



Coordinated Control of GFM and GFL Inverters: A Hybrid Approach for Improved Grid Support

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DECLARATION

This Final year Capstone Project report is submitted to the department of Electrical and Electronic Engineering, University of Liberal Arts Bangladesh in partial fulfillment of the requirements for the degree of Bachelor of Science. So, we hereby, declare that this report is based on the work done by us. Materials of work found by other researchers are mentioned by reference. This project report, neither in whole, nor in part, has been previously submitted for any degree.

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SUPERVISOR'S CERTIFICATION / APPROVAL

The Final year Capstone Project report entitled “Coordinated Control of GFM and GFL Inverters: A Hybrid Approach for Improved Grid Support” is submitted to the department of Electrical and Electronic Engineering, University of Liberal Arts Bangladesh, Dhaka in partial fulfillment of the requirements for the degree of Bachelor of Science.

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ABSTRACT

Modern power grids are undergoing a profound transformation due to the increasing integration of renewable energy sources, such as solar and wind power, which are interfaced with the grid via inverter-based resources. These changes have led to a reduction in grid inertia, posing challenges to voltage and frequency stability. This study investigates the performance of Grid-Forming (GFM) and Grid-Following (GFL) inverters, both in standalone operation and in a coordinated hybrid configuration. Detailed MATLAB/Simulink simulations were performed to evaluate voltage and frequency stability, harmonic distortion, transient response, and power sharing behavior.

The findings indicate that while the GFM inverter can independently form a stable grid, the GFL inverter requires an existing voltage reference and cannot operate alone. When integrated in a hybrid system, the GFM inverter establishes the grid reference while the GFL inverter injects controlled active and reactive power, resulting in improved voltage quality, reduced Total Harmonic Distortion (THD), and enhanced transient response. Mathematical models, including dq-frame current control, droop control equations, and PLL synchronization, were used to analyze and validate the results. This study demonstrates that hybrid GFM+GFL control strategies offer a robust solution for modern renewable-dominated grids, providing stability, reliability, and improved power quality.

Keywords: Grid-Forming, Grid-Following, Inverters, Hybrid Control, Microgrid, Power Quality, MATLAB/Simulink.

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Chapter 1

Introduction

1.1 Background

The global energy sector is undergoing a profound transformation, driven by the urgent need to decarbonize electricity generation. This paradigm shift is characterized by the rapid and large-scale integration of renewable energy sources (RES), primarily wind and solar photovoltaic (PV) systems. While this transition is essential for a sustainable future, it fundamentally alters the architecture and dynamics of traditional power systems. Historically, the grid's stability and reliability were underpinned by conventional synchronous generators (SGs). These large rotating masses provided inherent stability services, including inertia (resistance to frequency changes), frequency regulation (primary and secondary control), and voltage support (reactive power provisioning) [1], [2].

The replacement of SGs with Inverter-Based Resources (IBRs) creates a critical challenge: while IBRs enable carbon-free power generation, they do not naturally replicate the stabilizing properties of SGs. Power electronic converters act as an intermediary between the variable RES and the grid, decoupling the generator's dynamics from the system. Consequently, modern power systems are transitioning from a high-inertia, electromechanically dominated regime to a low-inertia, electronically dominated one. This evolution introduces vulnerabilities, such as increased rates of change of frequency (RoCoF), voltage instability, and reduced resilience to disturbances, particularly in weak grids or isolated systems [3], [4]. The question of how to maintain and enhance grid stability in this new context is, therefore, a central research imperative.

The functionality and impact of an IBR on the grid are dictated almost entirely by its control strategy. Two dominant control philosophies have emerged to address this challenge: Grid-Following (GFL) and Grid-Forming (GFM). Their core operational principles, strengths, and limitations are fundamentally different.

Grid-Following (GFL) Inverters are currently the most prevalent type. They operate as controlled current sources, injecting power into a grid whose voltage and frequency are established by other sources. To synchronize, GFL inverters rely on a Phase-Locked Loop (PLL), a control algorithm

that continuously tracks the grid's phase angle [5]. While highly efficient and straightforward for feeding power into a robust grid, this dependency on a stable voltage reference is their primary weakness. Under weak grid conditions, the PLL can interact adversely with the network, leading to synchronization instability and potential disconnection [6].

Grid-Forming (GFM) Inverters, in contrast, are designed to mimic the behavior of SGs. They operate as controlled voltage sources with an internal oscillator that autonomously sets the grid voltage and frequency [7]. By establishing the voltage waveform, GFM inverters can create a stable grid anchor, to which other resources can synchronize. This capability enables them to start a grid from a blackout (black-start), operate in islanded mode, and, most importantly, actively strengthen weak grids by providing virtual inertia and short-circuit power [8]. The trade-offs include increased control complexity and challenges in precise power sharing in parallel operation [9].

