Current
DC	:	Direct Current
EMS	:	Energy Management System
ESS	:	Energy Storage System
FLC	:	Fuzzy Logic Controller
GC	:	Grid-Connected
GFL	:	Grid Following
GFM	:	Grid-Forming
HESS	:	Hybrid Energy Storage System
IBR	:	Inverter-Based Resources
IS	:	Islanded
LIB	:	Lithium Ion Battery
PCC	:	Point of Common Coupling
RoCoF	:	Rate of Change of Frequency
RTC	:	Real-Time Controller
SC	:	Supercapacitor
SG	:	Synchronous Generator

ABSTRACT

Full Name : [Youssef MHD Jamal Awda]
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Due to the increasing carbon emission in the atmosphere, the world is witnessing a transition in the power system with the integration of renewable energy sources (RESs). According to the international energy agency (IEA), RESs are set to expand by 50% between 2019 and 2024. Moreover, 50% of the generation is planned to be from RESs in Saudi Arabia by 2030. However, these RESs require interfacing devices to be properly integrated into the grid, i.e., inverters. As a result, inverter-based resources (IBRs) are respectively increasing. However, the working principle of IBRs is completely different from synchronous generators (SGs) which are the main energy source in the conventional grid. Therefore, the need for new control methodologies, which resolve the stability problem of low-inertia grids, is critically substantial. In this Thesis, we propose a microgrid system comprising a DC side, an AC side, and an external grid. A hierarchical control algorithm is proposed to manage the power flow between the DC side components (PV, batteries, and supercapacitors) while regulating the DC bus voltage. The regulated DC bus voltage is fed into the AC side, which features a grid-forming inverter based on the virtual synchronous generator (VSG) topology. Two control methodologies are proposed to enhance the VSG inverter. The first is an adaptation control method based on a fuzzy logic controller (FLC) that optimizes the inverter's frequency performance. The gains of the FLC

are optimized using the differential evolution (DE) algorithm. The second is a seamless transition control method that enables seamless switching between the islanded and grid-connected modes. The proposed control methodologies are validated through comprehensive analysis and nonlinear simulations using MATLAB/Simulink. The results demonstrate that the proposed hierarchical control algorithm and control methodologies effectively regulate the microgrid operation and enhance the performance of the VSG inverter, making it suitable for various applications.

ملخص الرسالة

الاسم الكامل: يوسف محمد جمال عودة

عنوان الرسالة: تحسين الجهد والتردد للشبكات الدقيقة القائمة على العاكس مع مراعاة انخفاض القصور الذاتي في الشبكات

التخصص: الهندسة الكهربائية

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نظرًا لزيادة انبعاثات الكربون في الغلاف الجوي ، يشهد العالم تحولًا في نظام الطاقة مع تكامل مصادر الطاقة المتجددة (RESs). وفقًا لوكالة الطاقة الدولية (IEA) ، من المقرر أن تتوسع مصادر الطاقة المتجددة بنسبة 50٪ بين عامي 2019 و 2024. علاوة على ذلك ، من المخطط أن يكون 50٪ من التوليد من مصادر الطاقة المتجددة في المملكة العربية السعودية بحلول عام 2030. ومع ذلك ، تتطلب هذه الموارد وجود أجهزة اتصال بشكل صحيح مدمجة في الشبكة ، أي المحولات. نتيجة لذلك ، تتزايد الموارد القائمة على العاكس (IBRs) على التوالي. ومع ذلك ، فإن مبدأ عمل IBR يختلف تمامًا عن المولدات المتزامنة (SGs) التي تعد مصدر الطاقة الرئيسي في الشبكة التقليدية. لذلك ، فإن الحاجة إلى منهجيات تحكم جديدة ، والتي تحل مشكلة استقرار الشبكات منخفضة القصور الذاتي ، أمر بالغ الأهمية. في هذه الأطروحة ، نقترح نظام شبكة صغيرة يشتمل على جانب DC وجانب AC وشبكة خارجية. تم اقتراح خوارزمية تحكم هرمية لإدارة تدفق الطاقة بين المكونات الجانبية للتيار المستمر (PV ، والبطاريات ، والمكثفات الفائقة) أثناء تنظيم جهد ناقل التيار المستمر. يتم تغذية جهد ناقل التيار المستمر المنظم في جانب التيار المتردد ، والذي يتميز بعاكس لتشكيل الشبكة على أساس طوبولوجيا المولد المتزامن الافتراضي (VSG). تم اقتراح طريقتين للتحكم لتحسين محول VSG. الأول هو طريقة التحكم في التكيف التي تعتمد على وحدة التحكم المنطقية الضبابية (FLC) التي تعمل على تحسين أداء تردد العاكس. تم تحسين مكاسب FLC باستخدام خوارزمية التطور التفاضلي (DE). والثاني هو طريقة تحكم سلسلة في الانتقال تتيح التبديل السلس بين وضعي الجزيرة والمتصلة بالشبكة. يتم التحقق من صحة منهجيات التحكم المقترحة من خلال التحليل الشامل والمحاكاة غير الخطية باستخدام MATLAB / Simulink. توضح النتائج أن خوارزمية التحكم الهرمي المقترحة ومنهجيات التحكم تنظم بشكل فعال عملية الشبكة الدقيقة وتعزز أداء عاكس VSG ، مما يجعلها مناسبة للتطبيقات المختلفة.

CHAPTER 1: INTRODUCTION

1.1 Motivation

Controlling the power grid is the main concern of power system operators. Having robust control of the power system will lead to a high level of stability and reliability. Back in 2003, the biggest power outage (blackout) in North America's history occurred across the Canadian province of Ontario and the northeastern part of the United States, which as a result left more than 50 million people without electricity [1]. This blackout is an evident reminder that the sophistication of the power system's interconnection witnessed considerable growth exceeding the infrastructure ability of power system control and operations.

Due to the increasing carbon emission in the atmosphere, the world is transforming toward sustainability with the integration of renewable energy sources (RESs). According to the international energy agency (IEA), RESs are set to expand by 50% between 2019 and 2024 [2]. Moreover, 50% of the generation is planned to be from RESs in Saudi Arabia by 2030 with less than 1% currently installed [3]. Since RESs produce a different kind of electrical energy, e.g., PV produces DC power while most of the demand is AC power. Therefore, these RESs require interfacing devices to be properly integrated into the grid, i.e., inverters, which convert DC power into AC power. As a result, inverter-based

resources (IBRs) are respectively increasing. As the working principle of IBRs is completely different from synchronous generators (SGs), which are the main energy source in the conventional grid, the need for new control techniques becomes crucial.

Inverters can be mainly categorized into two types: (a) Grid-following (GFL); and (b) Grid-forming (GFM) inverters. GFL inverters are the dominant IBRs that are easy to control and implement since they follow the voltage and frequency of the connected power grid using the phase-locked loop (PLL) mechanism, which depends on the generated voltage of the grid [4]. However, GFL inverters require robust grid inertia to stably operate [4]. As the percentage of RESs increase relative to SGs, the inertia of the grid reduces. Hence, maintaining the stability of the power system becomes more challenging. Grid-forming (GFM) inverters can be a promising solution since GFM inverters simulate the behavior of an SG [5].

1.2 Background

The main parameters that must be continuously controlled in the power grid are voltage magnitude and the corresponding frequency. The reason is due to the fact that the power grid is interconnected and needs to be synchronized. In a highly inductive grid where $X/R \gg 1$, which is usually the case, the voltage magnitude is mainly affected by the reactive power, whereas the frequency, is mainly affected by the active power. However, in a resistive grid where $R/X \gg 1$, the voltage magnitude is mainly affected by the active power, whereas the frequency, is mainly affected by the reactive power [6].

Conventionally, the majority of power generation comes from bulk SGs, which have a high inertia. This inertia is determined by considering all the rotating masses of SGs connected to the grid. The inertia constant of an SG decides the time interval at which the SG can supply its rated power by only using the stored kinetic energy of its rotating shaft. Equation. (1.1) defines the inertia constant H [7].

$$H = \frac{E_{kin}}{S_R} = \frac{1}{2} \frac{J \omega_R^2}{S_R} \quad (1.1)$$

Where E_{kin} , S_R , J and ω_R are the kinetic energy, rated power, the moment of inertia, and rated angular frequency of the SG respectively.

Several control strategies are employed to maintain the nominal value of frequency as well as voltage magnitude. In other words, maintain the synchronization of the power grid. In the following subsections, the basic frequency control and voltage control strategies are illustrated.

1.2.1 Frequency control

In a power system, the frequency is determined by the balance of generation and load. The frequency of the power system is directly related to the speed of rotation of the generators, which are typically driven by steam turbines or gas turbines.

In an ideal power system, the frequency is maintained at a constant value, typically 50 or 60 Hertz, by controlling the balance between generation and load. When there is a mismatch between generation and load, the frequency of the power system will deviate from its nominal value. For example, if there is more generation than load, the frequency will increase, and if there is more load than generation, the frequency will decrease.

To maintain the frequency at the desired level, power system operators use a variety of control strategies, including automatic generation control (AGC) and frequency response mechanisms. AGC adjusts the output of generators in real-time to match changes in load, while frequency response mechanisms can include the use of spinning reserve, fast-start generators, and energy storage systems to respond to frequency deviations and help restore balance to the power system.

Overall, maintaining a stable frequency is essential for ensuring the reliable and efficient operation of the power system.

The relationship between the input mechanical power P_m and the output electrical power P_e is governed by the well-known swing equation [8] and represented in (1.2), being δ is the angular motion of the SG. Therefore, the degree at which a disturbance can change the frequency of the system is inversely proportional to the available amount of inertia in the system.

$$\frac{2H}{\omega_R} \times \frac{d^2 \delta}{dt^2} = P_m - P_e \quad (1.2)$$

In steady-state operation, the input mechanical power and the output electrical power are equaled, and therefore, a constant synchronous speed is maintained. This synchronous speed is defined in the following paragraph.

Synchronous speed is the speed at which the rotating magnetic field produced by the stator of a synchronous motor or generator rotates. It is determined by the frequency of the AC power supply and the number of poles in the motor or generator.

The formula for calculating the synchronous speed S (in RPM, i.e., revolution per minute) of a specific SG is given by:

$$S = (120 \times \text{frequency}) / N$$

where the frequency is in Hertz and the number of poles N refers to the number of pairs of magnetic poles in the stator. For example, a synchronous motor with four poles and connected to a 60 Hz power supply would have a synchronous speed of:

$$S = (120 \times 60) / 4 = 1,800 \text{ RPM}$$

At synchronous speed, the rotating magnetic field produced by the stator rotates at the same speed as the rotor, which is locked in step with the magnetic field. This is what gives synchronous motors their name. Synchronous motors are used in a variety of industrial applications, including electric power systems, machinery, and transportation.

The most commonly used controller for maintaining the frequency is the speed-droop control which creates a relationship between the change in load power ΔP_L and its corresponding change in frequency Δf . Figure. 1.1 shows the characteristic curve of speed-droop [9].

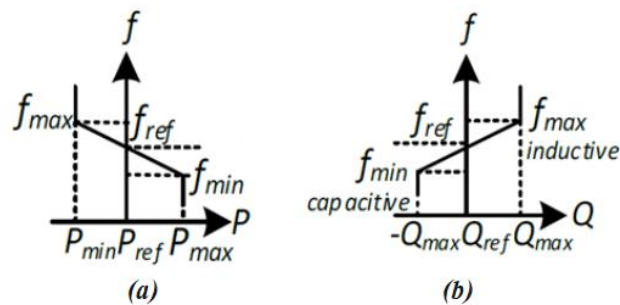


Figure 1.1: The frequency characteristic curve of droop control, (a) inductive grid, (b) resistive grid.

A governor then is responsible for giving the required amount of mechanical power to match the nominal frequency according to the speed-droop settings, i.e., accelerate the shaft to match the frequency in case of increasing the load power and vice versa. Notably, in a system with multiple generators, each generator would have its own droop curve and all generators must coordinate to achieve system synchronization. Figure 1.2 shows the control block diagram when two generators are coordinated. The same procedure applies when more generators are involved.

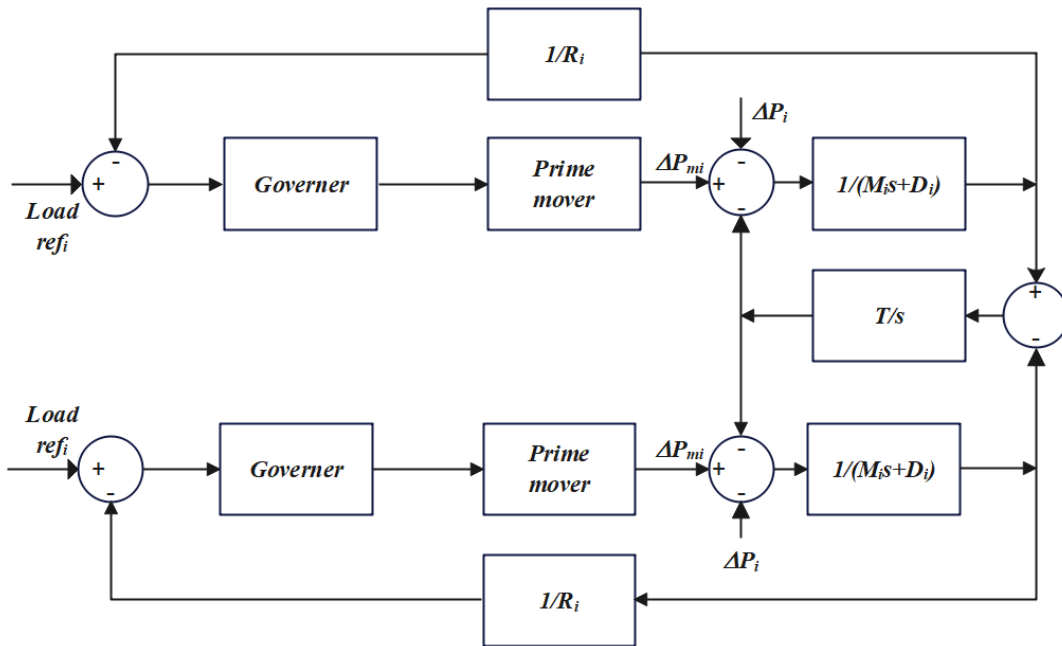


Figure 1.2: Simple block diagram of interconnected generators.

Where the subscript i denotes the number of the generator unit, $load\ ref$ is the power set point, R is the slope of the characteristic curve (also known as droop coefficient), M and D are the rotating mass and damping coefficient of the i th generation unit, respectively. As can be seen from Figure 1.2, each generation unit has its own closed-loop controller to ensure the power balance. However, as previously discussed, maintaining the power

balance means maintaining the frequency. Therefore, they both contribute to maintaining the frequency. The amount of contribution of each generator is then determined by the characteristic curve of the droop control (see Figure 1.1). It should be mentioned that each generator has its own characteristic curve.

1.2.2 Voltage control

There are mainly two ways to control the voltage in an interconnected power grid. First, the excitation system of the synchronous machine which uses a similar control mechanism as the frequency control, i.e., speed-droop control, but in this case, the created relationship is between the change in voltage and the corresponding change in reactive power, since the voltage magnitude and reactive power are associated with each other as indicated in Figure 1.3. Second, by using different types of compensators across the power grid, such as static VAR compensators, capacitor banks, and dynamic voltage restorers (DVR) [10] to compensate for the consumed reactive power and therefore improve the voltage profile of the power grid.

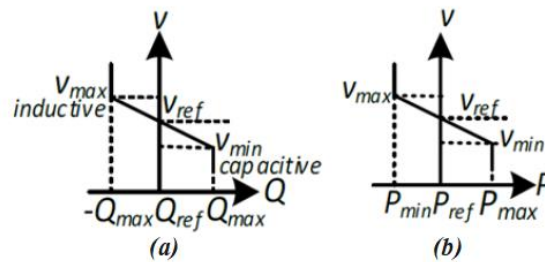


Figure 1.3: The voltage characteristic curve of droop control, (a) inductive grid, (b) resistive grid.

1.2.3 Microgrid definition

A microgrid is a localized group of electricity sources and loads that can operate independently of the main grid. It can include various distributed energy resources (DERs)

such as solar panels, wind turbines, diesel generators, and energy storage systems, along with local loads such as homes, businesses, and critical infrastructure [11].

A microgrid can either operate in grid-connected (GC) or islanded (IS) mode. In GC mode, the microgrid is connected to the main grid and can export or import electricity as needed. In IS mode, the microgrid is disconnected from the main grid and relies solely on its own resources to meet local energy demands [12].

Microgrids are often used in remote or off-grid areas where it is difficult or expensive to connect to the larger grid, or in areas where the grid is unreliable or prone to outages. They can also be used to provide backup power for critical facilities during emergencies, such as hospitals, military bases, and data centers. Additionally, microgrids can help integrate renewable energy sources into the grid, improve energy efficiency, and reduce greenhouse gas emissions [13].

The use of inverters is important in such microgrids as it ensures that all the resources can be integrated and controlled effectively. Inverters allow for the integration of various renewable energy sources with different power ratings and output characteristics, while also enabling efficient and stable energy supply to the microgrid. In addition, inverters can also provide power quality support and protection to the microgrid in case of voltage or frequency deviations as will be elaborated later.

Furthermore, with the increasing adoption of renewable energy sources, the use of inverter-based microgrids is becoming more common as it provides an efficient and reliable way to integrate renewable energy into the grid. The use of inverters also makes it

possible to manage the variability and intermittency of renewable energy resources, which is crucial for maintaining grid stability and reliability [14].

1.3 Thesis Objective

It should be pointed out that the work of this thesis will be on inverter-based microgrid, which is a type of microgrid where all the resources within the system are connected to the grid through inverters. This means that the resources such as solar panels, and energy storage systems, all convert the DC power they generate to AC power using inverters before feeding it into the microgrid. Therefore, there are no non-inverter resources in the microgrid.

Ultimately, the fact that the work is on inverter-based microgrids with no non-inverter resources in the microgrid highlights the importance of inverters in integrating and controlling renewable energy resources within the microgrid. This approach enables an efficient and stable energy supply while also ensuring the reliability and stability of the microgrids.

The main objective of this thesis is to control the operation of a microgrid including the DC, AC sides and the transitioning between the IS and GC modes of operation. The following points elaborate on the main objectives:

- To conduct a comparison analysis between the GFL and GFM inverters in terms of frequency support.
- To manage the power flow between the DC side components, i.e., batteries, supercapacitors (SCs), and PV panels.

- To ensure a stable DC bus voltage by utilizing the SCs.
- To develop a control methodology that optimizes the frequency performance of the employed GFM inverter.
- To establish a control strategy for a seamless transition between the IS and GC modes of operation.

1.4 Thesis Organization

This thesis is organized as follows: Chapter 2 provides an overview of the microgrid control layers. Moreover, a literature review on the recent optimization methods applied to microgrid energy management is conducted. Further, the recent control methodologies applied to control IBRs in microgrids are reviewed which include the following: 1) DC stabilization and power management, 2) Control of GFM inverters, 3) transitioning control strategies between the IS and GC modes. Chapter 3 provides the overall approach of this Thesis and summarizes the studied system architecture and control methodology. In Chapter 4, the mathematical model of the studied system is presented. This model, mainly, includes three parts: 1) DC-side microgrid model, 2) AC-side microgrid model, and 3) external grid model. In Chapter 5, which is the core of this thesis, we present the control methodology. This chapter essentially includes three parts. First, the proposed EMS and DC stabilization of the DC microgrid is discussed. Then, the proposed adaptive virtual synchronous generator with optimal frequency control is analyzed. Finally, the control strategy of the proposed seamless transition between the islanded and grid-connected modes is illustrated. In Chapter 6, the obtained simulation results that have been acquired from MATLAB/Simulink environment are demonstrated. In addition, several case studies

are conducted to validate the proposed control methodology. Finally, the conclusion and the possible future work are drawn in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

This chapter is divided into three sections. Section 2.1 is dedicated to providing an overview on the microgrid control layers. In Section 2.2, a literature review on the recent optimization methods applied to microgrid energy management is conducted. In addition, the recent control methodologies applied to control IBRs in microgrids are reviewed in Section 2.3. In Section 2.4, the DC stabilization and power management for a hybrid system is discussed. Sections 2.5 and 2.6 review the novel control methods of GFM inverters, as well as the strategies applied for transitioning from GC to IS modes and vice versa. Finally, the identified literature gaps and Thesis contributions are drawn in Section 2.7.

2.1 Overview

Archetypally, the microgrid control is divided into three main hierarchical control layers as shown in Figure 2.1, i.e., primary control, secondary control, and tertiary control [15].

Primary control has the fastest response among the three hierarchical control layers. The distributed generation (DG) units in this control layer can be mainly categorized into two control algorithms: 1) V/f control (GFM); and 2) P/Q control (GFL).

The highest hierarchical level in islanded microgrids is the secondary control. This layer of control is referred as the EMS of the microgrid and can be further categorized into two main approaches: 1) centralized; and 2) decentralized architectures.

The tertiary control layer is the highest level of control, and it is only considered when two or more microgrids are involved to achieve long-term goals such as supporting the grid, and maintaining a certain amount of reserve and/or regulation capacity.

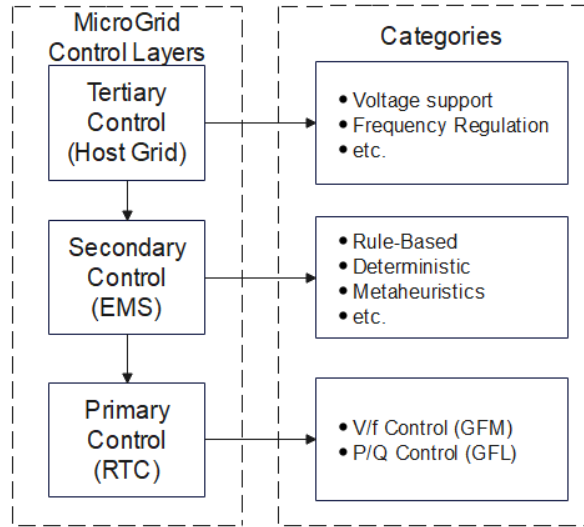


Figure 2.1: Microgrid control layers.

2.2 Optimization Methods applied to Microgrid Energy Management

The main objective of the microgrid EMS is to provide the optimal or near to optimal operation of the microgrid while satisfying the physical and economical constraints of the microgrid system. In this section, a literature review, that outlines some methods of EMS applications to microgrids, is conducted.

2.2.1 Rule-Based

In rule-based (RB) EMS, the power flow is basically determined based on a set of defined rules [16]. For instance, the authors in [17] developed and compared two EMSs, the first one was RB-EMS where the rules maintain the power balance with the help of an ESS, while the second EMS was optimization-based. The results showed a better performance favor to the optimization-based EMS with some communication delays and

gaps between the real-time measurements and set points. Moreover, a novel RB model predictive control (MPC) was developed in [18] for EMS of a grid-connected microgrid. The role of RB algorithm was to decide the binary variables in the microgrid, i.e., charging/discharging the ESS and ON/OFF status of the generators. In this way, the mixed-integer linear programming (MILP) problem was converted to a linear one, which significantly reduces the computational time.