Recent research has moved beyond viewing GFM and GFL inverters as mutually exclusive solutions. Instead, a consensus is emerging that a hybrid system, leveraging the complementary strengths of both paradigms, is essential for the stability and efficiency of future power systems [10], [11].

Studies on synchronization stability have proposed advanced self-synchronizing strategies for GFM inverters that eliminate PLL dependency, enabling seamless reconnection in islanded microgrids [12]. Comprehensive reviews consistently reinforce the critical role of GFM inverters as a cornerstone for enhancing power system reliability [13]. However, comparative analyses clearly demonstrate that neither GFM nor GFL inverters alone can fully address the wide spectrum of operational challenges presented by weak and dynamic grids [14], [15]. A purely GFM-based system may face challenges in optimal power dispatch, while a purely GFL-based system is fundamentally unstable without a strong voltage-forming backbone.

This insight points toward the necessity of coordinated control in hybrid systems. In such an architecture, a subset of inverters (GFM) acts as the stability-enhancing "backbone," defining voltage and frequency, while the majority (GFL) operate efficiently as controlled power injectors. This approach promises a system that is not only stable but also economically optimal and flexible [16].

1.2 Problem Statement

The gradual replacement of synchronous machines with inverter-based generation has exposed the modern power grid to a new class of vulnerabilities rooted in control dynamics rather than physical mechanics. The core of the problem lies in the inherent limitations of the two dominant inverter control philosophies when deployed in isolation.

Grid-Following (GFL) inverters, although commercially mature and efficient for power injection, are fundamentally dependent followers. Their reliance on a Phase-Locked Loop (PLL) to synchronize with a strong external voltage makes them fragile in grids with low system strength (i.e., low Short Circuit Ratio). As detailed in numerous stability analyses, such as the work, the PLL can lose lock or even contribute to instability when faced with voltage distortions or phase jumps common in weak grids. This dependency renders GFL-only systems incapable of black-start operations or stable islanded microgrid functionality, leading to voltage collapse in the absence of a grid-forming source.

On the other hand, Grid-Forming (GFM) inverters offer a direct solution by acting as voltage sources that autonomously establish grid frequency and voltage. They are indispensable for providing black-start capability and enabling stable operation in weak or isolated grids. However, their performance is not without challenges. When a single GFM inverter is tasked with supplying a dynamic or nonlinear load, it often faces a critical trade-off between fast transient response and accurate power sharing, an issue central to droop control design. This can result in voltage waveform distortions and places a significant control burden on a single unit, leading to inefficiencies and potential quality issues.

The central problem, summarized in Table 2, is that neither control strategy alone provides a complete solution for a resilient, high-performance, renewable-dominated grid. GFL inverters offer efficient power injection but lack independence, while GFM inverters provide stability but struggle with quality and efficiency under stress.

Table 1.2: Summary of Standalone Inverter Limitations

Inverter Type	Core Limitation	Consequence in Weak/Islanded Grids
Grid-Following (GFL)	Dependence on external voltage via PLL	PLL instability, loss of synchronization, voltage collapse
Grid-Forming (GFM)	Sole responsibility for voltage/frequency regulation	Waveform distortion, control burden, poor power sharing accuracy

Therefore, this thesis addresses the critical research question: How can GFM and GFL inverters be effectively coordinated in a hybrid architecture to leverage the grid-forming stability of the former with the efficient power injection of the latter? This project seeks to demonstrate that such a coordinated strategy can overcome the standalone limitations of each technology, providing a robust path toward improved stability, power quality, and overall grid support.

1.3 Motivation of the Study

The transition to a renewable-dominated power system presents a critical paradox: while inverter-based resources (IBRs) are essential for decarbonization, their proliferation displaces the very synchronous generators that have historically guaranteed grid stability. The rapid decline in system inertia is no longer a future projection but a present-day operational challenge for grid operators worldwide, leading to an increased risk of fast frequency excursions and other instability phenomena after disturbances. This creates an urgent need for new sources of grid stability that must come from the power electronics themselves. The core motivation for this research stems from the understanding that neither of the primary inverter control strategies is, by itself, a sufficient solution. Relying solely on Grid-Following (GFL) inverters, while cost-effective, would create a fragile grid that is highly susceptible to collapse, especially in regions with weak network infrastructure. Conversely, while a full-scale deployment of Grid-Forming (GFM) inverters could theoretically solve the stability problem, it presents significant economic and technical challenges, including higher control complexity and potential performance trade-offs when operating alone.

Therefore, the most promising and practical path forward lies in the development of hybrid systems where GFM and GFL inverters are coordinated to work synergistically. This hybrid approach is motivated by the potential to achieve a "best of both worlds" outcome: leveraging a smaller, strategic fleet of GFM inverters to provide system strength and stability, while allowing the vast majority of GFL inverters to continue their primary role of efficient bulk power injection.

This project is motivated by the need to provide a clear, quantitative, and comparative analysis of this hybrid strategy. By simulating and directly comparing the performance of standalone and coordinated configurations, this study aims to contribute practical and accessible insights into how such a hybrid architecture can be effectively implemented to ensure a stable and reliable power grid for the future.

1.4 Objectives of the Study

The primary goal of this study is to provide a definitive, simulation-based comparison of GFM, GFL, and hybrid inverter configurations, demonstrating that a coordinated control architecture is essential for achieving robust grid support. To accomplish this, the research pursues a set of objectives that directly correspond to the experimental cases presented in this report:

- To characterize the standalone performance of a Grid-Forming (GFM) inverter. This objective involves modeling the GFM inverter to establish a baseline for grid stability while quantifying its inherent limitations, specifically the voltage waveform distortions and frequency oscillations observed under dynamic load conditions.
- To empirically demonstrate the operational failure of a standalone Grid-Following (GFL) inverter. By simulating a GFL inverter without an external grid, this objective aims to validate its fundamental dependency on a Phase-Locked Loop (PLL) reference, thereby proving its inability to form a stable grid on its own.
- To validate the enhanced performance of a coordinated hybrid GFM+GFL system. This objective focuses on showing demonstrable improvements in power quality and frequency stability that result from the synergistic operation where the GFM provides the grid reference and the GFL injects controlled power.

- To parametrically analyze the hybrid system's power control flexibility. This final objective involves evaluating the system's response under three distinct GFL power command scenarios:
 - Idle Mode ($I_{dref}=0, I_{qref}=0$)
 - Power Injection Mode ($I_{dref}<0, I_{qref}>0$)
 - Power Absorption Mode ($I_{dref}>0, I_{qref}>0$)

1.5 Organization of the Report

This report is structured into six chapters to guide the reader logically from the foundational concepts and literature review through to the final conclusions and recommendations.

Chapter 1: Introduction provides a comprehensive overview of the research. It establishes the context, defines the core problem created by declining grid inertia, outlines the study's motivation and objectives, and presents the key research questions that guide the investigation.

Chapter 2: Literature Review surveys the foundational and contemporary academic landscape relevant to this work. It examines key studies on power system stability, inverter control topologies, and the evolution of grid-support functions, situating this project within the broader field of power electronics and renewable energy integration.

Chapter 3: Theoretical Framework is dedicated to the analytical underpinnings of the study. It presents the theoretical principles and mathematical models for Grid-Forming (GFM) and Grid-Following (GFL) inverters, detailing concepts such as dq-frame transformations, droop control theory, and Phase-Locked Loop (PLL) synchronization.

Chapter 4: Methodology and Design details the practical implementation of the project. This chapter describes how the theoretical models from Chapter 3 were translated into a functional simulation environment using MATLAB/Simulink. It covers the specific design of the inverter plant, control circuits, and the setup for each test case.

Chapter 5: Results and Analysis presents and interprets the findings from the simulations. It provides a comparative analysis of the standalone performance of GFM and GFL inverters,

followed by a detailed evaluation of the enhanced stability and power quality achieved in the coordinated hybrid configuration.

Chapter 6: Conclusion and Future Work summarizes the main outcomes of the study. It confirms whether the research objectives were met, discusses the implications of the findings.

Chapter 2:

Literature Review

2.1 Introduction

The proliferation of inverter-based resources (IBRs) has fundamentally altered the landscape of power system operation and stability. This chapter provides a comprehensive review of the academic literature that charts this transition, moving from the foundational principles of synchronous machine-dominated grids to the advanced control strategies required for modern, renewable-rich power systems. The review will delve into the control architecture, operational principles, and inherent limitations of both Grid-Following (GFL) and Grid-Forming (GFM) inverters. The core differences, advantages, and limitations of these two primary inverter technologies, as established in the literature.

2.2 Literature Review on GFM and GFL Inverters

The integration of renewable energy into power systems has shifted the focus toward inverter-based resources, where stability depends heavily on advanced control methods. Grid-forming inverters are designed to establish the reference for voltage and frequency, while grid-following inverters depend on that reference to inject power. Coordinating these two types of inverters is therefore a key step toward achieving stable and flexible microgrid operation. The present project takes this context as its foundation, exploring how hybrid coordination of GFM and GFL inverters can practically solve the challenges that many researchers have identified. One study worked on synchronization strategies that allowed GFMs to reconnect seamlessly in islanded microgrids. The important part of this contribution was that the synchronization did not require any communication network, which means the inverter could operate independently and still achieve stability. This result showed that GFMs could be used in practical systems without additional communication overhead, which is crucial in weak and isolated grids. Another study carried out a detailed review of GFM control methods and emphasized their central role in ensuring reliable grid operation. By compiling different approaches and explaining their effect on power system support, this review confirmed that GFMs are not optional but rather necessary when building stable inverter-based