Fuzzy logic control (FLC)-based supervisory system has a similar approach as the RB technique, since it has an inference step that determines which rules to be fired out of a set of user-defined rules. However, these rules are defined as fuzzified membership functions which give a flexible determination in selecting the rules. The main steps of FLC algorithm are fuzzification, inference, and defuzzification [19]. In fuzzification and defuzzification processes, the numerical variables, which are usually the measurements, are converted to linguistic variables and vice versa. The authors in [20] developed a new FLC-based supervisory to reduce the power sharing mismatch during the intermittency of the RESs and improve the voltage regulation of the microgrid. In addition, a supervisory controller based on FLC was proposed in [21] to guarantee that the ESS of the islanded microgrid does not exceed its power and energy limits. However, in case of having extra PV generation the use of a micro gas turbine is needed.

2.2.2 Deterministic Techniques

Deterministic techniques are utilized to find the optimal EMS of the microgrid. These techniques include, but are not limited to, Linear programming (LP), mixed-integer

linear programming (MILP), mixed integer non-linear programming (MINLP), quadratic programming (QP), dynamic programming (DP).

The selection of the above techniques is based on the type of variable included in the objective function and constraints. For instance, LP is an optimization technique used to minimize or maximize an objective function subject to restricted constraints in which all variables must be an integer value; Similar to LP, MILP is used for optimizing the objective function. However, variables can be either integer or discrete. As for MINLP, the variables include non-integer variables. QP is a type of nonlinear programming optimization technique involving quadratic functions and linear constraints. DP is a programming computer technique used to find the optimal solution in case of overlapping subproblems [22].

Various mathematical optimization models have been developed for optimal EMS of the microgrid. For instance, the authors in [23] utilized virtual power producer (VPP) to find the optimal operation of an islanded DC microgrid to achieve the minimum operation costs and optimized time of ESS charging/discharging. The MILP is adopted to acquire the optimal operation of the DG units, i.e., ESS, wind turbine, solar unit. The developed model is applied to a real case study in Budapest tech. The results showed the robustness of this method in finding the optimal operating condition of the DC microgrid renewable energy park. Moreover, demand side management (DSM) strategy based on a microgrid scheduling algorithm using linear programming was done in [24] for reducing the peak demand. The application of the proposed system on an Indian distribution system reflected a reduction of 1.7 % and 5.16% in peak load demand and electricity cost respectively. In addition, a new concept was introduced in [25] of end-user-driven microgrid and a new

approach was proposed for optimal power scheduling of the battery based on QP. The generated model provided optimal management of the battery resulting in a minimum power from the grid. Also, the model was applied to two microgrids connected at different points. The results provided end-user flexibility, minimum cost, and insurance of grid-level reliability. Furthermore, MINLP optimization technique is acquired by authors in [26] to find optimal EMS taking into consideration different scenarios. Also, to obtain the maximum utilization of the distributed energy sources and achieve the cheapest price. For the validation of the model, the developed algorithm is experimentally tested using a simulation setup on a real microgrid testbed. A 15% reduction in the total cost of energy is achieved compared to the conventional EMS.

2.2.3 Metaheuristic Techniques

A metaheuristic is a high-level technique or heuristic meant to locate, produce, or choose a heuristic (incomplete search algorithm) that may offer a sufficiently satisfactory solution to an optimization issue, particularly when information is incomplete or inaccurate or compute capability is restricted [27], [28]. In metaheuristics techniques, few assumptions can be made to the optimization problem being addressed and hence may be applicable to a wide range of applications [29].

Genetic algorithm (GA) is considered as metaheuristic technique. In other words, GA is a population-based technique that searches for optimal points according to the probabilities of the used key parameters [30]. A hierarchical GA-based EMS is proposed in [31] for a grid-connected microgrid with. The objective of this study is to maximize the profit generated by the energy exchange with the grid under a time of use pricing policy.

Particle swarm optimization (PSO) is another metaheuristic technique that is also a population-based. In [32] a modified PSO was used for real-time EMS to optimally find the ESS control of the microgrid. The modification of the PSO algorithm was done by changing the cost function to properly reflect the battery charging/discharging profile. Case studies were made to verify the effectiveness of the modified PSO. Compared to the conventional PSO, the proposed algorithm reduced the operational cost by 12%.

2.3 Real-Time Control (RTC)

To interface an IBR into the grid, a certain control strategy is applied to the power converter. In the following subsections, classifications of IBRs are discussed according to their control scheme.

2.3.1 GFL Inverter

GFL inverters follow the voltage and frequency of the connected power grid by using phase-locked loops (PLL) that depends on the generated voltage of SGs [33]. Figure 2.2 depict a simplified control diagram of the GFL inverter. This type of inverter works in current control mode (CCM), so they are considered as a controlled current source in parallel with a high impedance that injects a specific amount of active or reactive power to the connected grid [34].

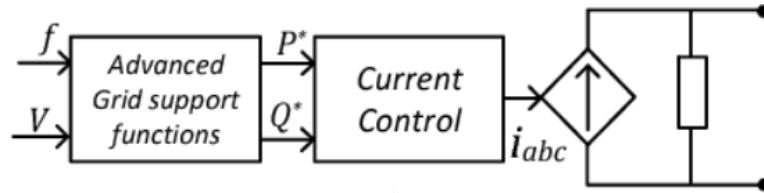


Figure 2.2: Simplified control diagram of GFL inverter.

2.3.2 GFM Inverter

GFM inverter is usually associated with an energy storage system (ESS) for islanded operation. Figure 2.3 depicts a simplified control diagram of the GFM inverter. This type of inverter can generate their voltage and frequency to form the grid and operates in a voltage control mode (VCM), so they are considered as a controlled voltage source in series with a low impedance that injects the required amount of active or reactive power to abide the state of charge (SoC) of the ESS module as well as improve the power quality and voltage profile.

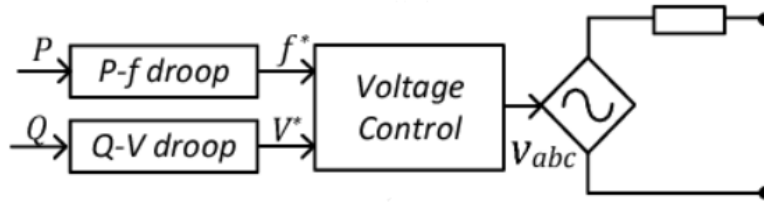


Figure 2.3: Simplified control diagram of GFM inverter.

GFL inverters are fundamentally controlled using the principle of the vector current control. Contradictorily, GFM inverters can form a voltage phasor at the point of common coupling (PCC) since they are considered as a voltage source. The control mechanism of a GFM inverter is configured to dynamically attain synchronization and support the grid in contingency [35]. Therefore, GFM inverters are constructed with multiple control loops, e.g., current control loop, virtual impedance loop, intermediate-voltage control loop, active power controller (APC), and reactive power controller (RPC). The APC and RPC determine the voltage magnitude and frequency, thus the phase angle at the PCC.

Table 2.1 summarizes the main differences between GFL and GFM inverters.

Table 2.1: GFL Vs. GFM

Category	GFL	GFM
Dependency	Dependent on another source such as SGs to follow its voltage and frequency.	Independent and can form and maintain a grid voltage and frequency.
Controllability	CCM, i.e., controls the amount of injected power to the grid	VCM, i.e., control voltage magnitude, frequency/phase for improved power stability.
Need of PLL	Mandatory	Might utilize PLL to shift between modes
Contribution to the grid	Limited	Effectively black-start a power system
The scenario of 100% IBRs	Not able to operate with 100% IBRs	Able to operate with 100% IBRs, in addition to other GFL inverters.

Conceptually, the control methodology of the GFM inverters can be mainly divided into three categories:

1. Droop control:

This methodology is the most dominant and well-known technique out of the three methodologies. The principle of droop control arises from the governor's action which allows the parallel operation of several SGs. The target of implementing such a methodology is to protect the islanded microgrid from any load variations by simply adjusting the droop characteristics of the inverter. These droop characteristics are categorized into P/f droop for active power control and Q/V droop for voltage control.

Moreover, this technique is divided into three categories, i.e., frequency-based droop (FBD) [36], angle-based droop (ABD) [37], and power synchronization control (PSC) [38].

2. Virtual synchronous generator control (VSGC):

The major drawback of droop control is the absence of an inertial response. Therefore, VSGC is proposed to include the damping and inertial properties of the SG. This VSGC methodology introduces a two-shaft SG model involving the stator and excitation windings as well as the damping property.

Furthermore, this technique is mainly divided into three categories, i.e., augmented virtual SG control [39], swing equation emulation [40], and synchronverter [41].

3. Other control techniques:

In addition to the above-mentioned control techniques, there are other several control methods for GFM inverters such as virtual oscillator-based [42], frequency shaping-based [43], and virtual synchronous control using the dynamics of DC-link technique [44].

2.3.3 Other Types of Inverters

In addition to GFL and GFM inverters, there are other two types of inverters, i.e., grid supporting and interlinking inverters.

1. Grid supporting inverter:

This type of inverter is mainly used to support the grid against disturbances, i.e., not as an energy source. Therefore, it is adopted with ESS and can be operated in VCM or CCM. In

CCM, it can inject the required amount of active/reactive power by using the inverse droop control. In VCM, it can adjust its output voltage and frequency according to the grid by using the direct droop control [45]. The major disadvantage of this type of inverters, they suffer from low inertia, as a result, microgrids become susceptible to instability.

2. Interlinking inverter:

As the name suggests, the interlinking converters are used to interlink the two types of microgrids, i.e., DC and AC microgrids. Therefore, they can be operated as an inverter or a rectifier and support the bi-directional power flow. They are mainly used for controlling power flow, ancillary service, and improving the power system stability as well as quality. However, in [46] serious issues were highlighted including the non-linear load behavior when conducting power flow from AC to DC microgrids, the circulating current between the interlinking converters in parallel operation, and restoration issues after fault clearing scenario. Moreover, utilizing these converters for ancillary services, where the ESS is mainly used for ancillary services, could decrease the maximum consumption of RESs and therefore, minimize the overall system efficiency.

2.3.4 GFM and GFL Comparison

Many research works have been done to conduct comparison analysis in terms of frequency support between GFM and GFL inverters. For instance, the authors in [47] investigated the impact of the transfer function and the current limiting of the controller as well as the fluctuations in the DC-link in both transients and steady-state fault responses. However, the grid was modeled as an infinite bus. Moreover, in [48], the inertial behavior of the GFM inverter with the SG was tested theoretically and via simulation. The

simulation was conducted by connecting both the GFM inverter and the SG to a controllable voltage source. This voltage source was used to emulate the grid, and hence, the frequency ramp is achieved. This grid emulation does not reflect the real grid with low inertia and no GFL inverter was tested. In addition, a case study of an existing island was implemented in [49] under the assumption of 100% IBRs. The study investigated the influence on the control parameters, location, number, and size of the IBRs that work as GFM concerning the frequency dynamics. The made assumption was not to consider any existing SGs or GFL inverters. Further, an inertia-damping-strengthened method is proposed in [50] for frequency stability improvement when the GFM inverter is attached to a weak grid. The analysis was conducted for different short circuit ratios (SCR) and neglected the effect of the inertia of the grid. Additionally, a comparative study was carried out in [51] to investigate the large-signal stability of the GFM and GFL inverters while considering a weak grid connection. Yet, no investigation was done on the amount of available inertia in the grid.

2.4 DC Side Stabilization and Power management

In the literature, the main two control methodologies for energy management of HESS are classical control and intelligent control which are discussed among their advantages and disadvantages as follows:

1. Classical control
 - *Filter-Based Control (FBC)*

The principle of the FBC technique is to separate the power flow of the ESS into high-frequency (HF) and low-frequency (LF) components by utilizing a filter circuit.

Consequently, the power flow of the ESS is composed of HF and LF elements. The LF components pass during normal conditions whereas the HF components are occurred due to intermittency of the RESs or sudden load variations. Therefore, for the HF components, an ESS with a high power density is needed and an ESS with a high energy density is needed for the LF components [52].

The major drawback of this technique is the high sensitivity to the HF components which allows unnecessary discharging of the high-power density of the ESS, i.e., the SC.

- *Rule-Based Control (RBC)*

RBC algorithm basically determines the power flow of the ESS based on a set of defined rules [53]. Depending on the application, the rules are defined so that the SC will contribute if the battery current exceeds a certain limit. Consequently, this control technique suffers a lack of flexibility and sometimes the response of the system is slower than the demand requirements, which increases the stress on the high energy density of the ESS, i.e., the battery.

2. Intelligent Control

The intelligent control techniques have shown a much better performance than the traditional techniques [54]. In the literature, many intelligent control techniques have been proposed. For instance, a fast model predictive control (MPC) is proposed in [55] to reduce the common-mode voltage in a five-level dual T-type multilevel converter. In addition, the authors in [56] have presented a neural network model to eliminate the need for understanding the exact model of the system. Furthermore, the work in [57] combined the

MPC and particle swarm optimization (PSO) to forecast the power demand for better energy management.

In this study, however, the focus was on the fuzzy logic controller (FLC) to PV applications with HESS. Just like any intelligent algorithm, FLC was used for PV applications in several research studies. For instance, the authors in [58], [59] utilized the FLC for energy management. However, the DC bus regulation was not considered, and a perfect DC bus was assumed. The DC bus was regulated in [60] by only the battery which makes the system impractical in islanded mode. although the DC bus was regulated in [61], the SoC was ignored.

2.5 Control of GFM Inverters

Novel control strategies are proposed in the literature to enable inverter-based resources (IBRs) to contribute to the frequency stability of the power grid. For instance, the droop control strategy is proposed in [62] and, [63] to protect islanded microgrids from any load variations by simply adjusting the droop characteristics of the inverter. These droop characteristics are categorized into P/ω droop for active power control and Q/V droop for voltage control. The major drawback of this control methodology is the lack of inertial response. To overcome this issue, the authors in [64] proposed an inertial droop control to emulate the inertial response of SGs. However, the damping factor was neglected in this study. The virtual synchronous generator (VSG) was proposed to mimic the SG and provide the fundamental properties and features of the SG [65]–[68]. These features include the damping factor and the so-called virtual inertia. The study in [68] compared the dynamic behavior between droop control and VSG. The authors concluded that the

damping factor of the VSG is equivalent to the droop characteristic in the case of the islanded mode of operation. In addition, VSG control inherits all advantages of droop control.

In the aforementioned references based on VSG control, the virtual inertia parameter value is fixed at one value during the operation. In some studies [69]–[72], virtual inertia constant values are chosen based on a trade-off or graphical study of the system's frequency response and dynamic performance. As a result, substantial eigenvalue sensitivity analysis is required, and it may result in inappropriate selection or adjustment mistakes, resulting in system instability. In addition to inertia constant, system frequency and power fluctuate following disturbances, although the transient tolerance of IBR is substantially lower than that of an SG. As a result, choosing a fixed virtual inertia constant would have a major impact on the frequency stability of the system under various disturbances.

To avoid the problems caused by having constant inertia and damping coefficients, self-adaptive inertia and damping control are proposed in [73] to support the frequency stability. Although both inertia and damping coefficients are adaptively tuned, they were set based on the swing equation principle without optimization. Hence, the optimal setting is not guaranteed. Further, the authors in [74] proposed an optimization algorithm to search for optimal settings of inertia and damping coefficients. However, due to the high time burden needed to solve the optimization problem, some of the parameters are neglected, such as the inertia coefficient, during the operation. Moreover, a bang-bang control strategy is introduced in [75] to develop an alternating moment of inertia and a fuzzy logic controller is developed in [76] to adaptively tune the virtual inertia coefficient.

Nevertheless, both [75] and [76] neglect the optimization of the damping factor which limits the capability of GFM inverters.

To ensure optimal frequency performance, we propose a fuzzy logic controller (FLC) to adaptively and simultaneously optimize the virtual inertia and the damping coefficients of the VSG. We also use the differential evolution (DE) algorithm to optimize the FLC gains. We formulate a multi-objective function when optimizing the FLC gains which include the minimization of frequency deviation, rate of change of frequency (RoCoF), and frequency settling time. To decide the optimal FLC gains, a Pareto front is obtained from the multi-objective optimization problem. Further, the most compromised solution is selected by calculating the minimum distance from the origin.

2.6 Transition strategies between IS and GC Modes

In the literature, the widely used approach is to have two different control strategies for each mode of operation, i.e., grid-following (GFL) control strategy (in GC mode), and grid-forming (GFM) control strategy (in IS mode) [77]–[79]. Unintentional islanding could suddenly happen due to a disturbance from the grid side. Thus, strong disturbances will affect the microgrid's voltage and current amplitudes, threatening system stability. The authors in [80] proposed a capacitor current feedback and output current feedforward as an input to both linear voltage and current controllers, respectively, to mitigate the voltage and current fluctuations during unintentional switching from GC to IS mode. However, switching from IS to GC mode was ignored in this study.

Some research studies employ single control strategies for both modes of operation, which are based on nonlinear control theory, such as Lyapunov-based technique [81], [82],

model predictive control [83], [84], this control technique requires the exact model of the system and the dynamic behavior. Such controllers are sophisticated, computationally intensive, and difficult to implement in practice.

Most of the implemented control strategies for a seamless transition between GC to IS mode and vice versa considered the grid as an infinite bus or a strong grid with high inertia. However, to emulate the case of high renewable penetrations [85], the inertia of the grid must be considered to insure reliable operation even with high renewable penetrations where the inertia of the grid is reduced.

2.7 Literature Gaps and Thesis Contribution

2.7.1 Literature Gaps

Based on the conducted literature review, the following gaps were found in the literature:

- The lack of conducted comparison analysis between the GFM and the GFL inverters, specifically, by considering the grid inertia as a manipulated variable.
- Ignore the voltage stabilization in islanded systems during the charging process of the batteries, which are responsible for the voltage stabilization in most cases.
- Fixing the virtual inertia and damping coefficients of the VSG or changing them in a not optimal manner.
- Using two control algorithms for each mode of operation, i.e., GC and IS modes, which results in a non-desirable discontinuity.

2.7.2 Thesis Contribution

The key contributions of this thesis can be summarized as follows:

- Conducting a systematic analysis to study the ability of a microgrid to provide frequency support to the grid as the inertia reduces. We compare two types of inverters in terms of their ability to support the frequency of the grid: 1) the widely used type (GFL inverters), and 2) the state-of-art type (GFM inverters). In addition, the support of frequency is measured under multiple microgrid sizes and multiple levels of grid inertia using three metrics. The metrics under consideration are: 1) maximum frequency over/undershoot, 2) maximum rate of change of frequency (RoCoF), and 3) frequency settling time.
- Proposing a hierarchical control algorithm to control the operation of a DC microgrid with a hybrid energy storage system (HESS). The control algorithm consists of two layers: a) a supervisory layer overseeing the states of all controllable devices connected to the input-side of the DC bus and is based on fuzzy logic control, and b) a local control layer for each device based on PI control which receives inputs from the supervisory layer. The goal of the algorithm is to achieve a stable DC-bus voltage to be the input of GFM inverters. In addition, the algorithm determines the power flow of each component connected to the input-side of the DC bus considering the components' capabilities and constraints.

- Proposing a control algorithm that hybridizes fuzzy logic controller (FLC) and differential evolution (DE) optimization to adaptively tune the virtual inertia and the damping factor of the VSG. Unlike the other proposed algorithms in the literature [74], [75], which are complex to implement and need high computational power, the proposed hybrid FLC-DE is a model-free and easy-to-apply control algorithm. The hybridization is achieved by optimizing the FLC parameters using the DE algorithm. We formulate a multi-objective problem to minimize: 1) frequency deviation, 2) RoCoF, and 3) frequency settling time. We then obtain the Pareto front of the multi-objective optimization problem to investigate the tradeoffs between the three objectives and to select the most appropriate solutions.
- Proposing an improved virtual SG (VSG) (a type of GFM inverter) to seamlessly switch between the modes of operation by modifying the governor of the VSG to adjust the voltage magnitude and frequency to match the grid during the transition from IS to GC mode for a smooth transition. A seamless transition is also achieved during the unintentional transition from GC to IS mode because of the self-ability of the VSG to regulate the voltage and frequency. In this way, we avoid the discontinuity of the control operation and deploy a single control strategy in both modes of operation.

CHAPTER 3: OVERALL APPROACH

3.1 Overview

This chapter provides an overall approach to the proposed microgrid system (architecture and control). First, we start by introducing the structure and the modeled components in section 3.2, followed by the overall control structure in section 3.3.

3.2 Microgrid Architecture

Based on the obtained research gap in the previous chapter, the illustrated AC/DC microgrid system in Figure 3.1 is developed.

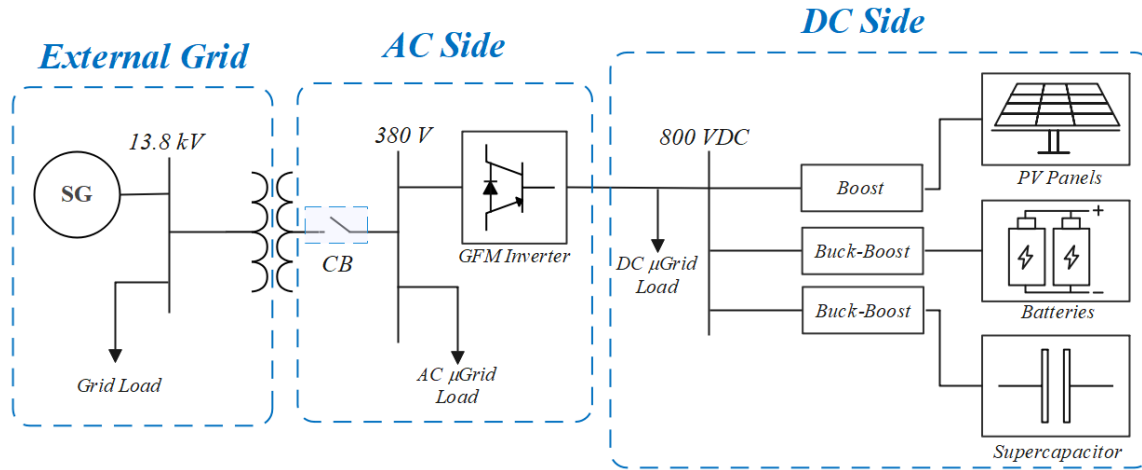


Figure 3.1: System architecture.

This microgrid consists of a DC side, an AC side, and an external grid. The DC side of the microgrid consists of PV panels, batteries, supercapacitors, power converters, and a local DC load. The used power converters in the DC microgrid are: 1) a boost converter for the maximum power point tracking (MPPT) of the PV panels, and 2) two separate

bidirectional buck-boost converters for both batteries and supercapacitors. The primary source of this hybrid microgrid is the photovoltaic (PV) solar panels and the batteries, which are used to store the extra energy produced by the PV panels during the day and consume it during the night, where the supercapacitors are used in transient situations to save the life span of the batteries.