networks [1], [2]. Further investigations attempted to improve flexibility at the device level. One of them developed an integrated controller that allowed a single inverter to switch between GFM and GFL modes whenever needed. This approach provided adaptability since the inverter could function as the reference source or as a supporting unit depending on system requirements. Another related work focused on designing a GFM controller that mimicked the dynamic behavior of synchronous generators. The main achievement of this design was that it could provide the same kind of stability response traditionally expected from large rotating machines, but using only power electronics. These works showed that it is technically possible to merge both roles in one inverter, but they approached the challenge from a control-design perspective rather than from the system-coordination angle that the present project emphasizes [3], [4]. Reviews and modeling studies provided further insight into the limitations of existing strategies. A comprehensive survey of GFM inverters identified several challenges, such as resonance issues and converter-driven instabilities, which remain unsolved in many cases. This shows that GFM control is powerful but still vulnerable in certain operating conditions. Alongside this, another study built and validated large-scale models for both GFM and GFL inverters. By simulating their interaction in distribution systems, the research demonstrated that GFM inverters clearly enhance transient stability during disturbances, while GFL inverters alone fail to provide the same level of support. These studies together highlight that GFMs are indispensable but not sufficient to cover every aspect of grid stability, which is why hybrid operation has become an attractive solution [5], [6]. Some researchers explored unification strategies that allowed a single inverter to perform both functions. In one such study, a unified control framework was developed so that the inverter could operate seamlessly in either GFM or GFL mode without external intervention. This demonstrated that flexibility can be achieved at the controller level. Another research contribution showed that GFM control plays an important role in frequency stability and that it can even provide synthetic inertia to low-inertia grids, effectively compensating for the absence of synchronous machines. Both works reveal the importance of blending roles and show the potential of hybrid control concepts, while the current project contributes by validating the same principle through coordination of separate GFMs and GFLs rather than redesigning a single device [7], [8]. Other studies addressed resiliency under uncertain and faulted conditions. One contribution introduced robust μ -synthesis controllers that improved the ability of inverters to maintain stability despite variations and unpredictable disturbances. Another work focused on system resiliency by suggesting that GFL

inverters should be able to temporarily take over the role of GFMs in the event of a failure. This strategy allowed the system to remain operational even when a GFM unit was lost, ensuring higher reliability. These approaches show how advanced designs can strengthen inverter networks, while the present project builds the foundation by demonstrating that even simple coordination of GFM and GFL inverters already leads to substantial improvements in voltage and stability [9], [10]. Experimental and comparative studies also provide important insights. One experimental validation proved that GFMs perform much better than GFLs when it comes to stability, clearly showing their superiority in maintaining system operation. However, further comparative studies examined both inverter types under disturbance conditions and revealed that their strengths are complementary rather than identical. GFMs provided stability but struggled with power-sharing flexibility, while GFLs could share power efficiently but lost stability in weak grids. These results directly support the idea behind the present project, since they show that neither inverter type alone is sufficient, but their combination can overcome the weaknesses observed in practice [11], [13]. Finally, state-of-the-art reviews and experimental validations confirmed these conclusions on a broader scale. One comprehensive review summarized the key challenges still faced by GFMs, pointing out that more work is needed for their full integration in microgrids. Another study used hardware-in-the-loop experiments to test the performance of both GFM and GFL inverters under realistic low-inertia conditions, showing the real-world effectiveness of GFM operation. A further mathematical analysis investigated hybrid GFM+GFL operation and demonstrated its small-signal stability. These contributions strongly align with the present project, which extends their insights by showing through simulation that coordinated operation of GFM and GFL inverters provides a practical pathway toward stability, reliability, and flexibility [14], [16].

Table 2.1: Comparative Analysis of GFL and GFM Inverter Technologies Based on Literature

Feature	Grid-Following (GFL) Inverter	Grid-Forming (GFM) Inverter
Control Philosophy	Current Source [6]: Injects a specified current waveform into an existing grid using PLL-based	Voltage Source [11]: Establishes its own voltage waveform, defining grid frequency and amplitude through droop

	current control.	or VSM control.
Synchronization	PLL-Dependent [6]: Requires a Phase-Locked Loop (PLL) to track the external grid voltage angle.	Self-Synchronized [1], [10]: Uses internal oscillators or synchronous machine emulation; no PLL required.
Stability Role	Grid Follower [6], [8]: Contributes to instability in weak or low-inertia grids due to PLL dynamics.	Grid Leader [11], [15]: Provides foundational stability, synthetic inertia, and system strength in both weak and islanded grids.
Key Advantage	High efficiency and simplicity for bulk power injection into strong grids [6], [12].	Ability to operate in islanded mode, provide black-start capability, and stabilize weak grids [1], [9].
Primary Limitation	Cannot operate without a grid reference; vulnerable to instability in weak grids [6].	More complex control and potential power-sharing inaccuracies with simple droop-based strategies [9], [16].

2.3 Research Gap and Conclusion

The literature clearly charts a path from inertia-rich, synchronous machine-based grids to inverter-dominated, low-inertia systems. It establishes the limitations of GFL inverters and presents GFM technology as a critical solution for providing stability. The most current research overwhelmingly points towards hybrid GFM-GFL systems as the optimal architecture for future power grids. While the qualitative benefits of hybrid systems are well-established, there remains a need for clear, comparative analyses that parametrically evaluate the performance of standalone versus hybrid configurations under identical conditions. This project aims to fill that gap by providing a direct, simulation-based comparison, thereby offering quantitative evidence of the hybrid model's superiority.

Chapter 3:

Theoretical Framework

3.1 Introduction

The ongoing global transition towards renewable energy sources such as solar photovoltaic (PV) and wind power has brought about a profound transformation in the architecture and operational dynamics of modern power systems. For more than a century, conventional power grids were predominantly anchored by large-scale, centralized synchronous generators driven by steam turbines, gas turbines, or hydro units. These generators not only supplied bulk electrical energy but also played an indispensable role in ensuring system stability. Their rotating masses provided a natural buffer against sudden fluctuations in power balance through the phenomenon of inertia, which resists abrupt changes in frequency and allows sufficient response time for governors and other control mechanisms to act. This electromechanical inertia has historically been the cornerstone of grid reliability and resilience. However, as the share of renewable energy continues to grow, the dominance of these synchronous machines has gradually diminished. In their place, Inverter-Based Resources (IBRs) have emerged as the primary interface between renewable generation units and the alternating current (AC) grid. Unlike synchronous machines, inverters are entirely electronic devices with no moving parts. Their dynamic response and interaction with the grid are not determined by physical inertia but rather by embedded control algorithms and programmed operational strategies. While this feature provides remarkable flexibility and adaptability, it simultaneously introduces new challenges. The lack of natural inertia makes modern grids more vulnerable to rapid frequency deviations, voltage instabilities, and reduced fault-ride-through capability. Ensuring system reliability in this new paradigm therefore requires innovative inverter control strategies that can mimic or even surpass the stabilizing functions once provided by synchronous generators.

Against this backdrop, two principal classes of inverters have been developed to address these evolving needs: Grid-Forming (GFM) and Grid-Following (GFL) inverters. These two technologies embody fundamentally different operational philosophies. A Grid-Forming inverter is designed to establish and regulate the voltage and frequency at its point of connection, essentially

behaving like a voltage source. By emulating the behavior of a synchronous generator, GFM inverters can provide synthetic inertia, support system stability, and serve as reference units in weak or islanded networks. Conversely, Grid-Following inverters operate as controlled current sources. They synchronize to an already established grid voltage and frequency using a Phase-Locked Loop (PLL) and inject power accordingly. Their role is highly effective in delivering large amounts of renewable power under strong grid conditions, but they rely on an external voltage reference and therefore cannot independently sustain grid operation.

This distinction highlights the complementary nature of GFM and GFL inverters. While GFMs provide stability, reference signals, and synthetic inertia, GFLs contribute efficiency, scalability, and high penetration of renewable energy into robust grid environments. Recognizing this synergy, researchers and industry practitioners are increasingly exploring hybrid systems, in which both inverter types are deliberately combined at a common point of connection. In such configurations, Grid-Forming inverters establish the necessary grid conditions, while Grid-Following inverters efficiently inject renewable power by aligning themselves with those conditions. This hybrid operation has the potential to create more resilient and flexible power systems, capable of accommodating higher shares of renewable energy while preserving stability and power quality.

3.2 The Core Philosophy: Leaders vs. Followers

The most fundamental distinction between Grid-Forming (GFM) and Grid-Following (GFL) inverters lies in their underlying control philosophy, which can be aptly summarized through the analogy of a Leader and a Follower. This conceptual difference not only defines their individual behavior but also explains their complementary roles in modern power systems dominated by renewable energy integration.

A Grid-Forming (GFM) inverter operates as the Leader within the network. Its primary task is to establish and regulate the fundamental “electrical rules” of the system. Much like a traditional synchronous generator, the GFM inverter autonomously generates the voltage waveform, defines the phase angle, and sets the system frequency (typically 50 Hz or 60 Hz depending on regional standards). Importantly, it performs these functions independently, without relying on any external reference to synchronize its operation. This independence allows the GFM inverter to function as

a controlled voltage source. In this mode, it imposes a stable voltage at its terminals and allows the current to naturally adjust in response to the load demand. By taking on the responsibility of establishing voltage and frequency, GFM inverters essentially “form” the grid, providing the reference framework that other devices must follow. The ability to self-regulate makes GFM inverters particularly indispensable in scenarios where no pre-existing grid exists or where grid conditions are too weak to provide reliable references. For example, in remote microgrids or islanded systems where access to a strong utility grid is unavailable, GFMs can single-handedly create a stable local grid. Similarly, during black-start operations, when the main grid is completely de-energized, GFM inverters can initiate system restoration by supplying both voltage and frequency references. Even in weak-grid conditions, where long transmission distances or insufficient synchronous machine support result in poor stability, the robustness of GFM inverters makes them essential for ensuring proper operation. Thus, their role as Leaders extends beyond simple power conversion—they serve as the backbone of stability and resilience in non-ideal grid environments.