The AC side consists of the GFM inverter, an LC filter. In addition, the microgrid can connect/disconnect to/from the external grid through the circuit breaker (CB) which is located at the point of common coupling (PCC). For the external grid, an SG will be modeled to manage its inertia (more details in Chapter 4).

3.3 Control Architecture

For the DC side, a hierarchical control strategy will be developed to manage the power flow of each component based on its status, while simultaneously taking into account the DC bus regulation. Therefore, the proposed hierarchical controller consists of two layers: 1) a supervisory layer overseeing the states of all controllable devices and is based on fuzzy logic control, and 2) a local control layer for each device based on the PI controller.

The inertial response is needed in low-inertia grids or in no-inertia grids. The virtual synchronous generator (VSG)-based GFM inverter has the ability to provide this inertial response and hence increase the stability of the system. However, the frequency performance of the VSG depends on the virtual inertia and damping coefficients, which are constant values in the traditional VSG. To ensure the optimal frequency performance of VSG-based GFM inverter, the virtual inertia and damping coefficients must be

adaptively and continuously adjusted to provide optimal performance. Therefore, an adaptive optimization strategy is proposed to adjust the virtual inertia and damping coefficients of the VSG. Such a control strategy will be based on the fuzzy logic controller (FLC). The gains of this FLC are then optimized by the differential evolution (DE) algorithm.

Finally, for a reliable operation, the microgrid should be able to connect/disconnect safely and seamlessly to/from the external grid. For this purpose, a control strategy for the seamless transition between the IS and GC modes of operation is developed.

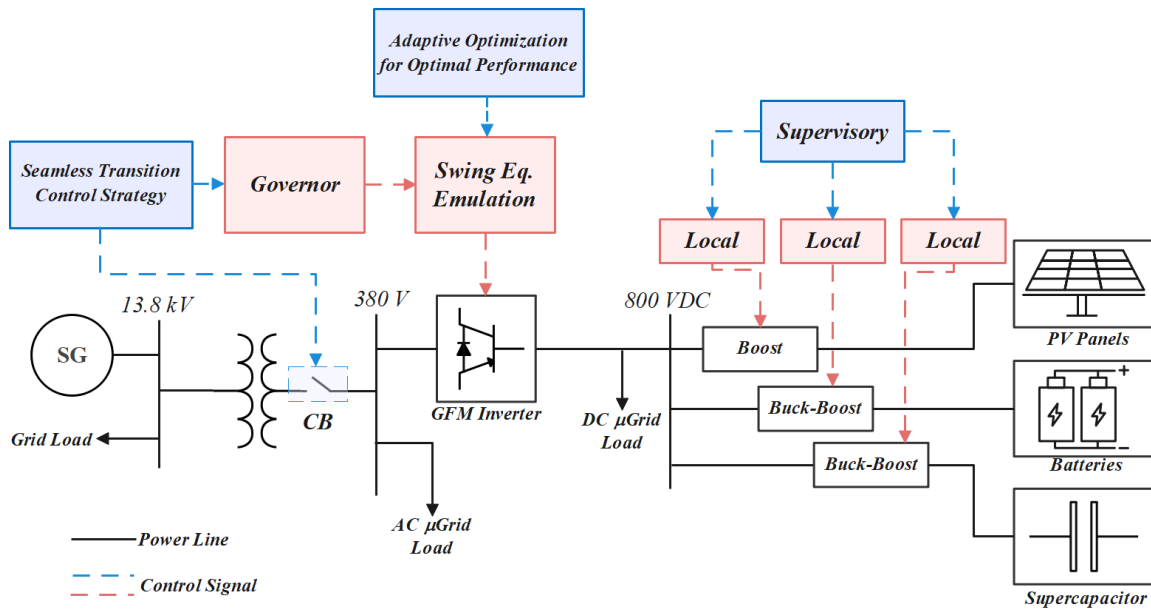


Figure 3.2: Basic control structure of the studied system.

CHAPTER 4: SYSTEM MODELING

4.1 Overview

In this chapter, the model and circuit diagram of the studied system (see Figure 3.1) are presented in detail. First, we start with the DC microgrid model in section 4.2, where the model of the energy storage systems, PV cells, and the utilized power converters are presented in detail. In section 4.3, the AC microgrid model is discussed. Mainly, the inverter and the LC filter. Also, the procedure of design such filters is included in this section. Finally, the model of the external grid, which is a synchronous generator (SG), is discussed in detail in section 4.4. Furthermore, the automatic voltage regulator (AVR) and automatic generation control (AGC) are discussed, which are essential parts of the SG.

4.2 DC Microgrid Modeling

4.2.1 ESS Model

- *Li-ion battery model*

Thevenin model of LIB is widely considered in many applications and it is used in this paper. The model has a simple representation and gives accurate results [86]. Figure 4.1 illustrates the Thevenin model of LIB.

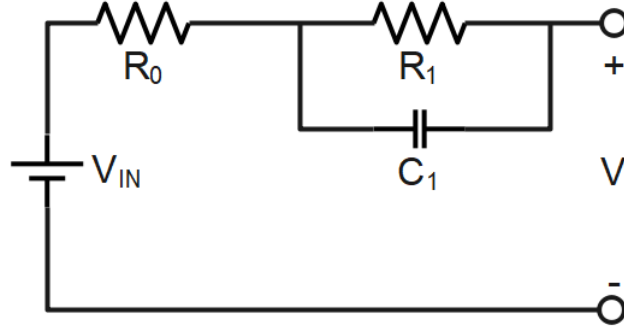


Figure 4.1: Thevenin model of LIB.

- *Supercapacitor Model*

Supercapacitor (SC) is nothing but a normal capacitor with a huge electric charge storing capacity. The SC is modeled as an RC circuit. Figure 4.2 illustrates the SC model.

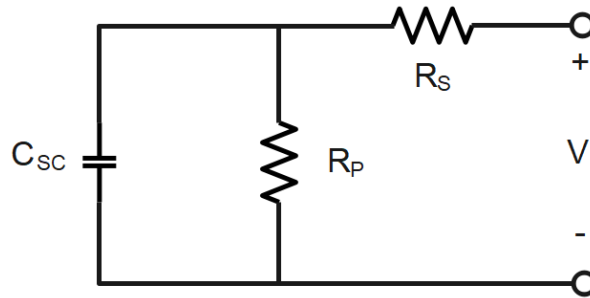


Figure 4.2: SC model.

The required energy from the SC can be calculated as follows:

$$Energy_{Required} = Power_{Rated} \times Time_{Needed} \quad (4.1)$$

Given that the stored energy should be higher than the required energy such that:

$$Energy_{Stored} > Energy_{Required} \quad (4.2)$$

Where the stored energy of the SC can be calculated as:

$$Energy_{Stored} = \frac{1}{2} C \times V^2 \quad (4.3)$$

Therefore, the capacitance of the SC can be finally obtained as follows:

$$C = 2 \frac{Energy_{Stored}}{V^2} \quad (4.4)$$

4.2.2 PV Model

The fundamental working principle of PV cells is to convert photonic energy into clean electric energy. Therefore, the circuit diagram of a solar cell is nothing but a diode in parallel with a current source in addition to two resistors one in series and the other in parallel to the diode and the current source. These resistors are considered to characterize the solar cell depending on the manufacturer. The equivalent circuit of the solar cell is illustrated in Figure 4.3. These solar cells are then arranged in series and parallel to form what so-called PV panel. Furthermore, PV panels are connected in series and parallel to form the PV arrays.

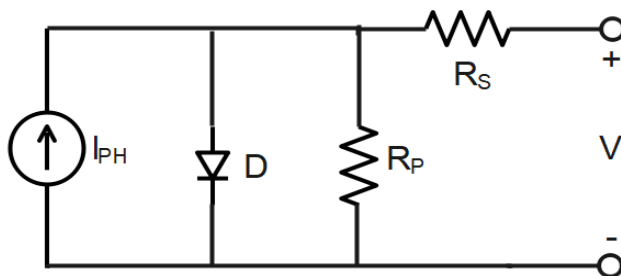


Figure 4.3: PV cell model.

4.2.3 Power Converters Model

In this research, the maximum power point tracking (MPPT) is considered to extract the maximum power of the PV module. However, the output voltage of the MPPT stage is deregulated [87]. Consequently, a control algorithm is proposed to switch between MPPT and voltage regulation mode, when necessary, more on that in section III. In addition, two

separate bidirectional buck-boost converters are used for each ESS for charging/discharging. A bidirectional buck-boost converter is nothing but a simple boost converter during the discharging and a simple buck converter during the charging operation. For deeper knowledge, chapter 5 in [88] illustrates the working principle of buck/boost converters. The circuit diagrams of the boost and bidirectional buck-boost converters are shown in Figure 4.4.

The parameters of each converter, i.e., inductors and capacitors, must be calculated to ensure a continuous conduction mode. Equations (4.1)-(4.4) are used to determine the minimum required values of the parameters.

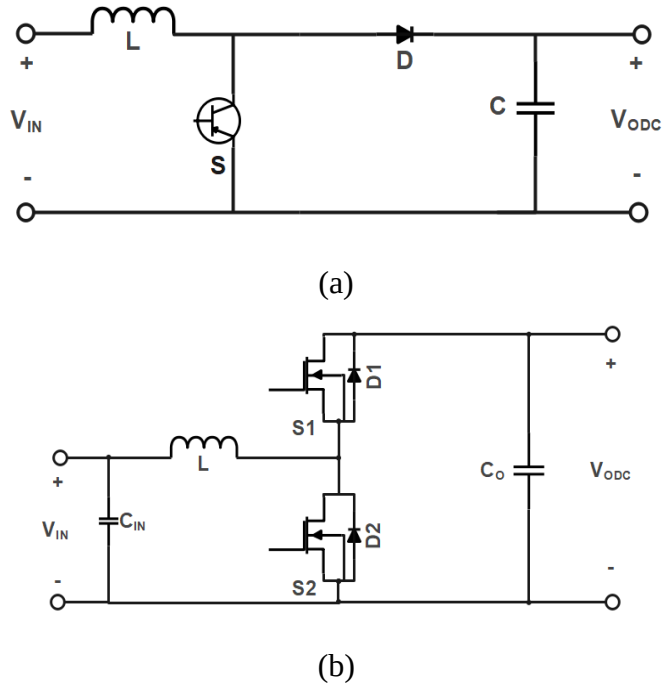


Figure 4.4: Circuit diagram of (a) boost, (b) bidirectional buck-boost converters.

For the boost converter:

$$L = \frac{V_{in} \times (V_{odc} - V_{in})}{\Delta I_L \times f_s \times V_{odc}} \quad (4.5)$$

$$C = \frac{I_{o,max} \times D}{f_s \times V_{odc}} \quad (4.6)$$

For the buck converter:

$$L = \frac{V_{odc} \times (V_{in} - V_{odc})}{\Delta I_L \times f_s \times V_{in}} \quad (4.7)$$

$$C = \frac{\Delta I_L}{8 \times f_s \times V_{odc}} \quad (4.8)$$

Where V_{odc} , V_{in} , D , f_s , ΔI_L , and $I_{o,max}$ are output, input voltages of the converter, the duty cycle of the switching device, the switching frequency, inductor current, and the maximum output current.

4.3 AC Microgrid Modeling

The most essential component in AC microgrids is the inverter which is crucial for ensuring the quality and reliability of electric power systems. A 3-phase inverter is a type of power electronic converter that transforms direct current (DC) voltage into alternating current (AC) voltage. It is a fundamental component of many industrial and residential applications, such as renewable energy systems, power quality improvement, and motor drives.

4.3.1 Inverter Model

The basic structure of a 3-phase inverter consists of power semiconductor switches, energy storage elements, and control circuits. Figure 4.5 shows the circuit diagram of a 3-phase inverter connected to an external grid through an LC Filter. The most commonly used topologies for 3-phase inverters are the voltage source inverter (VSI) and the current

source inverter (CSI). The operating modes of a 3-phase inverter can be either symmetrical or unsymmetrical, depending on the type of load and the desired output voltage waveform.

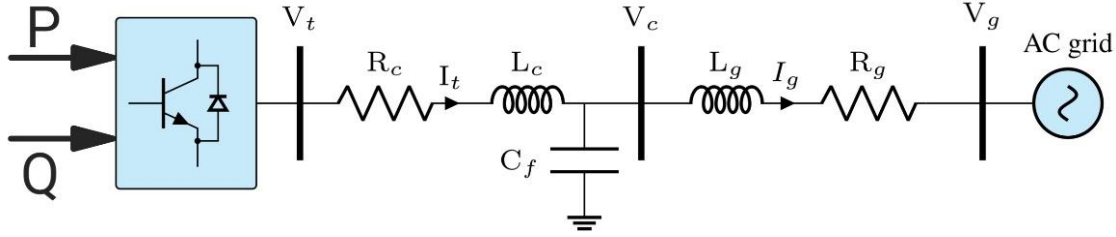


Figure 4.5: Circuit diagram of (a) boost, (b) bidirectional buck-boost converters.

The active and reactive power of the inverter could be expressed as:

$$P = \frac{3}{R_g^2 + X_g^2} \times (R_g V_c^2 - R_g V_g V_c \cos \delta - X_g V_g V_c \sin \delta) \quad (4.9)$$

$$Q = \frac{3}{R_g^2 + X_g^2} \times (X_g V_c^2 - X_g V_g V_c \cos \delta - R_g V_g V_c \sin \delta) \quad (4.10)$$

A 3-phase inverter works by converting DC voltage into AC voltage using power semiconductor switches. The switches are controlled by a digital or analog control circuit, which determines the voltage and current waveform of the AC output. The function of a 3-phase inverter in power electronics is to provide a clean and stable AC voltage source for various applications, such as motor drives and renewable energy systems.

4.3.2 LC Filter Model

An LC filter is a passive electronic filter that uses inductors (L) and capacitors (C) to filter out high-frequency harmonics in the output of an inverter. The LC filter improves the quality of the output voltage waveform by reducing the amount of total harmonic distortion (THD) in the AC output. The LC filter is a crucial component in many power

electronic systems, as it helps to ensure the reliability and stability of the AC voltage source.

The concept of an LC filter is based on the principle of impedance matching. The inductors and capacitors are connected in parallel or series, forming a resonant circuit that effectively filters out the high-frequency harmonics in the AC output. The LC filter is a passive filter, which means that it does not require any external power source to operate.

The values of the inductor (L) and the capacitor (C) in an LC filter are typically chosen based on the desired frequency response and the load impedance. The LC filter is used to filter the high-frequency components from the output of the inverter, and it helps to reduce the amount of harmonic distortion in the output waveform. Here is a general approach to determining the values of L and C in an LC filter:

1. Determine the desired cutoff frequency (f_c) of the filter: This is the frequency at which the filter starts to roll off, and it is typically chosen based on the maximum frequency content of the input waveform and the load impedance.
2. Calculate the reactance of the inductor and capacitor at the cutoff frequency (f_c): The reactance of the inductor and capacitance are given by:

$$X_L = 2 * \pi * f_c * L \quad (4.11)$$

$$X_C = 1 / (2 * \pi * f_c * C) \quad (4.12)$$

3. Choose the value of L: A common value for the inductor is to choose L such that $Xl = R$, where R is the load impedance. This will result in a Butterworth filter response.
4. Calculate the value of C: Once L is chosen, the value of C can be calculated using equation (4.12)

4.4 External Grid Modeling

As discussed in Chapter 3, the external grid is modeled as a synchronous generator (SG) to enable adjusting its inertia. An SG can be mainly divided into two parts, i.e., the electrical part and the mechanical part. Figure 4.6 shows the basic block diagram of the SG with an automatic voltage regulator (AVR) and automatic generation control (AGC).

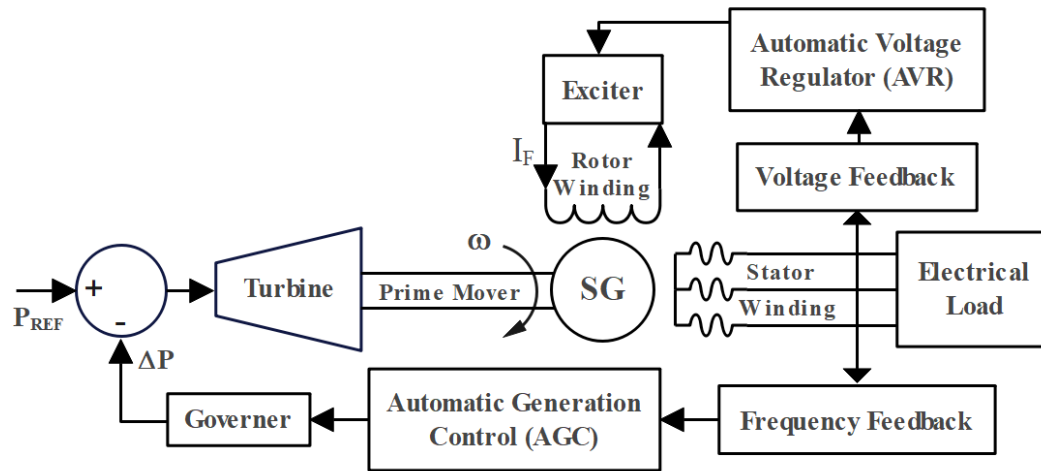


Figure 4.6: Block diagram of the SG with AGC and AVR.

The basic components of the electrical part are the stator and rotor windings. The output voltage of the stator winding is:

$$v_t = -R_s i - L_s \frac{di}{dt} + e \quad (4.13)$$

where v_t , R_s , L_s , and e are the terminal voltage, resistance, inductance, and induced electromotive force of the stator windings respectively.

The mutual inductance M_f between the stator and rotor windings proportionally relates the induced electromotive force and the field current i_f of the rotor winding. This relationship can be described as shown in (4.10) where θ is the electrical angle of the rotor. Therefore, the AVR will adjust the field current such that v_t is as desired.

$$e = M_f i_f \dot{\theta} \widetilde{\sin \theta} - M_f \frac{di_f}{dt} \widetilde{\cos \theta} \quad (4.14)$$

where:

$$\widetilde{\sin \theta} = \begin{bmatrix} \sin \theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad \widetilde{\cos \theta} = \begin{bmatrix} \cos \theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad (4.15)$$

In this paper, the IEEE-type ST1A excitation system was used for the AVR [89].

The essential component of the mechanical part is the prime mover, which can be a diesel engine, steam turbine, gas turbine, etc., considering the damping factor D , which is mainly produced by the rotor windings. This prime mover is governed by the following equation.

$$J\dot{\omega} = T_m - T_e - D\Delta\omega \quad (4.16)$$

where J , T_m , T_e are the moment of inertia of all rotating masses, mechanical and electrical torques, respectively. $\omega = \dot{\theta}$ is the electrical frequency of the SG, and $\Delta\omega = \dot{\theta} - \dot{\theta}_g$. Finally, $\dot{\theta}_g = \omega_g$ is the frequency at the point of common coupling (PCC).

It is noteworthy that the inertia constant H in power systems decides the time interval at which the SG/s can supply the rated power S_R by only using the stored kinetic energy E_{kin} of rotating shafts. This inertia constant is defined as [90]:

$$H = \frac{E_{kin}}{S_R} = \frac{1}{2} \frac{J \omega^2}{S_R} \quad (4.17)$$

The relationship between the electrical frequency ω and the mechanical frequency ω_{mech} is given in (4.14), being N is the number of poles of the stator.

$$\omega = N\omega_{mech} \quad (4.18)$$

Hence, the AGC is responsible to adjust the mechanical torque T_m such that the electrical frequency is as desired. In this paper, a diesel engine governor is used for the AGC. The transfer function of this governor is shown in Figure 4.7. This transfer function mainly consists of the control system and the actuator. The difference between the desired rotor speed and the measured one, i.e., the error is fed to the controller, then the controller action goes through the actuator to generate the appropriate mechanical power.

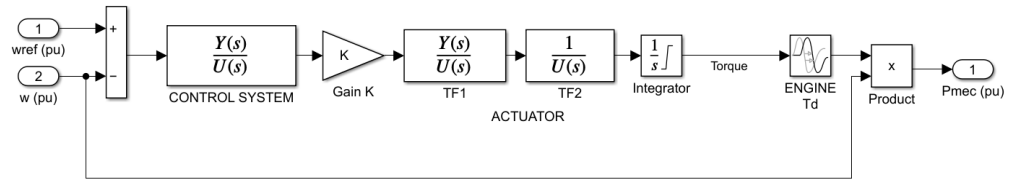


Figure 4.7: Transfer function of the governor.

CHAPTER 5: CONTROL METHODOLOGY

5.1 Overview

In this chapter, the proposed control methodologies to resolve the addressed issues of Chapter 3 are implemented. First, we start by introducing the method of managing the power flow between the DC side components as well as the DC bus stabilization in Section 5.2. In Section 5.3, the proposed adaptive VSG is implemented at which we discuss the FLC and the applied DE optimization algorithm. Finally, the control strategy of the seamless transition between the IS and GC modes is presented in Section 5.4.

5.2 Power Management and DC Bus Stabilization

In this section, a hierarchical control algorithm to control the operation of a hybrid system is proposed. The system under consideration is an islanded DC-microgrid composed of Li-ion batteries (LIB), supercapacitors (SC), and PV arrays. The control algorithm consists of two layers: a) a supervisory layer overseeing the states of all controllable devices and is based on fuzzy logic control, and b) a local control layer for each device based on PI control. The goal of the algorithm is to achieve a stable DC bus voltage so that it can be used as an input to the GFM inverters. In addition, the supervisory control layer can be used as an EMS in any hybrid system. First, in section 4.2, we start by reviewing different connection topologies and control strategies used in such hybrid systems. Then, we introduce the model of each component of the system in section 4.3. the proposed control strategy is presented in 4.4. in section 4.5, the simulation results are demonstrated. Finally, the conclusion is drawn in section 4.6.

5.2.1 Connection Topology

For such a HESS there are three possible connection topologies [91], which are discussed in the following subsections among their advantages and drawbacks of each.

1. Passive topology

Where both the LIB and SC are connected directly to each other to form the DC bus. This type of connection requires the matching voltage levels of both ESSs. Although it is the simplest topology and no power converters are required to interface the ESSs, it has no controllability on power flow and no energy management strategy can be applied for such a system [92]. Figure 5.1 depicts the passive connection topology.

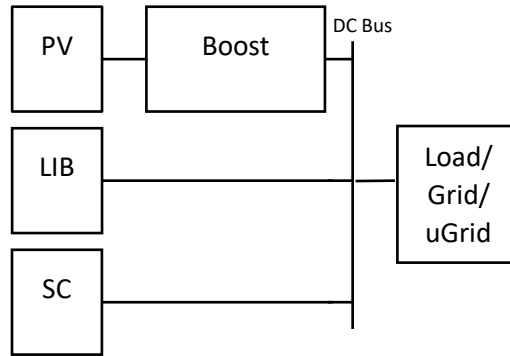


Figure 5.1: Passive connection topology.