In contrast, a Grid-Following (GFL) inverter plays the role of the Follower. Unlike GFMs, GFLs cannot establish an electrical grid on their own. Their operation fundamentally depends on the existence of a strong, stable reference provided either by a utility grid or by a GFM inverter acting as a Leader. To function, a GFL inverter employs synchronization mechanisms, typically through a Phase-Locked Loop (PLL), to lock onto the grid’s voltage waveform. Once synchronized, the GFL operates as a controlled current source, adjusting its output current in such a way that it injects precisely the desired amounts of active and reactive power into the system. In doing so, it ensures that its current remains perfectly aligned with the grid’s voltage waveform, maintaining power quality and avoiding instability. This follower role makes GFL inverters highly suitable for applications in large-scale renewable energy plants, such as utility-scale solar farms or wind parks. In these environments, the grid is typically strong enough to provide the necessary voltage and frequency references, allowing GFL inverters to focus exclusively on efficient and reliable power injection. Their comparatively simpler control structures and optimized current control strategies enable them to achieve high levels of efficiency, scalability, and cost-effectiveness. As a result, GFL inverters are widely deployed in bulk power generation, where their ability to “follow” an already established grid reference is sufficient and desirable.

3.3 Structure of The Grid-Forming (GFM) Inverter

A Grid-Forming (GFM) inverter's ability to act as a Leader does not arise from its hardware alone, since in terms of physical components it is almost indistinguishable from a conventional inverter. Like other inverter types, a GFM unit is built upon a DC energy source (such as a solar PV array, a battery, or a DC link capacitor), a power electronic bridge (commonly an H-bridge composed of insulated gate bipolar transistors (IGBTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs)), and an output filter that ensures sinusoidal current injection into the AC network. These components form the backbone of nearly all inverter-based technologies. What sets the GFM inverter apart, however, is not its physical circuitry but its unique internal control architecture, which acts as its "brain."

Unlike Grid-Following inverters, whose controls are designed to track an external grid reference, the GFM inverter is designed to autonomously synthesize its own voltage and frequency references. At the heart of this architecture is a voltage-source control philosophy, in which the inverter imposes its terminal voltage waveform and allows system currents to naturally follow in accordance with network conditions and load demands. This is achieved through advanced inner-loop controllers, typically regulating output voltage magnitude and frequency, and outer-loop controllers, which implement higher-level strategies such as power sharing, virtual inertia emulation, and grid support functionalities.

A key innovation in GFM control lies in the use of Virtual Synchronous Machine (VSM) concepts, droop control methods, or virtual oscillator control (VOC) strategies. These approaches enable the inverter to replicate the dynamic characteristics of synchronous generators, effectively embedding synthetic inertia and damping into the power electronic system. By doing so, GFM inverters can provide stabilizing responses to frequency and voltage disturbances, thereby fulfilling the stabilizing functions that synchronous machines once naturally supplied.

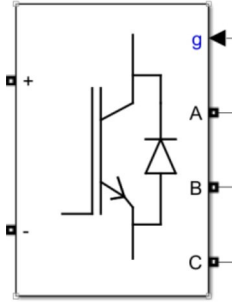


Figure 3.1: Universal Bridge

The internal operation of a Grid-Forming (GFM) inverter begins with what can be considered its “electrical heartbeat”: the Internal Frequency and Angle Generator. This block functions as the inverter’s internal clock. Unlike Grid-Following (GFL) inverters, which employ a Phase-Locked Loop (PLL) to synchronize with an external grid frequency, the GFM inverter does not depend on any external signal. Instead, it autonomously generates a stable frequency reference—commonly set at 50 Hz or 60 Hz depending on the system requirements. This frequency signal is then continuously integrated to produce a rotating angle, which acts as the foundational reference frame for all subsequent control actions. It is this self-generated angle that empowers the GFM inverter to operate independently of an external grid, thereby enabling its grid-forming capability. Once the reference angle is established, the next step is to accurately regulate the inverter’s output voltage and current. For this purpose, the inverter continuously measures the three-phase voltages and currents at its terminals. These raw signals, however, are expressed in the abc stationary frame, which makes direct control difficult due to the sinusoidal time-varying nature of AC waveforms. To simplify the control problem, these signals are processed using a mathematical transformation known as the dq-Transformation (Park’s Transformation). The dq-Transformation converts the three-phase time-domain signals from the abc reference frame into a rotating reference frame that is aligned with the inverter’s internally generated angle. In this transformed domain, the AC variables are represented as quasi-DC quantities: the d-axis component typically corresponds to active power (real power) control, while the q-axis component corresponds to reactive power (voltage support) control. This transformation greatly simplifies the design of controllers, since regulating DC-like quantities is far more straightforward than handling sinusoidal waveforms. By combining the internally generated frequency-angle reference with the dq-domain representation of measured signals, the GFM inverter achieves autonomous voltage and frequency regulation.

The internal controller then applies strategies such as droop control or virtual synchronous machine emulation to dynamically adjust its output in response to changes in load demand or disturbances. Through this mechanism, the inverter not only sustains its independent operation but also contributes essential services such as voltage support, frequency stability, and power-sharing in multi-inverter systems.

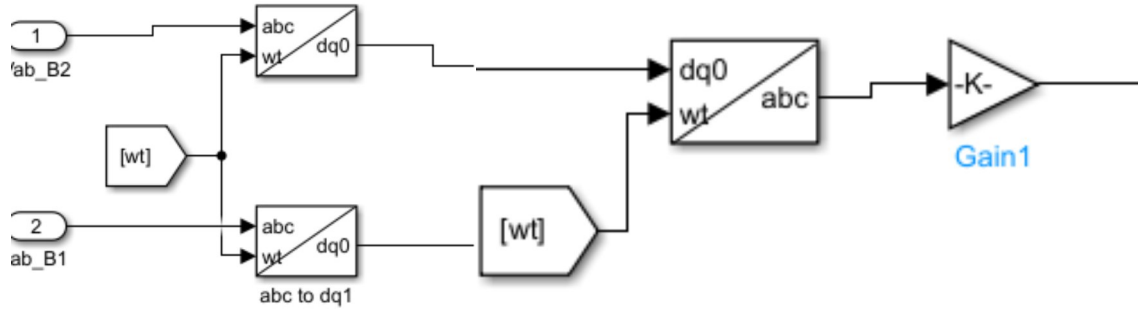


Figure 3.2: ABC to DQ control Frame

The control action of a Grid-Forming (GFM) inverter is implemented through a Cascaded Control Loop structure, carefully designed to ensure both stability and dynamic performance under a wide range of operating conditions. This layered control hierarchy separates the slow-acting outer loops from the fast-acting inner loops, allowing the system to respond effectively to disturbances while maintaining robust regulation of voltage and current. At the highest level of this structure lies the Voltage Control Loop, which functions as the outer loop. Its primary responsibility is to regulate the inverter's terminal voltage to a desired reference value. In practice, the three-phase terminal voltages are first measured and transformed into the dq rotating reference frame, which is synchronized with the inverter's internally generated angle. In this transformed domain, the d-axis voltage component directly represents the magnitude of the output voltage, while the q-axis component can be associated with reactive power exchange. The voltage controller continuously compares the measured d-axis voltage against a specified reference setpoint. Any deviation between the actual and reference values constitutes a voltage error, which is then processed by a Proportional-Integral (PI) controller. The PI controller plays a crucial role here: the proportional

term ensures a fast corrective action to counter sudden deviations, while the integral term eliminates steady-state error, ensuring that the inverter maintains its desired voltage level over time.

The output of this voltage controller is not a direct control signal to the switching devices but rather a reference current command. In other words, the voltage loop determines how much current the inverter must deliver (or absorb) in order to correct the detected voltage deviation. This reference current—defined separately for the d- and q-axis components—then serves as the command input for the inner Current Control Loop.

This cascaded arrangement ensures a clear separation of control objectives:

- The outer loop (voltage controller) guarantees that the inverter sustains the required voltage magnitude, thereby upholding its grid-forming role.
- The inner loop (current controller), which operates at a much faster bandwidth, ensures that the commanded current values are accurately tracked, providing both stability and rapid disturbance rejection.

By delegating the slower voltage regulation to the outer loop and the faster current regulation to the inner loop, the cascaded control system balances stability with responsiveness. This design is particularly effective under transient events, such as sudden load changes or grid disturbances, where the outer loop ensures long-term voltage stability while the inner loop provides immediate corrective action to maintain current tracking accuracy.