2. Semi-active topology:

With this topology, a bidirectional buck-boost converter is employed to interface the SC with the DC bus. Therefore, this type of connection can control the power flow of the SC only which makes the system inflexible for the energy management side, especially, when we have another energy source such as photovoltaic or wind energy [93]. Therefore, such type of connection is not recommended when renewable energy sources (RESs) are employed. Figure 5.2 depicts the semi-active connection topology.

3. Active topology:

In this topology, a bidirectional buck-boost converter is employed to interface each ESS separately (see Figure 4.5). This leads to high-level control flexibility where, depending on the system's requirements, many energy management strategies can be applied. In this paper, the active topology is considered since a RES is employed, i.e., photovoltaic solar panels. Figure 5.3 depicts the active connection topology.

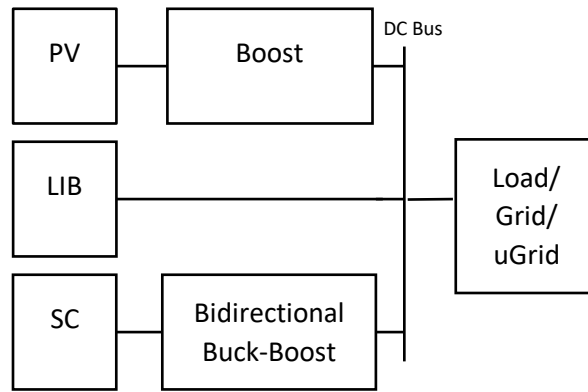


Figure 5.2: Semi-active connection topology.

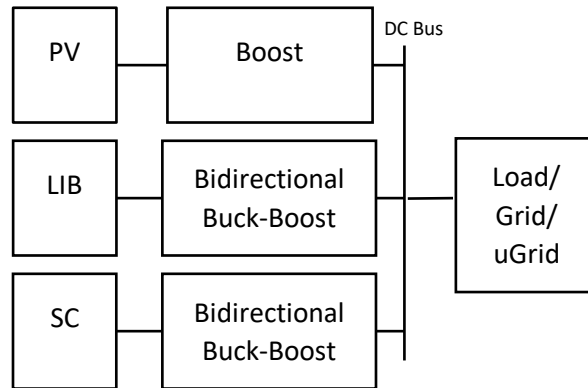


Figure 5.3: Active connection topology.

5.2.2 Control Strategy

In this study, a novel hierarchical fuzzy logic controller (HFLC) is proposed for both energy management and maintaining a stable DC voltage. The proposed HFLC is composed of two hierarchal levels of control; 1. Supervisory control (secondary) and 2.

Local control (primary). The local control is responsible for maintaining a stable fixed voltage at the DC bus while the supervisory control measures the necessary variables and then determines the power flow as well as the mode of operation of each element for optimal energy management. Figure 5.4 illustrates the configuration of the control system.

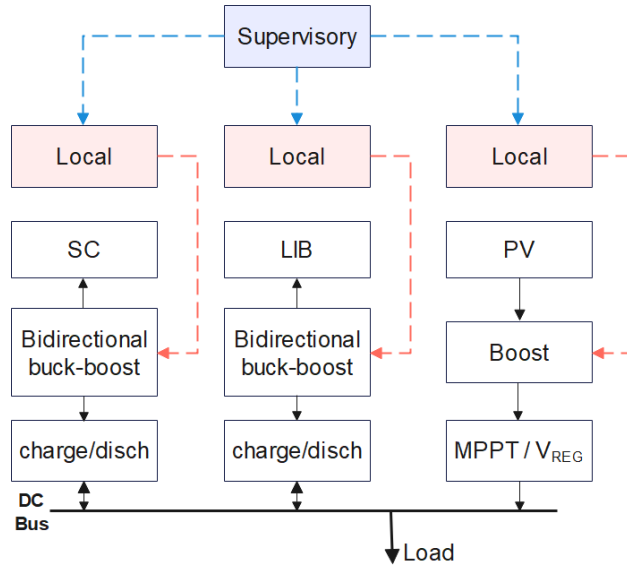


Figure 5.4: Proposed HFLC.

When it comes to a model-free controller, FLC has experimentally and in simulations shown satisfactory results [94], [95]. Therefore, FLC is adopted as it provides a robust control on systems in which no precise inputs are required. The main steps of FLC algorithm are fuzzification, inference, and defuzzification. In fuzzification and defuzzification processes, the numerical variables, which are usually the measurements, are converted to linguistic variables and vice versa whereas the inference process determines which rules to be fired out of a set of user-defined rules. For a better understanding of FLC, the reader is encouraged to go through [96].

A. Supervisory Control

Figure 5.6 illustrates the rules flowchart in which the mode of operation is selected. Depending on the selected mode, the power flow between the ESSs is determined accordingly. In Fig. 6, P_{PV} , P_L , SoC_B , SoC_{SC} , and ΔV are the PV and load power, SoC of the LIB and SC, and the rate of change of the DC bus voltage. Consequently, the inputs of the FLC are $\Delta P = P_{PV} - P_L$, SoC_B , SoC_{SC} , and ΔV , whereas the outputs are the control signals of the LIB, SC, and PV converters. Based on this control signal the converter will choose the mode of operation, i.e., charging/discharging for the LIB and SC, and MPPT/voltage regulation for the PV panels.

Mode 1: this mode will be activated if there is a change in the voltage of the DC bus or the SC needs to be discharged to turn its SoC back to its safe limit.

Mode 2: in this mode, P_{PV} is sufficient to deliver the required P_L and the SoC_{SC} is lower than the specified limit. Therefore, PV will operate in voltage regulation mode whereas the SC in charging mode.

Mode 3: just similar to the previous mode, but the LIB is being charged instead of charging the SC since the SoC_{SC} is safe and the SoC_B is low. consequently, PV will operate in voltage regulation mode whereas the LIB in charging mode.

Mode 4: when the SoC_{SC} and SoC_B are in the specified upper limit and P_{PV} is high enough, this mode will enable only the PV in the voltage regulation mode.

Mode 5: this mode is more or less similar to mode 2 except that $P_{PV} < P_L$. Consequently, PV and LIB will operate in MPPT and discharging modes respectively, whereas the SC in charging mode.

Mode 6: in this mode, $P_{PV} < P_L$ and the SoC_{SC} and SoC_B are within the specified limit. As a result, PV will operate in MPPT mode whereas the LIB in discharging mode.

Mode 7: this mode is activated when P_{PV} falls to meet the required P_L and the SoC_B is low. Therefore, the load will be shaded by P_{sh} that is calculated according to equation (5).

The membership functions of the supervisory control are depicted in Figure 5.5.

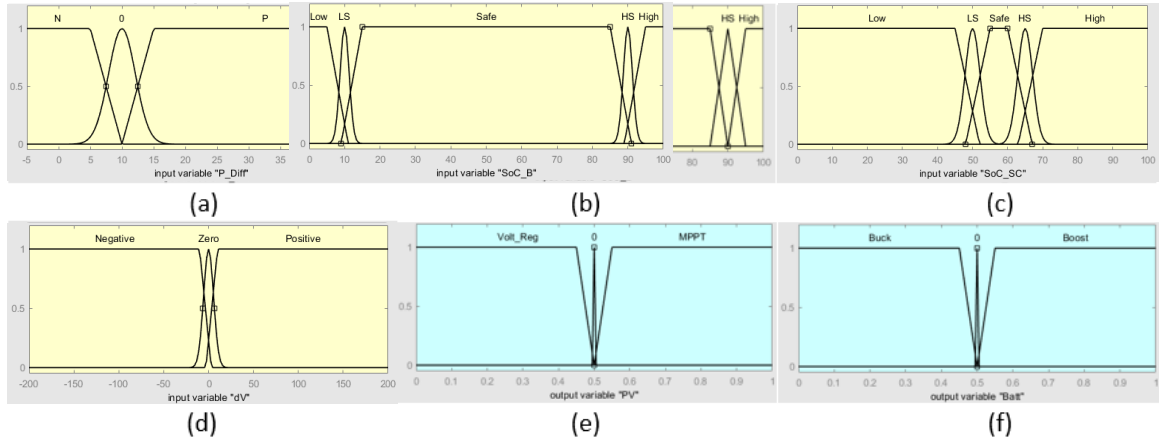


Figure 5.5: Membership functions of the supervisory controller (a) – (d) input membership functions, (e), (f) output membership functions.

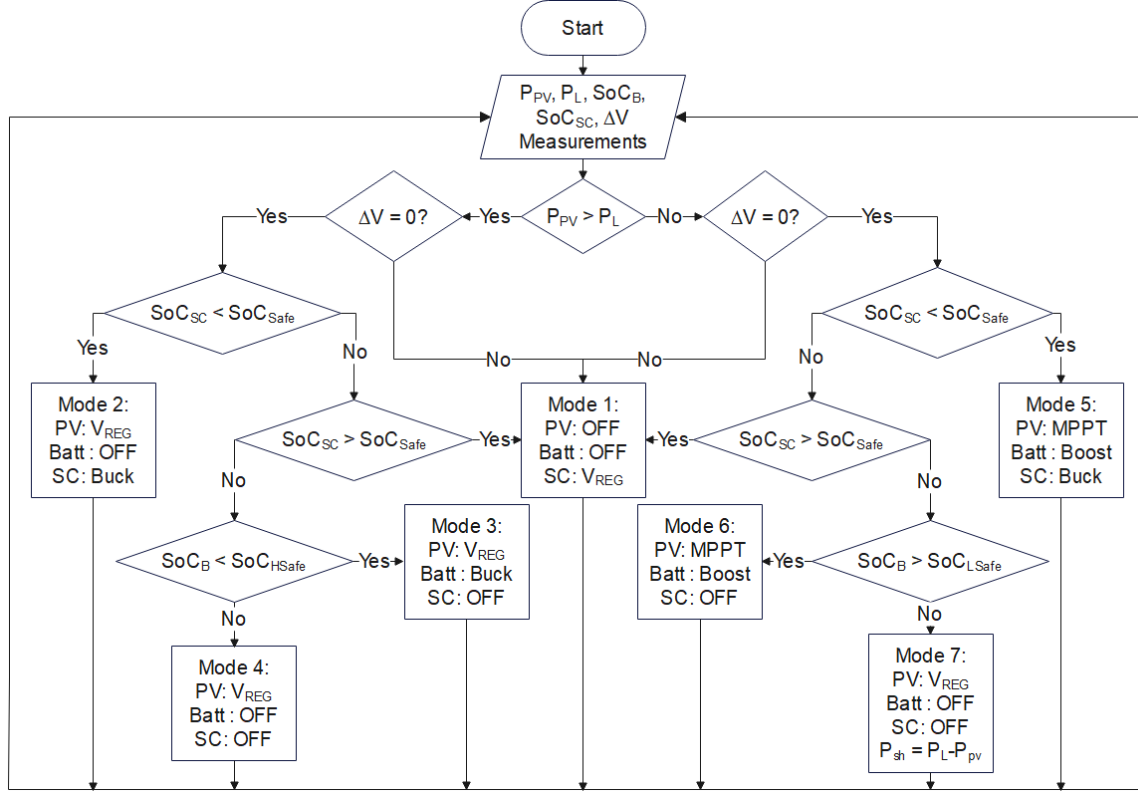


Figure 5.6: Rules flowchart of the supervisory control.

B. Local Control

Proportional integral (PI) controllers are easily implement-able and relatively cheap. In this paper, the PI controller was considered as the local controller, which is utilized for charging/discharging of the ESSs as well as voltage regulation and MPPT for the PV array.

1) Voltage control

The proposed double control loop in [97] was adapted for discharging the LIB and the SC as well as the voltage regulation of the PV. This control scheme is shown in Figure 5.7. In this way, the output action of the voltage loop controller is the reference of the current loop controller which is compared to the measured current of the inductor. The benefits of using such a scheme are eliminating the need of measuring the input voltage, having better

stability, and a zero steady-state error, and to protect the converter from overcurrent conditions.

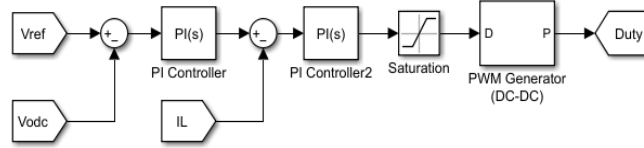


Figure 5.7: Control scheme of the double control loop.

2) Charging Control

The duty cycle of the buck converter is:

$$D = \frac{V_{Batt}}{V_{odc}} = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} \quad (5.1)$$

Since the converter has completely two different circuits during t_{on} and t_{off} , the average behavior of the converter will be derived as follows:

For the inductor current we have:

$$\begin{aligned} \frac{di_L}{dt} &= \frac{1}{L} [(V_{odc} - V_{Batt})D + (-V_{Batt})(1 - d)] \\ &= \frac{V_{odc}}{L} d - \frac{V_{Batt}}{L} \end{aligned} \quad (5.2)$$

For the capacitor voltage we have:

$$\begin{aligned} \frac{dV_C}{dt} &= \frac{1}{C} \left[\left(i_L - \frac{V_{Batt}}{R} \right) d + \left(i_L - \frac{V_{Batt}}{R} \right) (1 - d) \right] \\ &= \frac{1}{C} (i_L) - \frac{V_{Batt}}{RC} \end{aligned} \quad (5.3)$$

To represent the system in terms of its state variables, let:

$$i_L = x_1, V_{Batt} = x_2 = y, \text{ and } D = u$$

Therefore, equations (4.7) and (4.8) can be rewritten as:

$$\frac{dx_1}{dt} = -\frac{1}{L} x_2 + \frac{V_{odc}}{L} u \quad (5.4)$$

$$\frac{dx_2}{dt} = \frac{1}{C} x_1 - \frac{1}{RC} x_2 \quad (5.5)$$

Since both conditions of linearity are satisfied, i.e., homogeneity and superposition, equations (4.9) and (4.10) are linear. The input of the system is the duty cycle whereas V_{Batt} is the output of the system. After taking the Laplace Transform equations (9) and (10) become:

$$sX_1 = -\frac{1}{L} Y + \frac{V_{odc}}{L} U \quad (5.6)$$

$$sY = \frac{1}{C} X_1 - \frac{1}{RC} Y \quad (5.7)$$

Consequently, after simplifying equations (4.11) and (4.12), the transfer function of the system is:

$$\frac{Y(s)}{U(s)} = \frac{\frac{V_{odc}}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \quad (5.8)$$

Accordingly, the frequency response tuning method is used to tune the proportional and integral gains of the PI controller.

A simple current control loop is used to charge the LIB/SC. The reference current of the controller can be calculated as:

$$I_{ref} = \frac{P_{pv} - P_L}{V_{odc}} \times \frac{1}{D} \quad (5.9)$$

Figure 5.8 depicts the control scheme of the charging controller.

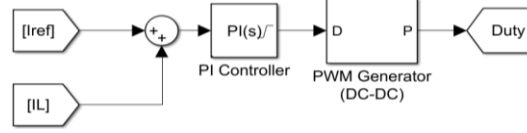


Figure 5.8: Control scheme of the charging controller.

3) MPPT Control

The well-known perturbation and observation (P&O) algorithm is used to inject the maximum power of the PV into the DC bus when $P_{PV} < P_L$. The principle of the P&O algorithm is to perturb V_{ref} till it observes the maximum power where V_{ref} should be [87]. Figure 5.9 shows the flowchart of P&O algorithm.

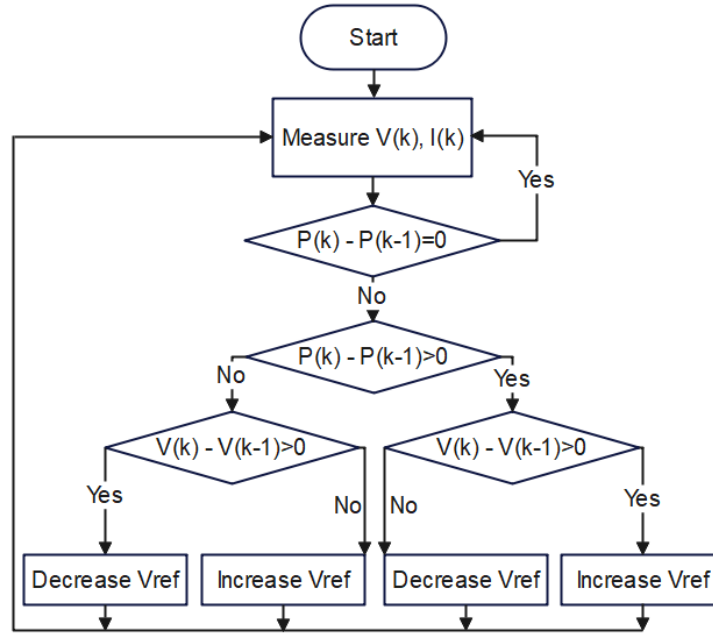


Figure 5.9: MPPT (P&O) algorithm.

5.3 Adaptive VSG

In this section, we propose an optimization method that sets the VSG damping and inertia coefficients in an adaptive manner based on the fuzzy logic controller (FLC). Further, the differential evolution (DE) algorithm is used to solve the formulated multi-

objective function to optimize the FLC gains. In this way, the damping and virtual coefficients are continuously and adaptively adjusted to provide optimal frequency stabilization.

5.3.1 VSG Control Structure and Model

The basic structure of the GFM inverter connected to the grid is shown in Figure 5.10 which consists of the DC source, which can be any distributed generator or an energy storage system (ESS), an LC filter, SG emulation algorithm, and double loop control of voltage and current. In this study, however, the input VDC source shown in Figure 5.10 is the regulated DC bus voltage in the previous section (see Figure 3.1). This GFM inverter can be seen as a voltage source in series with low impedance.

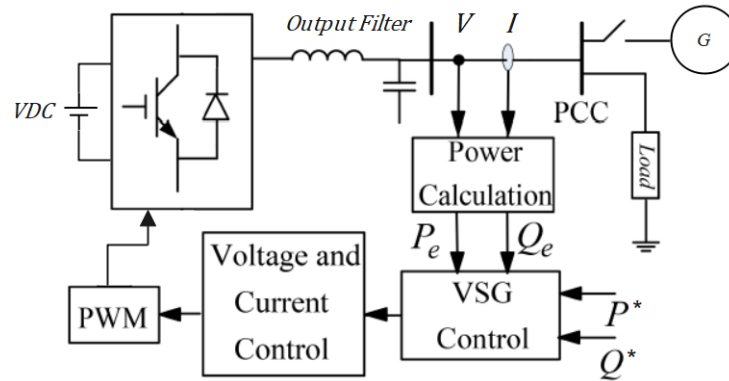


Figure 5.10: The basic structure of the GFM inverter.

Figure 5.11 depicts the detailed control structure of an inverter working on VSG algorithm. As can be seen from Figure 5.11, the essential two loops of the VSG are the active and reactive power loops. The active power loop uses the swing equation to mimic the SG and governor to regulate the frequency, while the reactive power loop utilizes the Q-V droop control to regulate the voltage by injecting the required amount of reactive

power. The obtained voltage of these two loops, however, is then fed to the double loop controller (voltage and current controller) to generate the appropriate reference voltage. Finally, the virtual impedance control loop is deployed to insure the power decoupling at the PCC [98]. In Fig. 5, R_f, L_f , and C_f are the resistance, inductance, and capacitance of the inverter filter, the subscripts N and e denote the nominal and measured values, V_{dq} and I_{dq} are the voltage and current in d-q frame, m and n are the active and reactive droop coefficients, respectively.

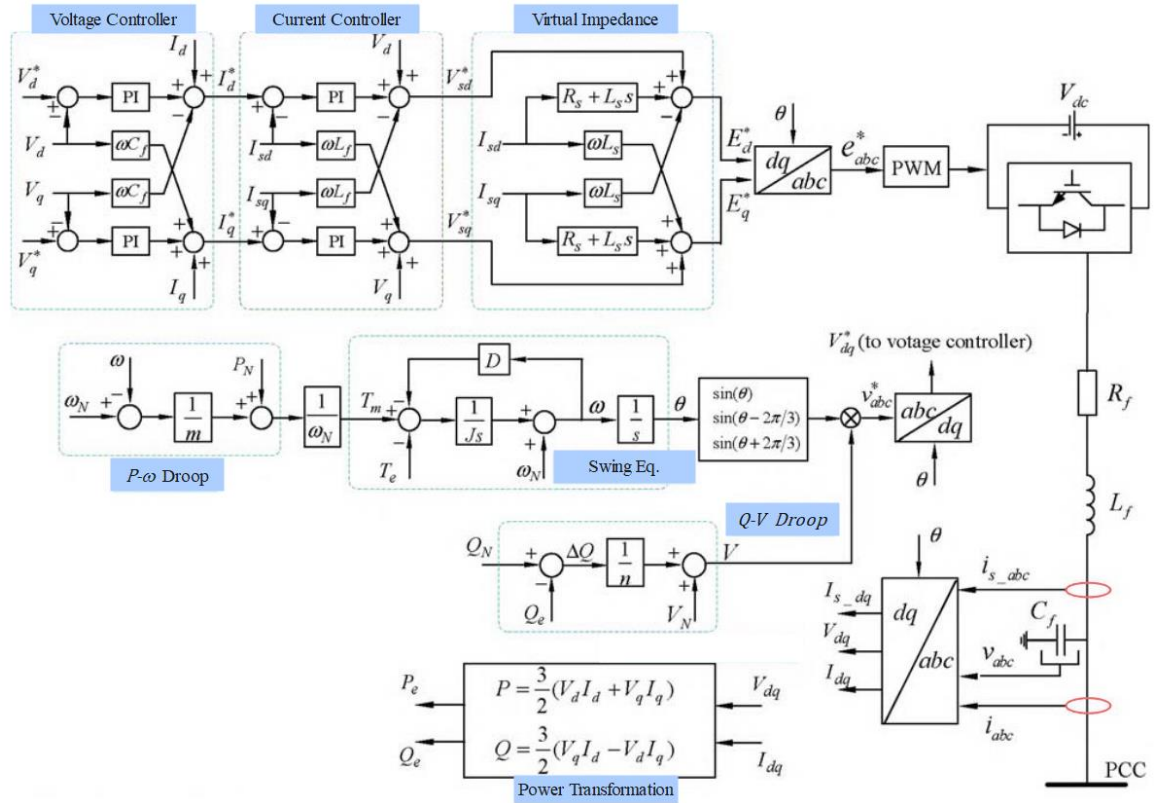


Figure 5.11: Detailed control structure of VSG topology.

5.3.2 Fuzzy Logic Controller Implementation

When it comes to a model-free controller, FLC has experimentally and in simulations shown satisfactory results [94], [95]. In addition, FLC was widely used to deal

with nonlinear systems and tune parameters that traditional controllers cannot tune [99]. The main steps of FLC are fuzzification, inference, and defuzzification. In the fuzzification process, the numerical variables, which are usually the measurements, are converted to linguistic variables, while the opposite occurs in the defuzzification process. The inference process determines which rules to be fired out of a set of user-defined rules. Besides, FLC has been widely used to tune the system's gains for decades [100]. Following a change in system operation, FLC adjusts the gains using a fuzzy logic based on a set of “*if-then*” rules.

In the last decade, VSG was proposed to emulate the SG and increase the stability of the system by providing the virtual inertia and damping factor. However, fixing the virtual inertia and damping factor at constant values will not give us the desired frequency performance. Therefore, the FLC is adopted as it can adaptively tune the virtual inertia and damping factor of the VSG in which no precise modeling is required. Figure 5.12 illustrates the proposed control scheme of the VSG which is based on FLC. This FLC basically measures the frequency deviation and RoCoF, then based on the FLC mechanism, the appropriate virtual inertia and damping factor will be adjusted.

The core part of the VSG control is the emulation of the swing equation which describes the rotor motion of the SG as in (4.12). Rearranging (4.12) we get:

$$\dot{\omega} = \frac{T_m - T_e - D\Delta\omega}{J} \quad (5.10)$$

Hence, for a constant $(T_m - T_e - D_P \Delta\omega)$, the virtual inertia J is inversely proportional to the RoCoF $\dot{\omega}$.

Similarly, by rearranging (4.12) we get:

$$\Delta\omega = \frac{T_m - T_e - J\dot{\omega}}{D} \quad (5.11)$$

Hence, for a constant $(T_m - T_e - J\dot{\omega})$, the damping factor D is inversely proportional to the frequency deviation $\Delta\omega$.

Therefore, increasing the virtual inertia will mitigate the RoCoF at the time of disturbance, and increasing D will mitigate the frequency deviation. On the other hand, if we simply keep J and D at high values, that will lead to serious problems such as slow demand response, frequency/power oscillation, and higher settling time. Consequently, J and D must be continuously and adaptively changed in an optimal manner to guarantee the optimal frequency response.

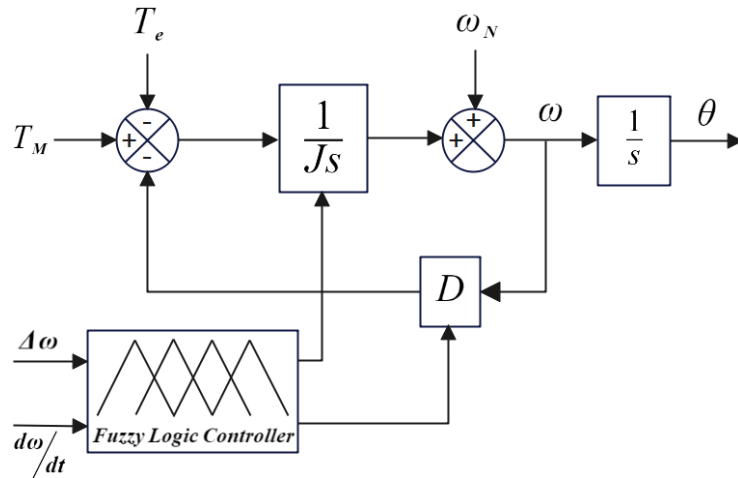


Figure 5.12: The control scheme of the proposed adaptive VSG.

The complete structure of the proposed FLC is depicted in Figure 5.13, wherein the inference process, there is a set of membership functions of each input/output to handle the desired fuzzification of the inputs and defuzzification of the outputs. Moreover, each input/output has its own scaling factor (SF). Although defining the rules in the inference process is the most important stage in the FLC, the selection of the optimal membership functions and SFs is necessary to provide optimal performance.

From (5.12) and (5.13), it can be observed that increasing the virtual inertia will minimize the RoCoF at the time of disturbance occurrence and increasing D will minimize the frequency deviation. These facts are used to obtain the rules, which are the heart, of the FLC. On the other hand, if we simply keep J at a high value, that will lead to a higher frequency settling time which makes the system slower to respond. Similarly, keeping D at a high value will lead to higher power oscillation.

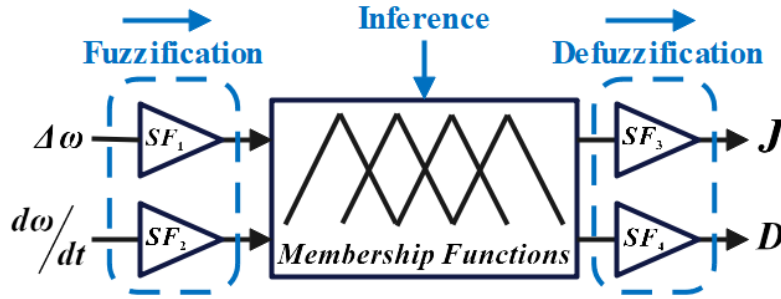


Figure 5.13: Control structure of the proposed FLC-based adaptive VSG.

Based on this knowledge, the fuzzy rules are determined as shown in Table 5.1 and Table 5.2. For the input sets, seven membership functions are utilized to smoothen the control action where Z, N, BN, EBN, P, BP, and EBP represent zero, negative, big negative, extremely big negative, positive, big positive, and extremely big positive respectively.

Table 5.1: Fuzzy rules of the adaptive VSG (first input/output).

$RoCoF$	EBN	BN	N	Z	P	BP	EBP
J	very high	High	Mid	Low	Mid	High	Very high

Table 5.2: Fuzzy rules of the adaptive VSG (second input/output).

Δf	EBN	BN	N	Z	P	BP	EBP
D	very high	High	Mid	Low	Mid	High	Very high

By utilizing the Mamdani type inference system, the output membership function is determined based on the following “if-then” rule:

If input 1 is A **and** input 2 is B **then** output is C

Where A and B are the measured values, i.e., Δf and $RoCoF$, and C is the desired output of the corresponding fuzzy sets.

Finally, the output can be determined using the centroid defuzzification method as follows:

$$x^* = \frac{\int \mu(x) \cdot x \, dx}{\int \mu(x) \, dx} \quad (5.12)$$

where x^* is the desired output of the corresponding fuzzy set, and $\mu(x)$ is the created curve caused by the aggregated area of the selected membership functions.

5.3.3 Differential Evolution algorithm

Differential evolution (DE) is a heuristic, population-based algorithm that searches for the global optimal solution. Due to its robustness, speed of convergence, and ease of implementation, DE has been utilized in many engineering optimization problems [101], [102]. It is also characterized by two key parameters, which are the mutation factor F and the crossover constant CR . The four fundamental steps of the DE algorithm are as follows:

- 1) Initialization: at this stage, being x is the representative vector of the optimized parameters, and with a population size of NP , the initial vectors are randomly generated as:

$$x_{i,j} = x_j^{min} + r \times (x_j^{max} - x_j^{min}) \quad (5.13)$$

where $i = 1, 2, \dots, NP$; $j = 1, 2, \dots, P$; P is the number of optimized parameters; x_j^{max} and x_j^{min} are the upper and lower bounds of the corresponding $x_{i,j}$; r is a randomly generated number with a uniform distribution with a range of $[0,1]$.

- 2) Mutation: at the mutation stage, each individual x_i in the population produces a mutant vector v_i based on a certain mutation operation. Although there are several mutation operations in the DE algorithm [103], the mutant vector v_i in this study was produced as follows:

$$v_i = x_{R1} + F \times (x_{R2} - x_{R3}) \quad (5.14)$$

where $R1, R2, R3$ are random integer numbers within the range $[1, NP]$ and they must satisfy $R1 \neq R2 \neq R3$.

- 3) Crossover: after creating NP mutant vectors, a trial vector t_i is produced by crossovering the mutant vector v_i with the individual vector x_i . In our work, t_i is produced as follows:

$$t_{i,j} = \begin{cases} v_{i,j} & \text{if } r \leq CR \\ x_{i,j} & \text{otherwise} \end{cases} \quad (5.15)$$

- 4) Selection: finally, the number of $x_{i,j}$ and $t_{i,j}$ vectors are 2NP. However, we need NP vectors x_i^{new} to be selected for the next generation. Being f is the objective function to be minimized, this is done as follows:

$$x_i^{new} = \begin{cases} t_i & \text{if } f(t_i) \leq f(x_i) \\ x_i & \text{otherwise} \end{cases} \quad (5.16)$$

It is worth mentioning that there is a final sub-step in the DE, i.e., the fitness evaluation. This is needed to store the best fitness out of the generated population for the termination criterion.

Figure 5.14 illustrates the flowchart which summarizes the stages of the DE algorithm, starting with initialization, and ending with the stopping criterion which is to have the same fitness for a certain number of generations.

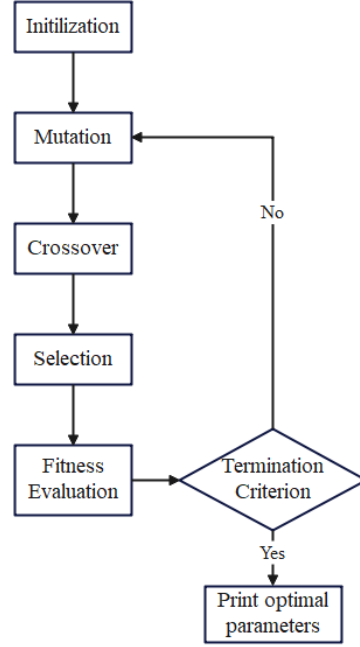


Figure 5.14: Flowchart of the DE optimization process.

5.3.4 Optimization Procedure

As previously mentioned, the objective is to minimize the frequency deviation, RoCoF, and frequency settling time t_s subject to the FLC gains as:

Minimize:

$$\begin{aligned}
 f_1 &= |\omega - \omega_N| \\
 f_2 &= \left| \frac{d\omega}{dt} \right| \\
 f_3 &= t_{settling}
 \end{aligned} \tag{5.17}$$

$$t_{settling} = \min \{t > 0: \frac{\omega(t') - 60}{60} \leq 0.05 \text{ for all } t' \geq t\} \tag{5.18}$$

where t' is the time of disturbance occurrence.

Subject to:

$$\begin{aligned} SF_k^{max} &\leq SF_k \leq SF_k^{min} ; k = 1, 2, \dots, 4 \\ set_{in}^{min} &\leq set_{in} \leq set_{in}^{max} \\ set_{out}^{min} &\leq set_{out} \leq set_{out}^{max} \end{aligned} \quad (5.19)$$

where set_{in} is the input fuzzy sets of the first and second inputs, i.e., Δf and RoCoF. Similarly, set_{out} is the output fuzzy sets of the first and second outputs, i.e., J and D . The superscripts min and max denote the lower and upper bounds of the corresponding factor. As there are no physical constraints on the SFs, their bounds are relaxed. The bounds set_{in} are set based on the maximum expected RoCoF and Δf . Similarly, The bounds of the first set_{out} , i.e., J , is set as $[0, 4]$ based on the typical value of the virtual inertia in the literature [104], while the bounds of the second set_{out} , i.e., D , is set based on the maximum rated power of the inverter, as D in VSG is equivalent to the active droop coefficient which determine the power contribution of the inverter.

The optimization procedure is carried out by running the microgrid model in Simulink for each individual vector from the generated population of the DE algorithm. Then, the result of each run is sent to MATLAB to evaluate each individual based on its fitness value. Finally, the DE operators are applied to the population to enhance performance. This procedure is repeated till the termination criterion is met, i.e., the optimal SFs and membership function of the FLC are found. Figure 5.15 depicts the overall approach of this optimization procedure.

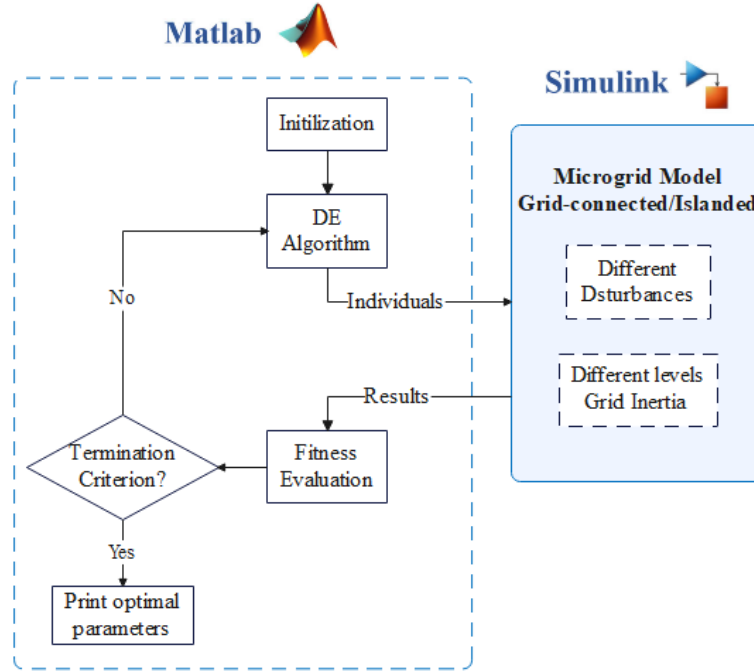


Figure 5.15: Flowchart of the DE optimization process.

5.4 Seamless Transition of Microgrid Connectivity to the Grid

The objective of this section is to develop a control strategy to insure a fast and smooth transition form IS to GC mode and a seamless transition from GC to IS mode. The basic structure of the proposed control strategy is shown in Figure 5.16, where three modes of operation are defined, i.e., IS, GC, and pre-synchronization modes. These modes, in this paper, are called mode 0, mode 1, and mode 2 respectively.

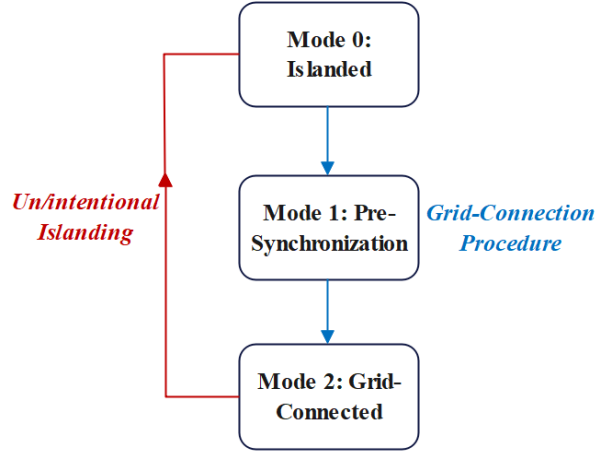


Figure 5.16: Basic structure of the proposed control strategy.

In practice mode 0 is primarily activated (before the connection to the main grid). After that, the control signal is received by the microgrid operator to connect to the main grid (mode 1 is activated at this time). Finally, if the voltage matching is detected, the controller will send a control signal to the circuit breaker (CB1 in Fig. 1) to close the switch and connect to the main grid (Mode 2 is activated in this case).

The basic idea of the proposed strategy is to modify the governor of the active power loop as well as the reactive power controller. The modified governor is shown in Figure 5.17. The active droop control is inversed to have a constant out power and variable frequency since this is the desired approach, i.e., to vary the frequency of the inverter to match the grid frequency while keeping the required power constant. In addition, a PI compensator is added to adjust the inverter frequency to match the grid when a pre-synchronization signal is received. The input to this compensator is the frequency adjustment coefficient α and can be calculated as follows:

$$\alpha = -\frac{\omega_N - \omega_e}{P_N - P_e} \quad (5.20)$$

Similarly, a PI compensator is added to droop control of the reactive power loop to adjust the inverter voltage to match the grid when a pre-synchronization signal is received. The modified droop control of the reactive power loop is shown in Figure 5.18. The input of the PI compensator is the voltage adjustment coefficient β and can be calculated as follows:

$$\beta = -\frac{V_N - V_e}{Q_N - Q_e} \quad (5.21)$$

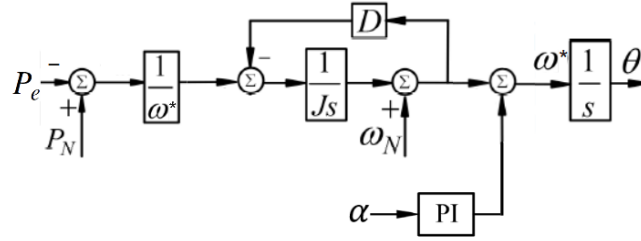


Figure 5.17: Basic structure of the proposed control strategy.

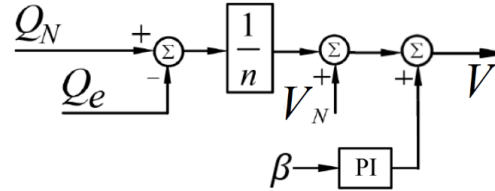


Figure 5.18: Basic structure of the proposed control strategy.

It is worth mentioning that the added compensators, i.e., the modified active and reactive control loops, are only activated when a pre-synchronization signal is received by the controller to connect to the main grid. Therefore, the output of the compensators will be zero in mode 0 and mode 2, and hence, the VSG will have the same control structure of Figure 5.11.

This feature allows the microgrid to seamlessly switch to the IS mode even if an unintentional disconnection is occurred.

5.5 Summary

In this chapter, a hierarchical control algorithm was proposed to control the operation of an islanded DC-microgrid composed of LIBs, SCs, and PV arrays. The proposed HFLC was developed for both energy management and maintaining a stable DC voltage.

In addition, the effect of virtual inertia and damping coefficients on the frequency of the virtual synchronous generator (VSG) is examined. It was theoretically found that not only the virtual inertia can mitigate the rate of change of frequency (RoCoF), but also the damping factor can suppress the frequency deviation. In this concept, an adaptive VSG based on the fuzzy logic controller is proposed to adaptively adjust the virtual inertia and damping factor. Moreover, the differential evolution (DE) optimization algorithm is applied to train the FLC giving the optimal frequency performance. The objective of this optimization is to minimize the frequency deviation RoCoF, and frequency settling time.

Finally, a control strategy for the seamless transition from IS to GC mode and vice versa is proposed. The idea of the proposed control strategy is to use a single control algorithm in both modes of operation (GC and IS). An improved (VSG) control is deployed. The governor of the VSG is modified to adjust the frequency by adding a frequency adjustment compensator. Also, the exciter system, droop control, of the voltage controller is modified by adding a voltage adjustment compensator to match the grid during the transition from IS to GC mode for a smooth transition. A seamless transition is also achieved during the unintentional transition from GC to IS mode because of the self-ability of the VSG to regulate the voltage and frequency.

CHAPTER 6: CASE STUDIES AND SIMULATION

RESULTS

6.1 Overview

This Chapter presents the simulation results of the proposed control methodologies for the studied microgrid system. The simulations are conducted in MATLAB/Simulink environment to validate the performance of the proposed control strategies using nonlinear time-domain simulations. The simulation results are presented in three main parts. First, we start with the comparison analysis between GFL and GFM inverters. The comparison is conducted to investigate the frequency support of both types of inverters as the grid's inertia is decreasing. In section 6.3, the simulation results of the proposed HFLC are conducted, where the DC side is simulated separately to examine the extreme cases/disturbances. Section 6.4 is divided into two parts. The first part presents the training procedure while the second part presents the testing results, where the proposed adaptive VSG is compared with the traditional one. Finally, the simulation results of the proposed seamless transition control strategy are presented in section 6.5. The seamless transition control strategy is designed to ensure a smooth and reliable transition between GC and IS modes of operation.

6.2 GFL and GFM Comparison

As an introduction, we first start by comparing the widely used IBR (GFL inverter) with the GFM inverter in terms of frequency support. In addition, the support of frequency is measured under multiple microgrid sizes and multiple levels of grid inertia using three metrics. The metrics under consideration are: 1) maximum frequency over/-undershoot, 2) maximum rate of change of frequency (RoCoF), and 3) frequency settling time. A simple control scheme is used for the GFL inverter that utilizes a PLL. The widely used virtual SG (VSG) control scheme is used to operate the GFM inverter.

6.2.1 Analysis Procedure

This section is dedicated to clarifying the taken steps and procedures to conduct the analysis, given that the nominal frequency of the system is 60 Hz. Figure 6.1 illustrates the studied system.

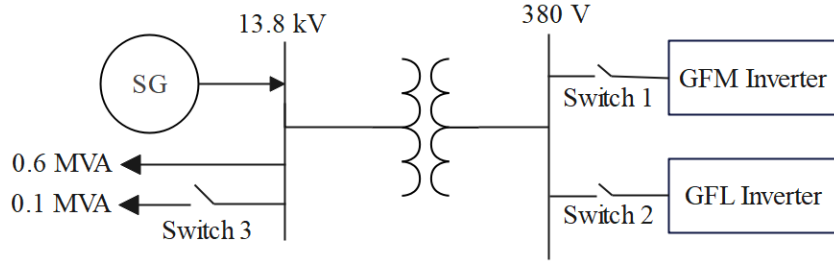


Figure 6.1: Analyzed system for GFL and GFM inverters comparison.

The total number of case studies is 7. Both switches, i.e., switch 1 and switch 2, in Figure 6.1 are open in the first case study. Switch 1 is closed and switch 2 is open in the second, third, and fourth case study. Switch 1 is open and switch 2 is closed in the fifth, sixth, and seventh case study. When connecting the inverters, both GFM and GFL, their rated power at the beginning was 10% of the grid rated power, then it is increased by 5%

for the next two case studies. Table 5.1 summarizes the rated power of each component during each case study.

The inertia H of the grid was decreased gradually from 4 to 0.6 with a step of 0.1 for all case studies. Consequently, each case study is repeated 35 times for different inertia constants. Moreover, switch 3 is closed during the operation in each case study as well.

It should be highlighted that the settling time defines the time at which the frequency enters the settling band and never leaves it after the disturbance. However, the considered settling band in this study was ± 0.05 Hz. For the sake of illustration, Figure 6.2 demonstrates the frequency entering the settling band for different inertia constants, i.e., 3s and 4s.

6.2.2 Results and Discussion

In order to make the analysis observable, the results were arranged according to the considered metrics. Further, each metric was divided according to the type of deployed inverter, i.e., GFM and GFL. Lastly, the results of each inverter were always sketched with the first case study, i.e., SG only, to compare the frequency support capability with and without deploying the specified type of inverter. These results are illustrated in Figure 6.3 (maximum frequency over/undershoot), Figure 6.4 (RoCoF), and Figure 6.5 (frequency settling time).

Table 6.1: Rated power of each Component.

	SG	GFM	GFL
Case 1	1 MVA	0	0
Case 2	1 MVA	100 kVA	0

Case 3	1 MVA	150 kVA	0
Case 4	1 MVA	200 kVA	0
Case 5	1 MVA	0	100 kVA
Case 6	1 MVA	0	150 kVA
Case 7	1 MVA	0	200 kVA

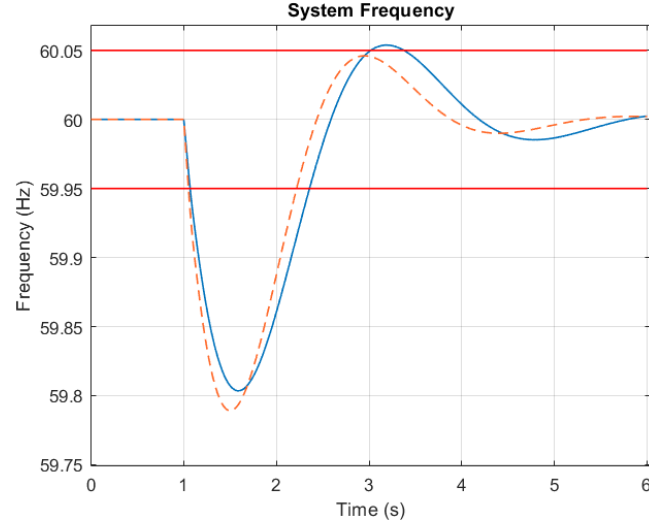


Figure 6.2: Illustration of the frequency entering the settling band for different inertia constants.

The contribution of the GFM inverter is evident in reducing the maximum over/undershoot. Moreover, the minimum inertia at which the grid remains stable without any support from the microgrid was 0.7 s. When the microgrid supports the grid using GFM inverter, this number was decreased to 0.6 s, i.e., the grid's inertia can be decreased further when microgrids with GFM are providing frequency support, which enables more renewable penetration into the power grid. This is because of the applied control topology of the GFM inverter, i.e., VSG, which uses (4) to emulate the behavior of an SG, and hence, provide inertial response. In addition, the maximum RoCoF was reduced as well due to the same mentioned reason, i.e., the provided inertial response of the SG emulation. However, the settling time was increased when deploying the GFM inverter due to its contribution to

the total inertia of the system, as the system with higher inertia takes more time to settle compared to a system with lower inertia. But thanks to the damping factor D_P in (4) which damps the maximum frequency overshoot at higher inertia constants.

On the other hand, when GFL inverter is used by the microgrid, the minimum inertia increased to 0.8 s. This is because of the utilized PLL mechanism of the GFL inverter to follow the grid voltage and frequency. This PLL needs a strong grid inertia to stably operate [105]. Consequently, for a stable operation, the minimum required inertia of the grid increased to 0.8 s. Furthermore, the RoCoF was increased when the GFL inverter is used by the microgrid, which is again due to the use of PLL that makes the stability of the system worse during disturbances. Finally, since the GFL inverter does not add any value to the grid inertia, the frequency settling time when using the GFL inverter is more or less the same as the settling time in the first case study.

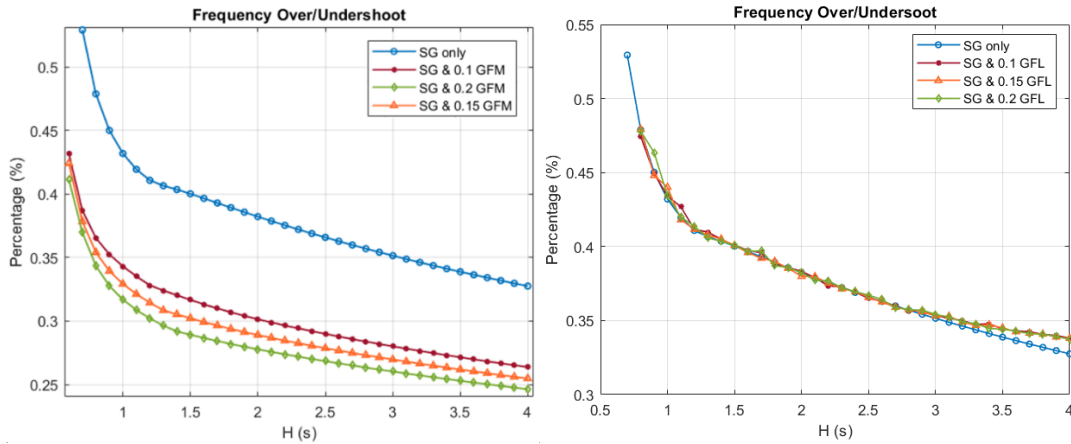


Figure 6.3: Frequency over/undershoot with GFM inverter (left) and GFL inverter (right).

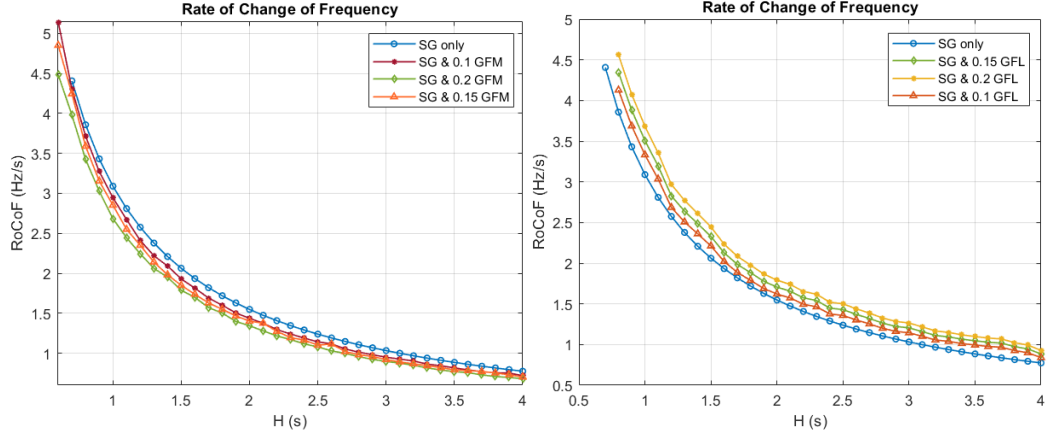


Figure 6.4: RoCoF with GFM inverter (left) and GFL inverter (right).

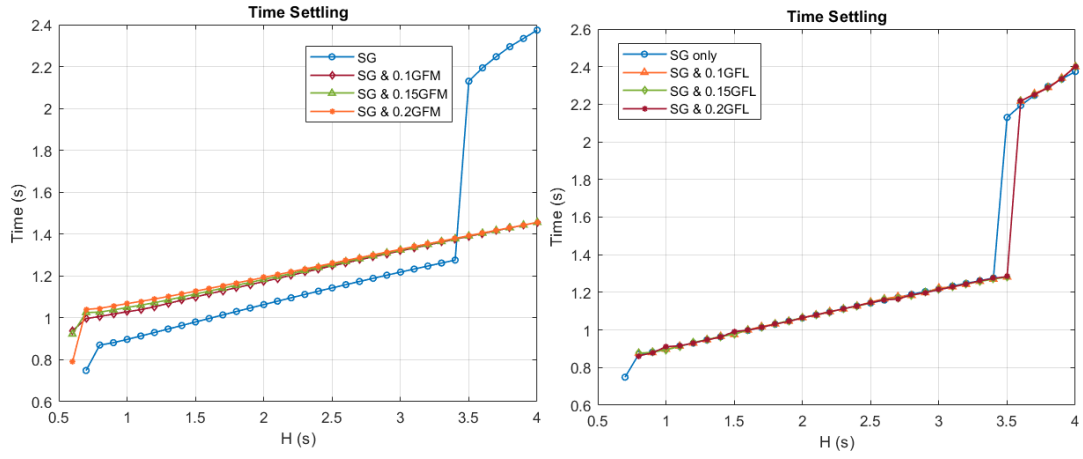


Figure 6.5: Frequency settling time with GFM inverter (left) and GFL inverter (right).

6.3 DC Side Simulation Results

In this section, the simulation results of the proposed HFLC are conducted, where the DC side is simulated separately to examine the extreme cases/disturbances. Therefore, only the DC side in Figure 3.1 is considered, that is shown below in Figure 6.6.

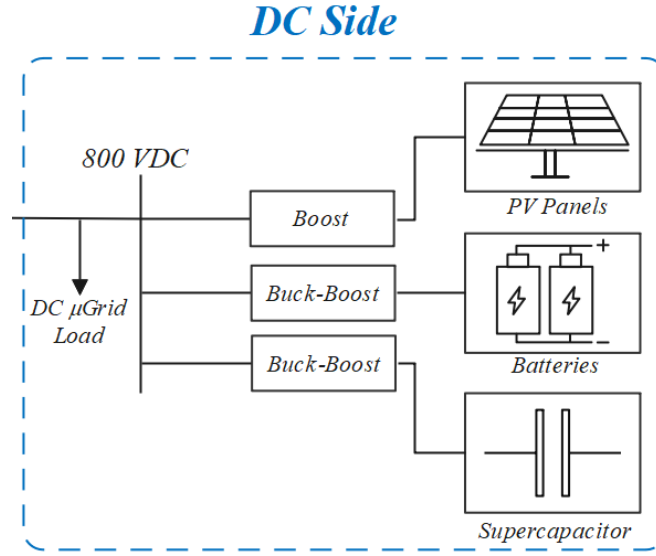


Figure 6.6: DC side of the studied microgrid system.

6.3.1 Analysis Procedure

To validate the proposed HFLC, nonlinear simulation is carried out in MATLAB/Simulink environment. During the simulation, different variations of the irradiance and the load are considered. These variations are shown in Figure 6.7. It should be mentioned that these variations and initial conditions of the SoC are selected to demonstrate the behavior of the system while shifting from one mode of operation to another. Specifically, the mode at which the LIB gets charged while simultaneously considering the voltage regulation. The parameters and the characteristics of the system are represented in Table 6.2.

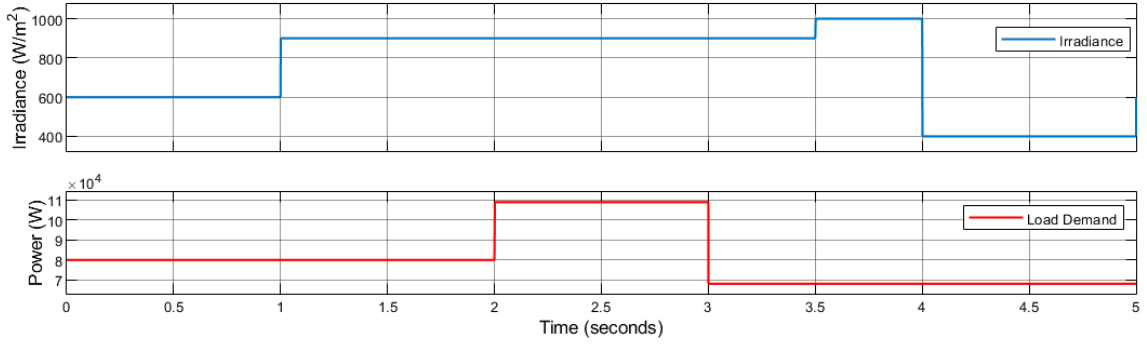


Figure 6.7: Variation of the irradiance (Top), and the load (bottom).

Table 6.2: System Parameters and Characteristics.

DC bus Voltage	720 V
Buck/boost inductance	1.45 mH
Buck capacitance	1000 μF
Boost capacitance	3227 μF
Initial SoC_B	50%
Initial SoC_{SC}	63%
Rated P_{PV} at 1000 W/m^2	100 kW
Capacitance of the SC	12 F

6.3.2 Results and Discussion

The voltage profile during the simulation is shown in Figure 6.8. Figure 6.9 and Figure 6.10 illustrate the SoC of the ESSs and the produced/consumed power of each component in the system, respectively.

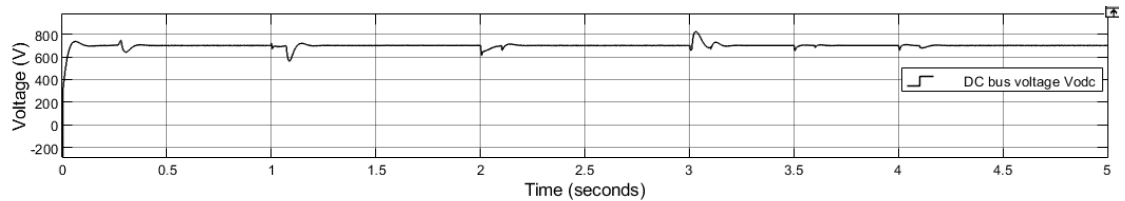


Figure 6.8: DC bus voltage during the simulation.

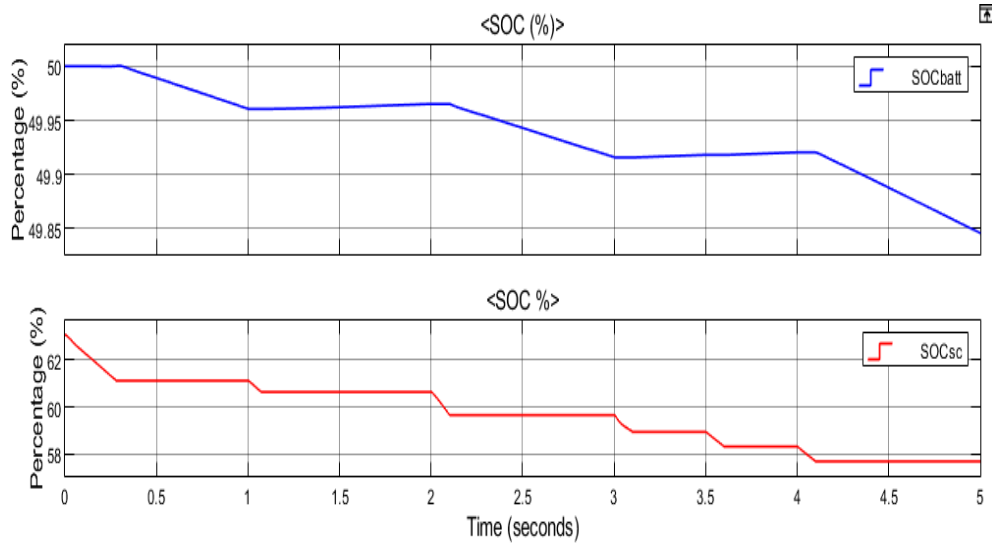


Figure 6.9: SoC_B and SoC_{SC}.

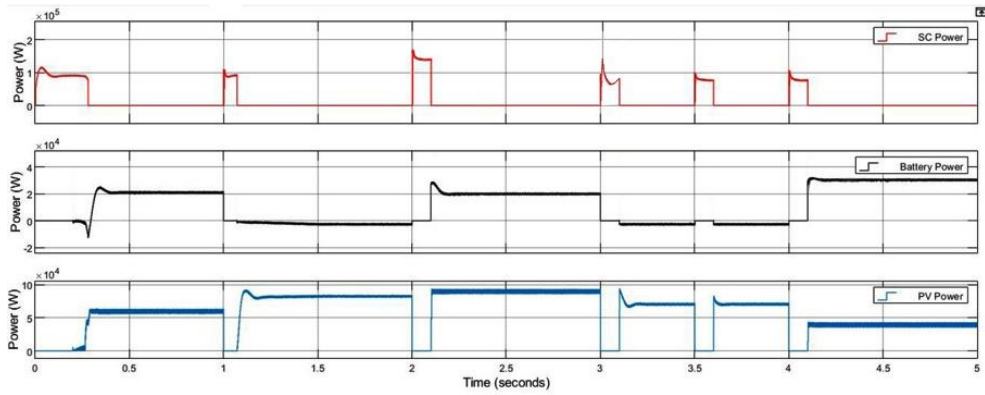


Figure 6.10: The produced/consumed power of each component in the system.

The obtained results show some fluctuations in the DC bus voltage during the transients, i.e., variation of irradiance or load. These transients' fluctuations are allowed as per the IEEE standard 1627-2019 because they are less than 20%. In addition, during the time 1-2 sec and 3-4 sec, $P_{PV} > P_L$ which results in charging up the LIB. Moreover, the evident contribution of the SC during transients increases the smoothness of shifting between the modes and saves the LIB from over-discharging, which is the key motive of utilizing the HESS. One may also observe the difference in SoC between the LIB and the

SC (see Figure 6.9). Within the 5 seconds of simulation, the SC contributed more percentage capacity due to its high-power density while the LIB utilization was kept at a minimum. It should be mentioned that the difference between Figure 5.10 (a) and Figure 5.10 (b) is negligible. The reason behind this is because the fuzzy logic here is acting as a rule-based system and we are not taking the full advantage of the fuzzification feature.

6.4 Adaptive VSG

In this section, after going through the analysis procedure, we will first start with the training stage of the adaptive VSG and then we will move to the testing stage. In the training stage, the optimal tuning of the FLC gains is ensured. Subsequently, the testing stage at which the proposed method is compared with the traditional VSG is implemented.

6.4.1 Analysis Procedure

To guarantee the optimal tuning of the FLC, different kinds of disturbances and levels of external grid inertia are considered while running the microgrid model in Simulink. We call this step “*Training stage*”, which is discussed in the following subsection. After the training stage, we will move to the *Testing stage* which is further discussed later.

The verification procedure was carried out while considering two aspects, i.e., 1) different load variations; and 2) different levels of grid inertia. For the first aspect, the FLC is first trained at a severe disturbance (15% of the rated grid power). Then, the FLC is trained at a moderate disturbance (10% of the rated power of the grid). Finally, both trained FLC was verified under the severe disturbance (Figure 6.11) and the moderate disturbance (Figure 6.12) for comparison. In addition, the disturbance is considered to be an increase

in the load (at $t = 1s$), and a decrease in the load (at $t = 5.5s$). Figure 6.11 and Figure 6.12 demonstrate the verification results of the first aspect. it should be noted that the applied changes in the load are solely intended for the active power.

The parameters and characteristics of the analyzed system are represented in Table 6.3. It is important to point out that the typical values of the SFs for FLCs are $[0, 1]$. However, as there are no physical constraints on the SFs, their bounds, in this study, are set as: $[-1000, 1000]$ to allow more flexibility, i.e., increase the search space of the optimal solution.

Table 6.3: System Parameters and Characteristics.

Nominal frequency	60 Hz
Microgrid nominal voltage	380 V
SG nominal power	1 MVA
Microgrid nominal power	100 kVA
Inverter switching frequency	10 kHz
LC filter	5 mH, 20 μ F
D Bounds	$[8, 35]$
J Bounds	$[0, 4]$
SFs Bounds.	$[-1000, 1000]$

6.4.2 Results and Discussion

As previously mentioned, this subsection will be divided into two stages, i.e., the training stage, and the testing stage. The simulation results of both stages are presented and discussed in the following.

- **Training Stage**

It is worth mentioning that dealing with multiple objectives will complicate the selection of optimal solutions. Therefore, the Pareto front is obtained to facilitate the selection process. Pareto-ranking system directly uses the idea of Pareto dominance. The population is ranked using a dominance rule, and each solution is allocated a fitness score based on its population rank rather than its actual objective function value.

As can be seen from Figure 6.11, the blue signal, which represents the frequency performance of the trained FLC at a severe disturbance, exhibits less amount of fluctuation than the trained FLC at a moderate disturbance. However, both frequencies show almost identical RoCoF over time, suggesting that they are equally responsive to changes in the system load.

Moreover, the difference between the frequencies in Figure 6.12 is negligible indicating a low correlation between the level of disturbance set at the training stage and the resultant frequency restoration during the verification stage. Therefore, the extreme case (sever disturbance) was considered to set the FLC gains.

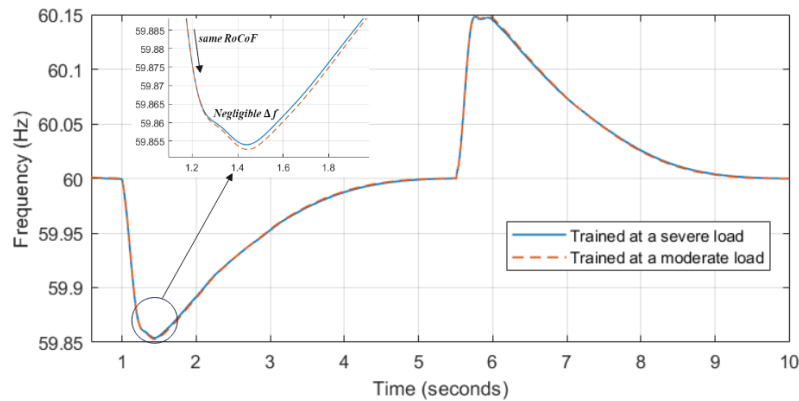


Figure 6.11: Testing result of the severe disturbance.

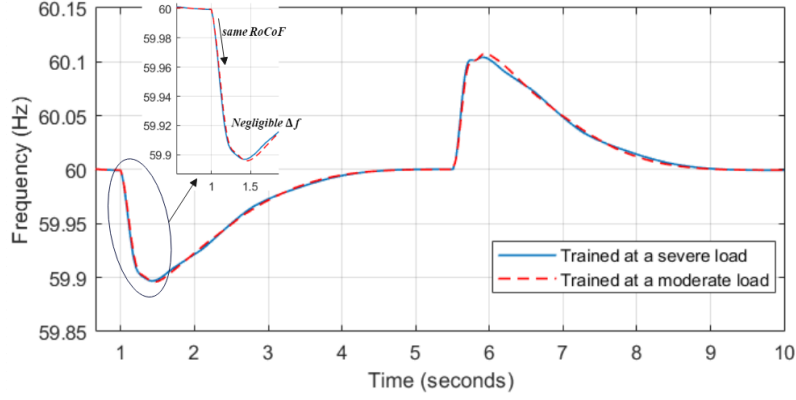


Figure 6.12: Testing result of the moderate disturbance.

For the second aspect, i.e., different levels of grid inertia, the same approach was made. First, the FLC is trained at large grid inertia ($H = 3.5$ s). Then, the FLC is trained at a medium grid inertia ($H = 2.5$ s). Finally, both trained FLCs were verified at the same level of inertia ($H = 3.5$ s) for comparison. Also, for the sack of investigation, a moderate increase of the load (at $t = 1$ s), and a moderate decrease in the load (at $t = 5.5$ s) were simulated. Figure 6.13 demonstrates the verification process of the second aspect.

Just similar to the first aspect, training the FLC at different grid inertia will not affect the response of the FLC. As can be observed from Figure 6.13, the difference between the frequencies is negligible indicating a low correlation between the level of inertia set at the training stage and the resultant frequency restoration during the verification stage. However, $H = 2.5$ s was considered in the training stage.

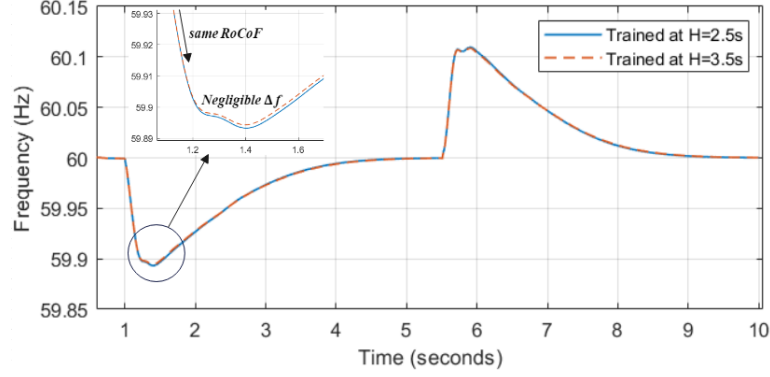


Figure 6.13: Testing result of two different levels of grid inertia.

The obtained optimal front, which corresponds to the severe load condition and moderate grid inertia, is shown in Figure 6.14. Each point on the curve represents a solution that is optimal with respect to all three objectives. The curve is generated by solving the formulated optimization problem that seeks to minimize all three objectives simultaneously, subject to the mentioned constraints in Section III. The Pareto optimal front provides decision-makers with valuable information about the trade-offs between the objectives. By examining the curve, one can determine which solution is optimal for a given objective. Additionally, the curve can help to identify which objectives are the most critical, as solutions that are closer to the curve tend to be more desirable. Also, one can observe that choosing a better solution for a certain objective will deteriorate the other objective, e.g., selecting the minimum RoCoF will result in selecting the maximum settling time. It should be emphasized that the axis in Figure 6.14 represents the fitness value rather than the true value of the objective.

Although the decision maker can select any solution from the Pareto front based on the objective priority, in this study we select the most compromise solution by finding the minimum distance from the origin.

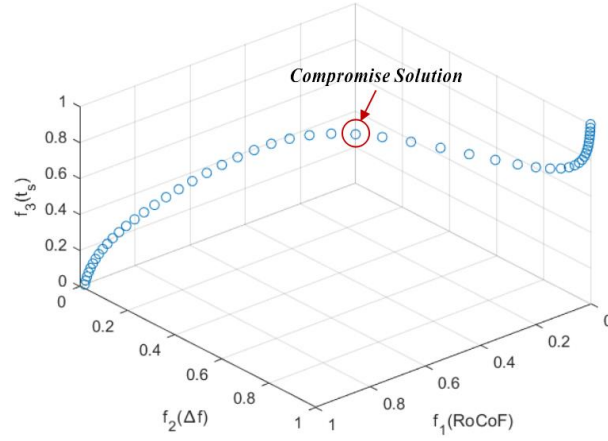


Figure 6.14: Pareto optimal front.

Finally, the corresponding parameters of the compromise solution are presented in Table 6.3 (scaling factors), Figure 6.15 (input membership functions), and Figure 6.16 (output membership functions), respectively.

Table 6.4: Optimal Scaling Factors.

SF_1	0.834
SF_2	1.322
SF_3	1.092
SF_4	0.903

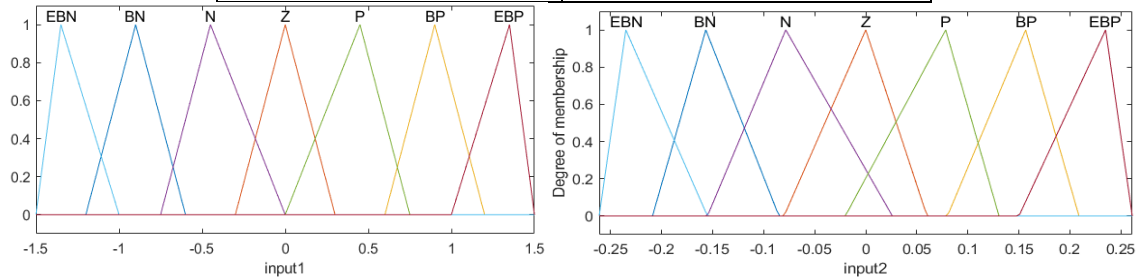


Figure 6.15: Optimal input membership functions.

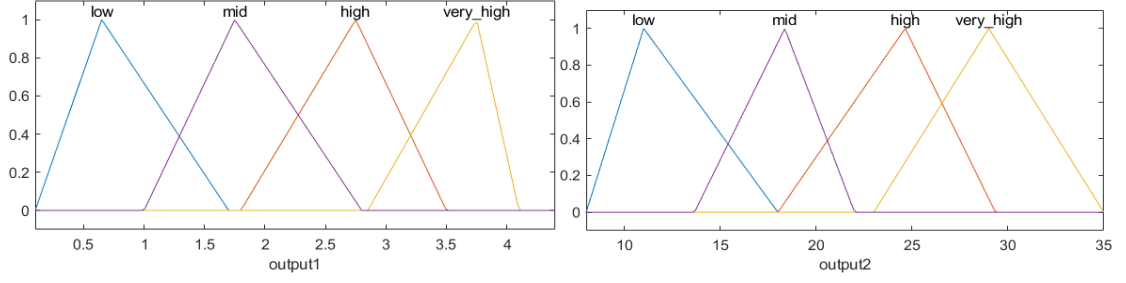


Figure 6.16: Optimal output membership functions.

- **Testing Stage**

To evaluate the efficacy and proper performance of the proposed method, an investigation is carried out between the proposed adaptive VSG-based optimal FLC and the conventional VSG control design-based derivative control method used in [27]–[30]. The investigation was performed through nonlinear simulations using MATLAB/Simulink software. Three levels of step increase/decrease in the load are conducted to examine the microgrid frequency performance. Figure 6.17 investigates the obtained improvement of the proposed adaptive VSG over the conventional one by considering three types of disturbances, i.e., mild load change (5% step increase/decrease of the rated power of the grid), moderate load change (10% step increase/decrease of the rated power of the grid), and severe load change (15% step increase/decrease of the rated power of the grid).

Based on the frequency performance depicted in Figure 6.17, it is evident that the proposed adaptive VSG has demonstrated remarkable improvements compared to the conventional VSG. A significant reduction in frequency deviation as well as an improved RoCoF are obviously noted for the proposed adaptive VSG. Despite the slightly higher settling time, the adaptive VSG's performance clearly surpasses the conventional VSG in terms of frequency stability. These results suggest that the adaptive VSG is a promising solution for enhancing frequency regulation in power systems, particularly in scenarios

where the fast and accurate frequency control is essential. Overall, the obtained results in Figure 6.17 highlights the effectiveness of the proposed adaptive VSG, which may lead to further advancements in power system stability and control.

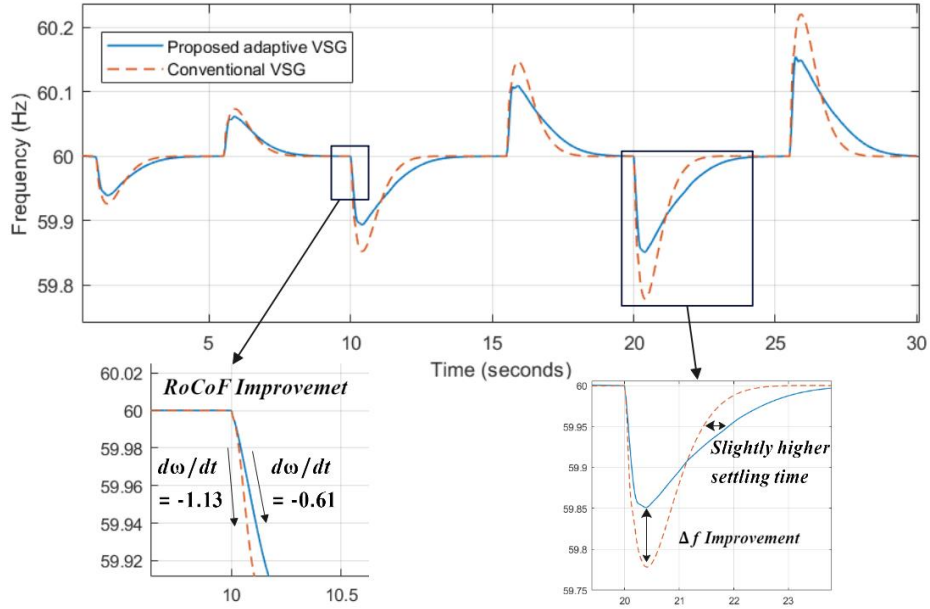
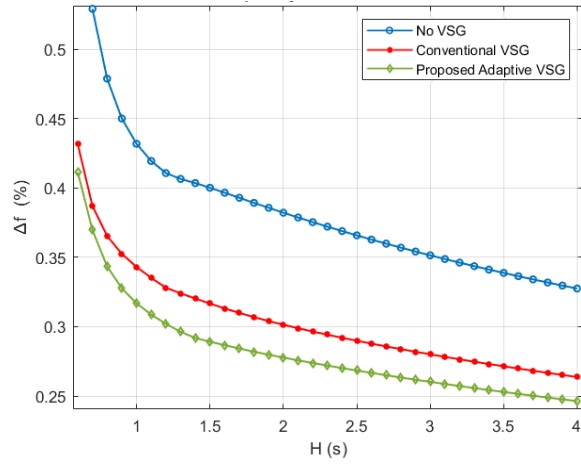
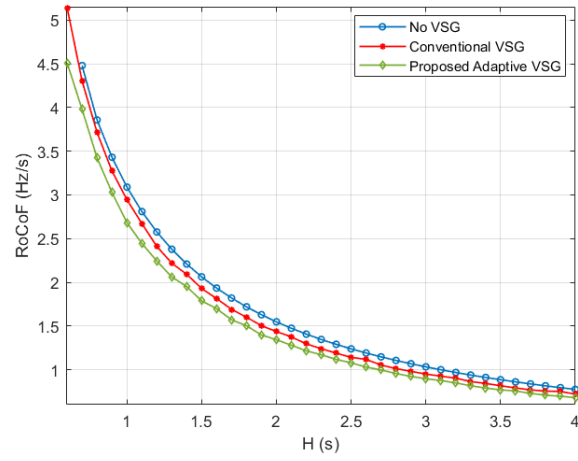


Figure 6.17: Frequency performance comparison between the proposed adaptive VSG and the conventional VSG.

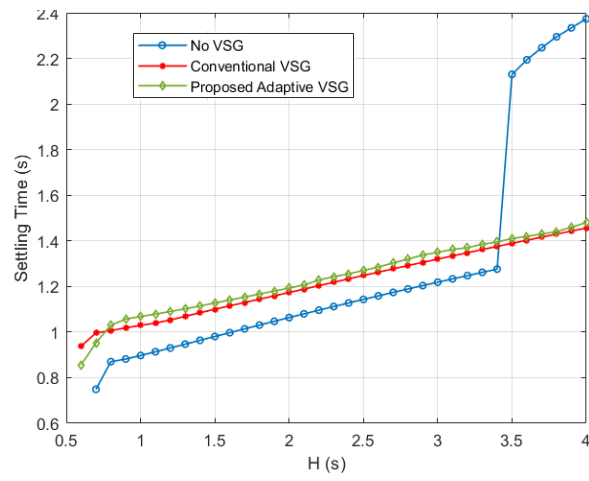
Moreover, a comparative analysis is made between the proposed method and the conventional method. To assess the proposed methodology, three frequency metrics are conducted: 1) maximum frequency over/undershoot; 2) maximum rate of change of frequency (RoCoF); 3) frequency settling time, i.e., which are the objectives of this study. Figure 6.18 explores the frequency performance as the renewable penetration increases (the grid inertia reduces). The inertia H of the grid was decreased gradually from 4 to 0.6 with a step of 0.1. It should be highlighted that the settling time defines the time at which the frequency enters the settling band and never leaves it after the disturbance. The considered settling band in this study was ± 0.05 Hz.



(a)



(b)



(c)

Figure 6.18: (a) maximum frequency over/undershoot, (b) RoCoF, and (c) frequency settling time.

As can be seen from Figure 6.18, the proposed method shows superior performance in terms of frequency deviation and RoCoF. On the other hand, the settling time of the proposed method is marginally higher than the conventional VSG. However, this can be avoided by choosing a different point from the Pareto optimal solutions, which as mentioned previously, depends on the decision maker. This can be confirmed by selecting the minimum solution with respect to f_3 , i.e., $\min t_s$. Figure 6.19 illustrates the comparison between the conventional VSG and the adaptive VSG. Since the $\min t_s$ was selected, the proposed adaptive VSG shows less settling time than the conventional one, but, the RoCoF are almost identical. On the other hand, the frequency deviation is still improved and not affected because D is, unlike J , an independent form t_s . This can be also verified in Figure 6.14.

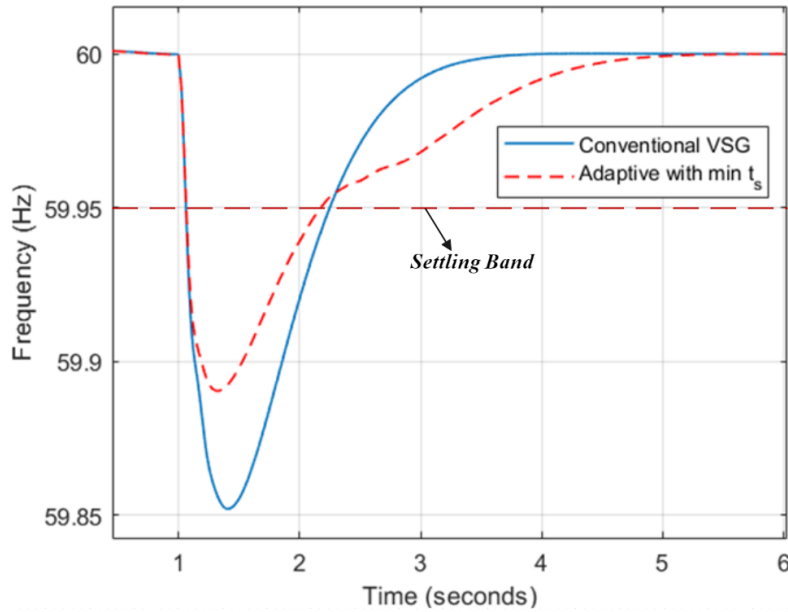


Figure 6.19: Adaptive VSG with $\min t_s$ Vs. conventional VSG.

It is worth mentioning that the settling time is the lowest when the SG is only in operation at $H < 3.5$. This is because of the real inertia of SG's rotor. For the purpose of

illustration, Figure 6.20 demonstrates the frequency entering the settling band for different inertia constants. As depicted in Figure 6.20, at $H = 3s$, the settling time $t_s = 1.218s$. Also, at $H = 4s$, the settling time $t_s = 2.374s$. This definition of the settling time is the cause to the discrete jump in the No-VSG case shown in Figure 6.18(c). However, when the VSG is connected, the virtual inertia contributes at the time of disturbance occurrence, which is attributed to the damping factor D in (4) which damps the maximum frequency overshoot at higher inertia constants.

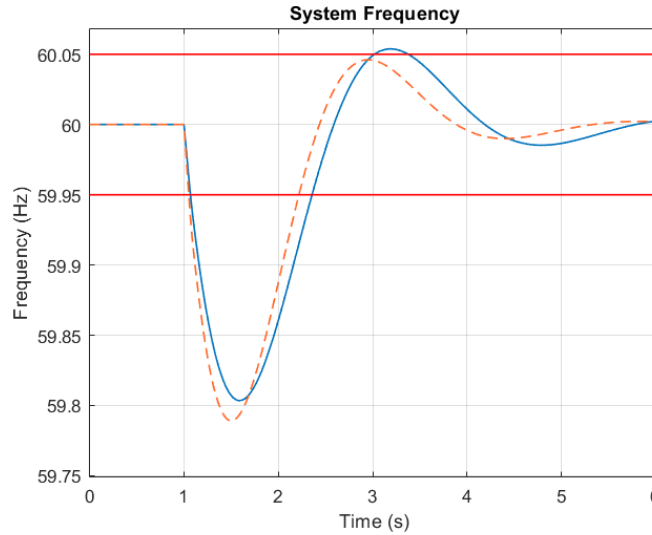


Figure 6.20: Illustration of the frequency entering the settling time (SG only).

6.5 Seamless Transition of Microgrid Connectivity to the Grid

This section is dedicated to presenting the simulation results that have been acquired from MATLAB/Simulink environment while shifting from GC mode to IS mode and vice versa.

6.5.1 Analysis Procedure

The parameters and the characteristics of the system are the same as those listed in Table 6.3. Two different scenarios are conducted for examining the transition behavior of the microgrid. In the first scenario, the microgrid is connected to the grid to sell energy, i.e., power flows from the microgrid to the external grid during the GC mode of operation. In the second scenario, the microgrid is connected to the grid to buy energy, i.e., power flows from the external grid to the microgrid during the GC mode of operation.

For the first scenario, the microgrid at the beginning was in mode 0 and supplying a load of 90 kW. At time $t = 1$ s, the controller received a signal to connect to the main grid. Hence, mode 1 is activated at that time. After ensuring the voltage matching (amplitude, frequency, and phase shift), the controller sends a signal to the CB1 to close. Hence, mode 2 is activated where a fast and reliable transition is achieved. In addition, to demonstrate the behavior of the microgrid in case of unintentional disconnection, at time $t = 3$ s, the CB1 was unintentionally in open position.

For the second scenario, the microgrid was initially in mode 0 and supplying a load of 100 kW. At time $t = 1$ s, the controller received a signal to connect to the main grid. Hence, mode 1 is activated at that time. In this scenario, however, the connection is needed to buy energy from the main grid. So, after ensuring the voltage matching (amplitude, frequency, and phase shift), the controller sends a signal to the CB1 to close. Hence, mode 2 is activated. In addition, to demonstrate the behavior of the microgrid in case of unintentional disconnection, at time $t = 3$ s, the CB1 was unintentionally in open position

6.5.2 Results and Discussion

In this subsection, the simulation results of the two mentioned scenarios are presented and discussed.

- **Scenario 1**

Figure 6.21 shows the synchronization process between the grid voltage and inverter voltage, where a smooth synchronization is achieved. Figure 6.22 to Figure 6.24 illustrate the inverter's current, frequency, and power, respectively. As the complete waveforms of voltage and current are not informative, Figure 6.21 and Figure 6.22 demonstrate the waveforms of voltages and current at the time of transition only.

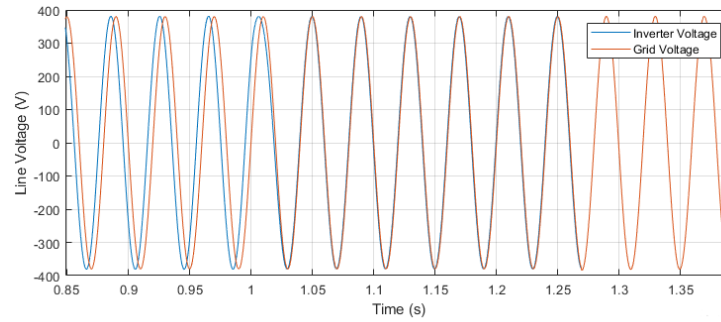
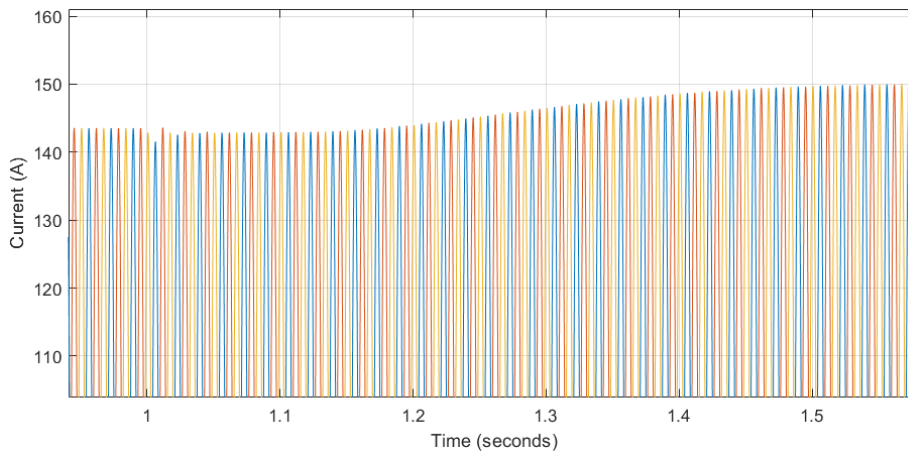


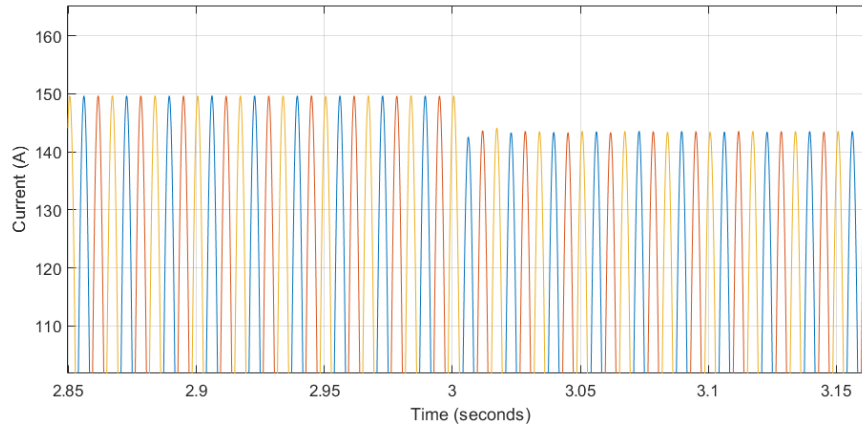
Figure 6.21: Synchronization process between the grid voltage and inverter voltage.

Based on the provided figures, it appears that the proposed control strategy effectively facilitates a smooth and reliable transition between grid-connected (GC) and islanded (IS) modes of operation for microgrids. In the first scenario, the microgrid power exhibits a gradual increase as the microgrid transitions from IS to GC mode (see Figure 6.23). This gradual increase is critical to ensuring a seamless transition without any sudden disruptions to the power supply. Similarly, the frequency in Figure 6.24 displays a gradual increase in the microgrid frequency as the microgrid transitions to GC mode, indicating that

the proposed control strategy maintains a stable frequency during the transition. Furthermore, the current waveform exhibits a smooth transition with minimal fluctuations. Correspondingly, the microgrid manifests a stable operation during the unintentional disconnection from the external grid, suggesting that the proposed control strategy can maintain stable operation, which is crucial for ensuring the reliability and safety of the power supply.



(a)



(b)

Figure 6.22: Three-phase inverter current during the transition (a) form IS to GC mode and (b) form GC to IS mode.

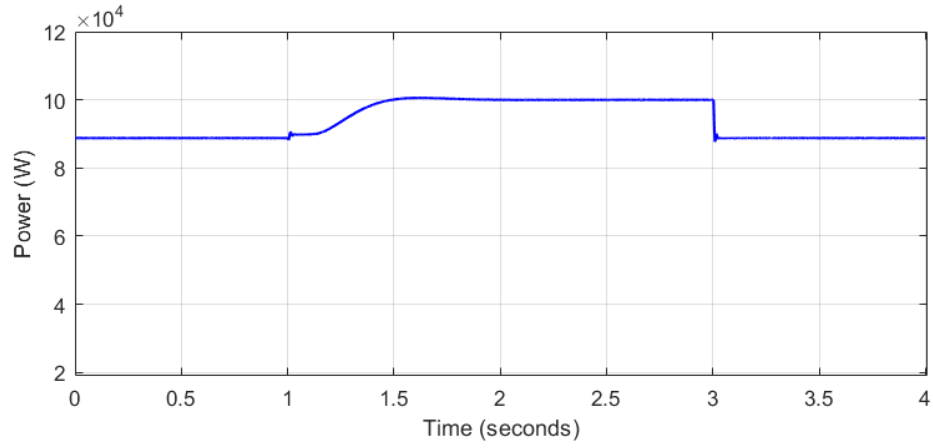


Figure 6.23: Microgrid output power during IS and GC modes.

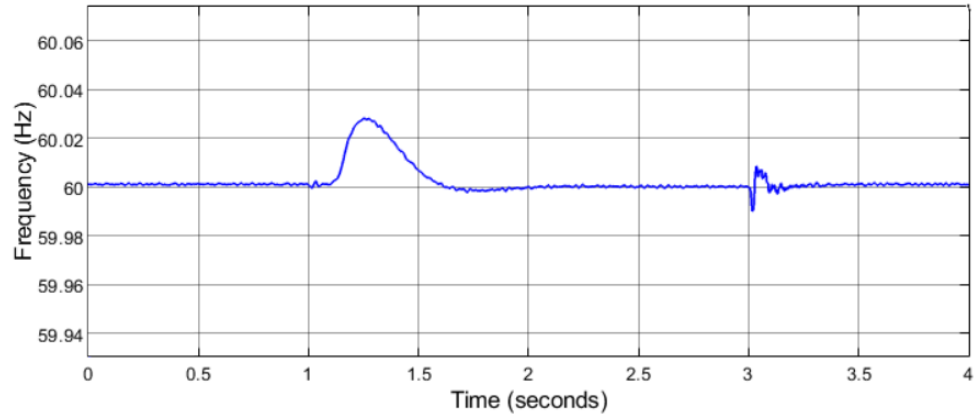


Figure 6.24: Microgrid frequency during IS and GC modes.

- **Scenario 2**

Figure 6.25 shows the synchronization process between the grid voltage and inverter voltage, where a smooth synchronization is achieved. Figure 6.26 to Figure 6.28 illustrate the inverter's current, frequency and power, respectively.

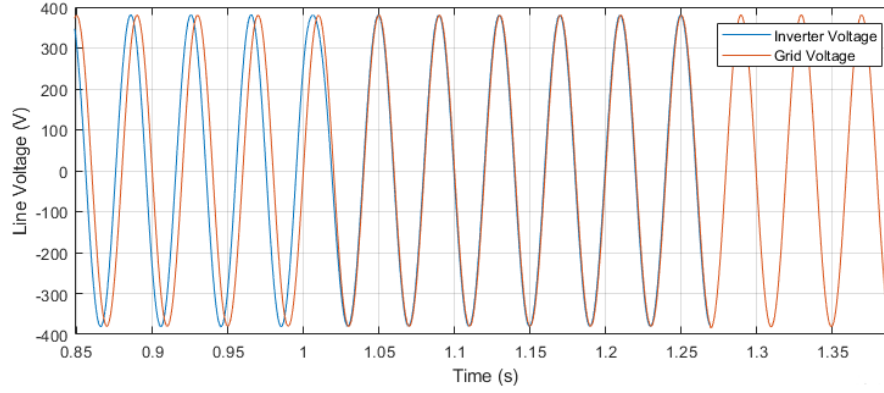
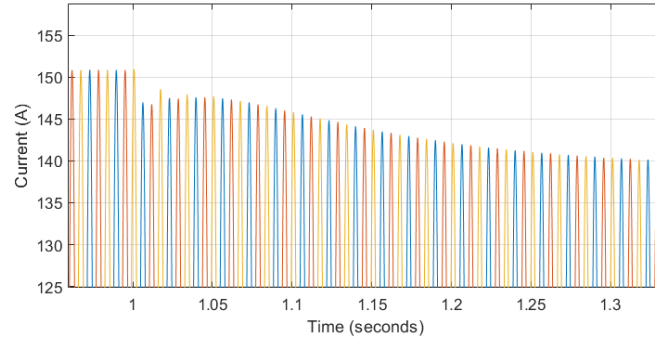


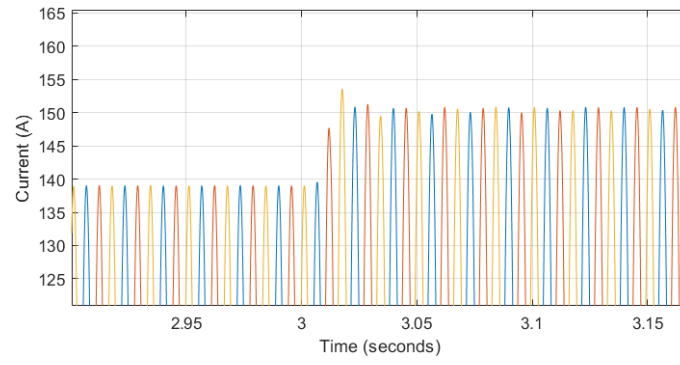
Figure 6.25: Synchronization process between the grid voltage and inverter voltage.

Likewise, in the second scenario, the power in Figure 6.27 reveals a gradual decrease in the output power as the microgrid transitions from IS to GC mode. The frequency in Figure 6.28 also exhibits an acceptable decrease of 0.05 Hz as the microgrid transitions to IS mode due to the unintentional disconnection from the external grid, indicating that the proposed control strategy maintains a stable frequency during the transition. Moreover, the current waveform in Figure 6.26 demonstrates a smooth transition with minimal fluctuations, further validating the proposed control strategy's effectiveness in maintaining stable current levels.

Overall, the illustrated figures provide strong evidence supporting the effectiveness of the proposed seamless transition control strategy in achieving a reliable and stable transition between GC and IS modes of operation for microgrids, regardless of the direction of power flow. The gradual changes in power output, frequency, and current levels during the transitions highlight the proposed strategy's ability to ensure a consistent and reliable power supply, which is critical for the stability and safety of the microgrid operation.



(a)



(b)

Figure 6.26: Three-phase inverter current during the transition (a) form IS to GC mode and (b) form GC to IS mode.

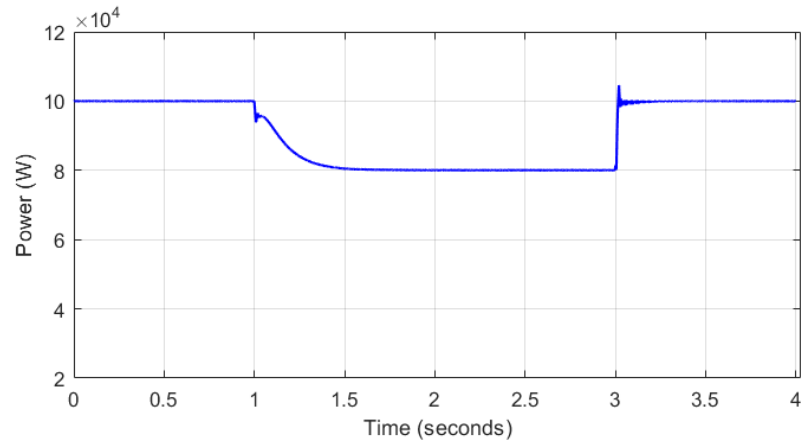


Figure 6.27: Microgrid output power during IS and GC modes.

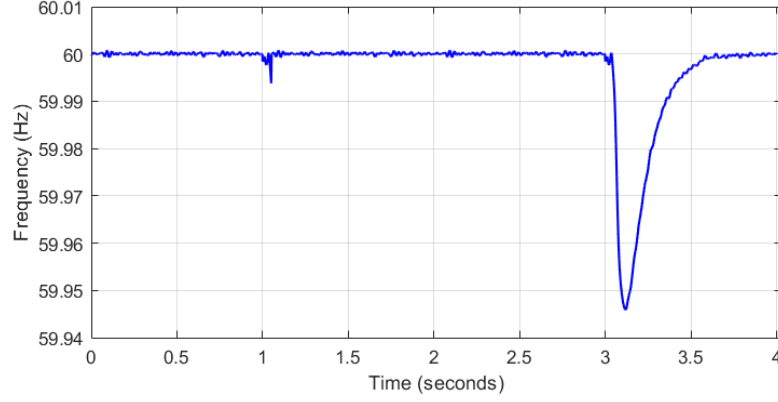


Figure 6.28: Microgrid frequency during IS and GC modes.

It should be mentioned that the relationship between frequency and power is obtained from the droop characteristic which is shown in Figure 6.29. In the beginning, when mode 0 was activated, the operating point was at **A**, i.e., $f = 60.06 \text{ Hz}$ and $P = 90 \text{ kW}$. When mode 2 was activated (GC mode), the operating point was at **B**, i.e., $f = 60 \text{ Hz}$ and $P = 100 \text{ kW}$. This means that the microgrid was operating in load following-mode at point **A**, while operating in grid-following mode at point **B**. Moreover, according to the droop characteristic in Figure 6.29, the microgrid turned automatically back to operating point **A** at the time of unintentional disconnection from the external grid.

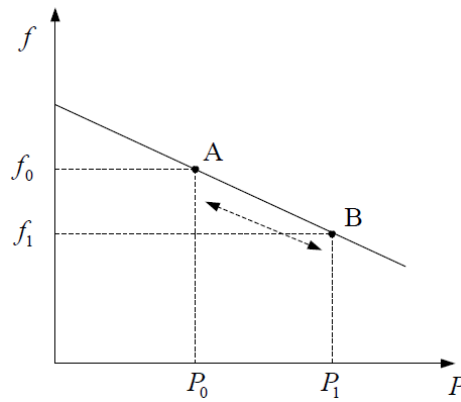


Figure 6.29: Active droop characteristic of the GFM inverter.

6.6 Generalized Case Study

The purpose of this section is to perform a simulation of the overall system shown in Figure 6.30, under different kinds of disturbances to validate the proposed control methodologies in Chapter 5 simultaneously.

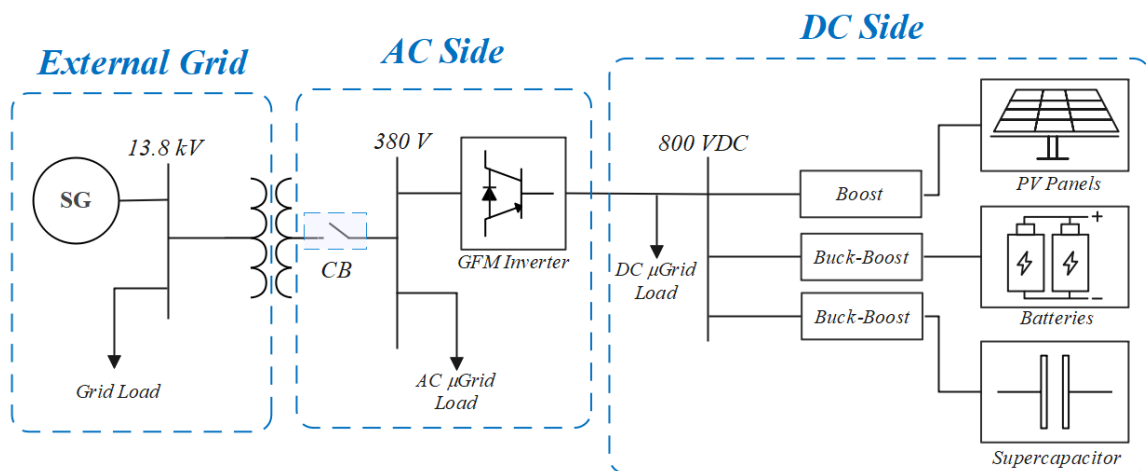


Figure 6.30: Active droop characteristic of the GFM inverter.

6.6.1 Analysis Procedure

The characteristics and parameters of the studied system are the same as those listed in Table 6.2 and Table 6.3. The disturbances are shown in Figure 6.31, which represents the change in the system's load/status. The up-arrow represents an increase, and the down-arrow represents a decrease in which they are labeled. Also, the points represent the time of transition, i.e., from IS to GC mode at $t = 0.1s$ for the blue point and unintentional transition from GC to IS mode at $t = 6s$ for the red point.

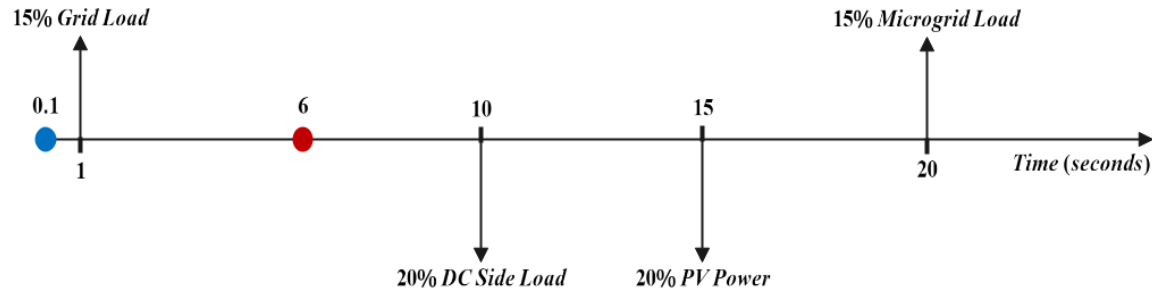


Figure 6.31: Simulated changes of the studied system.

6.6.2 Results and Discussion

It can be observed from Figure 6.32 that there are some minimal fluctuations in the frequency during the transitioning which reflects the reliability and effectiveness of the proposed seamless transition control strategy. Further, the frequency performance of the proposed adaptive VSG in Figure 6.32 gives satisfactory results. Additionally, Figure 6.33 illustrates the robustness of the HFLC in stabilizing the DC bus voltage regardless to the location of disturbance (DC side or AC side).

It is evident that the disturbances in the DC side at seconds 10 and 15 (see Figure 6.33) do not affect the frequency of the microgrid. The reason for this lies behind the fact that the VSG inverter is governed by the swing equation (see (4.12)), where the frequency depends on the balance between input power and output power. Hence, as far as the power balance is achieved, the frequency in the AC side will be stably maintained without disturbances.

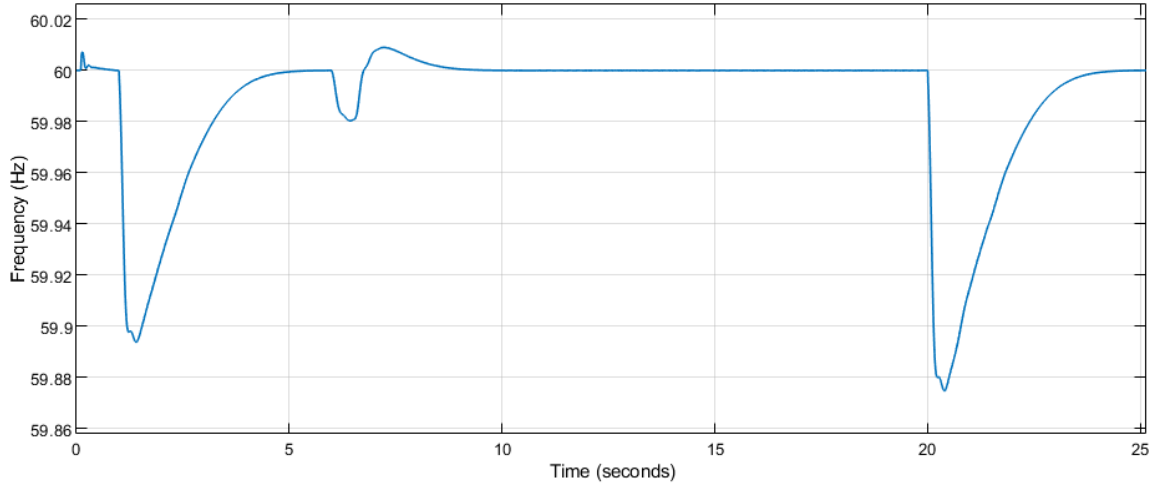


Figure 6.32: Frequency during the simulation of the generalized case study.

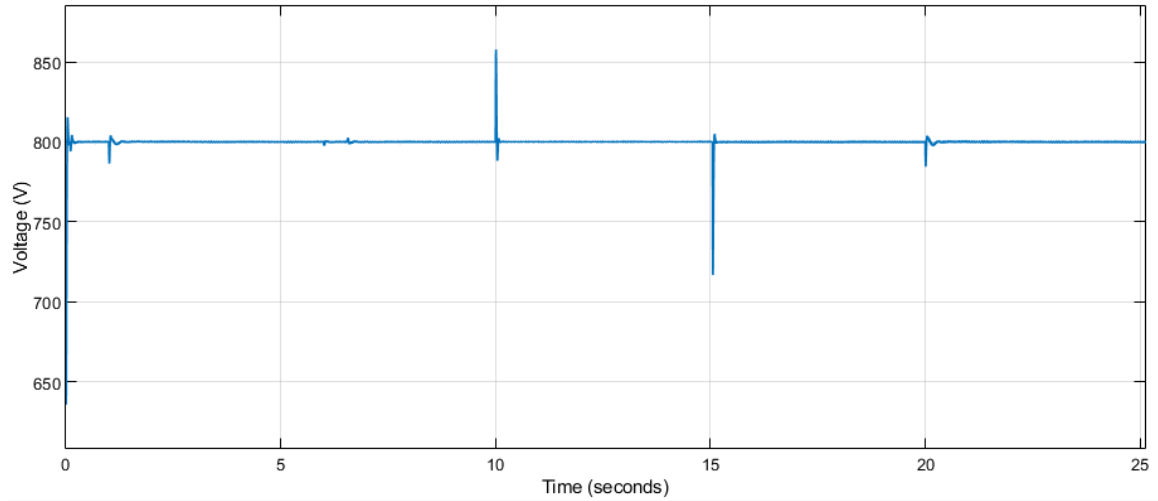


Figure 6.33: DC bus voltage during the simulation of the generalized case study.

6.7 Summary

In this Chapter, a systematic analysis of three frequency metrics was conducted with different case studies to compare the GFM and GFL inverters in terms of their ability to support the frequency of the grid. The metrics under consideration were: 1) maximum frequency over/undershoot; 2) maximum rate of change of frequency (RoCoF); 3) frequency settling time. The performed analysis showed a better performance in favor of

the GFM inverter. This should motivate the microgrid operators to replace the widely used GFL inverter with the GFM inverter to enable more renewable penetration and participate in ancillary service for supporting the grid.

In addition, the proposed HFLC was tested for both energy management and maintaining a stable DC voltage. The simulation results showed the robustness of the proposed control strategy in maintaining a stable DC voltage under different conditions. Also, the proposed algorithm was able to charge the LIB while simultaneously considering the regulation of the voltage.

Moreover, the proposed adaptive VSG which is based on FLC was trained using the DE algorithm. The DE algorithm was used to solve the formulated optimization problem, i.e., to train the FLC. The objective of this optimization is to minimize the frequency deviation RoCoF, and frequency settling time. To guarantee optimal tuning, different load variations and levels of grid inertia are tested. In addition, the optimal Pareto front is obtained to select the most compromised solution. Nonlinear simulations were carried out to confirm the efficacy and robustness of the proposed method over the conventional VSG in both modes of operation, i.e., islanded and grid-connected modes. Furthermore, the frequency performance as the renewable penetration increases (the grid inertia reduces) is investigated, which showed a remarkable performance to the proposed method.

Additionally, the proposed control strategy for the seamless transition between the IS and GC modes was validated through time-domain simulation in MATLAB/Simulink.

Finally, a generalized case study was simulated to validate the proposed control methodologies in Chapter 5 simultaneously.

CHAPTER 7: CONCLUSION AND FUTURE

WORK

7.1 Conclusion

In this thesis, a comprehensive research study was conducted on the state-of-art type of inverters (GFM inverters). We started with a literature review to identify the research gap. It was found that there is a lack of conducted analysis on GFM and GFL inverters' interaction with the low-inertia grids. Moreover, GFM inverters are associated with fixed input DC source. It was mostly considered the perfect DC bus case. Furthermore, VSG was proposed to emulate the inertial response of an SG by adopting the swing equation in the control loop. However, the virtual inertia and the damping coefficients were mostly constant. Finally, the GFM control strategy is mostly used in islanded microgrids, while in grid-connected mode the GFL control strategy is used. This approach creates a non-desirable discontinuity of the operation. To overcome these gaps, the following are a summary of the main contributions of this thesis:

- 1) A systematic analysis of three frequency metrics was conducted with different case studies to compare the GFM and GFL inverters in terms of their ability to support the frequency of the grid. The metrics under consideration were: 1) maximum frequency over/undershoot; 2) maximum rate of change of frequency (RoCoF); 3) frequency settling time. A general model was used in the analysis so that it can be valid for any power system configuration. A simple control

scheme was used for the GFL inverter that utilizes a PLL. The widely used virtual SG (VSG) control scheme was tested to operate the GFM inverter.

- 2) A hierarchical control algorithm was proposed to control the operation of an islanded DC-microgrid composed of LIBs, SCs, and PV arrays. Different connection topologies and control strategies were discussed among their advantages/disadvantages. The proposed HFLC was developed for both energy management and maintaining a stable DC voltage.
- 3) Proposing a control algorithm that hybridizes fuzzy logic controller (FLC) and differential evolution (DE) optimization to adaptively tune the virtual inertia and the damping factor of the VSG. Unlike the other proposed algorithms in the literature [70], [71], which are complex to implement and need high computational power, the proposed hybrid FLC-DE is a model-free and easy-to-apply control algorithm. The hybridization is achieved by optimizing the FLC parameters using the DE algorithm. We formulate a multi-objective problem to minimize: 1) frequency deviation, 2) RoCoF, and 3) frequency settling time. We then obtain the Pareto front of the multi-objective optimization problem to investigate the tradeoffs between the three objectives and to select the most appropriate solutions.
- 4) A control strategy for a seamless transition from IS to GC mode and vice versa was proposed. The idea of the proposed control strategy is to use a single control algorithm in both modes of operation (GC and IS). An improved (VSG) control is deployed. The governor of the VSG is modified to adjust the frequency by adding a frequency adjustment compensator. Also, the exciter system, droop

control, of the voltage controller is modified by adding a voltage adjustment compensator to match the grid during the transition from IS to GC mode for a smooth transition. A seamless transition is also achieved during the unintentional transition from GC to IS mode because of the self-ability of the VSG to regulate the voltage and frequency.

7.2 Future Work

The conducted analysis was performed while considering a balanced three-phase load. In addition, the proposed control algorithms/strategies are applicable only to balanced three-phase systems, while in practice, we might have unbalanced conditions. This should open the field for future studies on unbalanced conditions.

Moreover, the obtained results have been acquired from MATLAB/Simulink environment through time-domain simulation. A future experimental validation would be the future field of study.

Finally, the proposed adaptive VSG on the AC side was responsible for optimizing the frequency performance of the microgrid. The voltage, however, was maintained using the traditional droop control. Additional improvement on the voltage control loop, such as proposing a new voltage control algorithm is another prospective future work.

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Y. Awda, M. Alowaifeer, “Adaptive Optimization of Virtual Synchronous Generator Based on Fuzzy Logic Control and Differential Evolution,” 2023 Ain Shams Engineering Journal (Under Review).

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