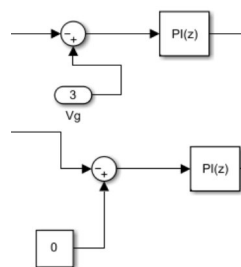


Figure 3.3 : Voltage Control Loop

Beneath the outer voltage regulation layer, the Inner Current Control Loop forms the fast-acting core of the cascaded control architecture. Its primary objective is to ensure that the inverter's output currents precisely follow the reference commands generated by the voltage loop. Because current dynamics are inherently faster than voltage dynamics, this loop is designed with a higher control bandwidth, allowing it to respond almost instantaneously to disturbances such as load variations or transient grid events. The process begins with the reference currents produced by the outer voltage controller, expressed in the dq rotating reference frame. These serve as the target values for the inner loop. At the same time, the inverter continuously measures its actual three-phase output currents at the terminals. Using the same dq-Transformation aligned with the internally generated reference angle, these currents are represented as i_d and i_q , which correspond respectively to active and reactive power control variables.

The controller then computes the current error by comparing the reference currents with the actual measured currents. This error is fed into a set of Proportional-Integral (PI) controllers, one for each axis. The PI controllers act rapidly to minimize this error:

- The proportional term ensures immediate corrective action to counter deviations.
- The integral term eliminates steady-state tracking errors, ensuring long-term accuracy in current regulation.

The outputs of these PI controllers are not currents themselves, but rather voltage command signals. These voltage references represent the required terminal voltages that the inverter must synthesize in order to force the output currents to match their desired values. In effect, the inner loop dictates the “driving voltage” needed to achieve precise current tracking. This voltage command is then transformed back from the dq-frame to the three-phase abc reference frame, producing sinusoidal reference waveforms. Finally, these reference voltages are fed into the Pulse Width Modulation (PWM) generator, which converts them into high-frequency switching signals for the inverter's semiconductor devices. Through this sequence, the inner loop ensures that the inverter's physical hardware operates in strict alignment with the control objectives defined by the cascaded structure. By virtue of its high responsiveness, the inner current loop plays a crucial stabilizing role. It ensures that the inverter can quickly adapt to sudden load changes, reject disturbances, and maintain robust current tracking even under weak grid conditions. This not only

prevents instability but also protects the inverter and connected loads from excessive stresses. The combination of a slower but steady outer voltage loop with a fast-reacting inner current loop therefore enables the GFM inverter to reliably establish and sustain voltage and frequency references while dynamically regulating current flow in real time.

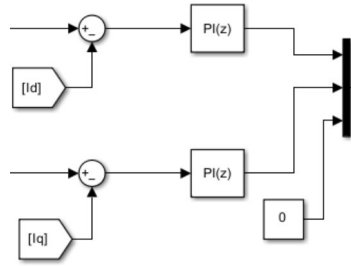


Figure 3.4: Current Control Loop

These voltage commands, now in the dq-frame, are then converted back into three-phase AC voltage signals using an Inverse dq-Transformation, using the same internal angle for consistency. These clean sinusoidal reference signals are then fed to a Pulse Width Modulation (PWM) block.

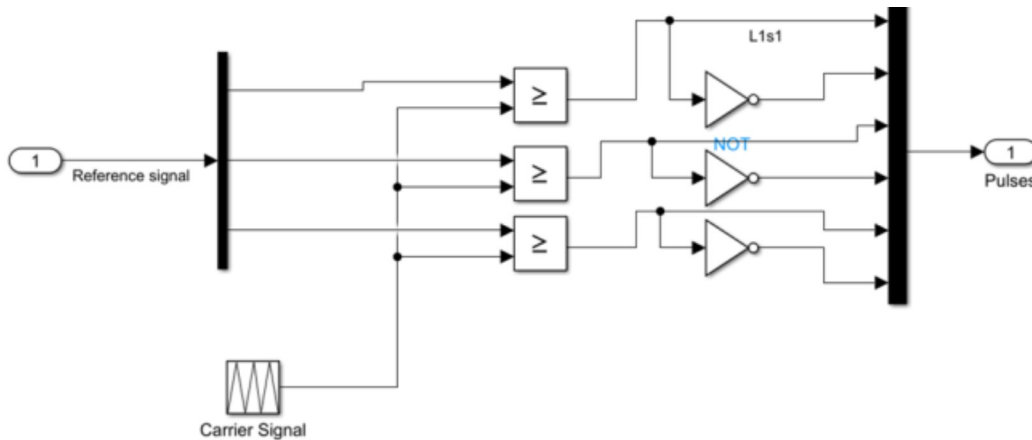


Figure 3.5: Pulse Width Modulation (PWM)

Once the inner current control loop has generated the required voltage references in the three-phase abc frame, the next step is to physically implement these voltages through the inverter hardware. This task is carried out by the Pulse Width Modulation (PWM) generation and switching

stage, which translates the reference signals into discrete ON/OFF commands for the inverter's semiconductor devices.

The principle of operation relies on the comparison between the sinusoidal reference waveforms (corresponding to the desired three-phase voltages) and a high-frequency triangular carrier signal. The sinusoidal references dictate the desired shape of the output waveform, while the triangular signal serves as the switching template. At each instant in time, whenever the sinusoidal reference exceeds the instantaneous value of the triangular carrier, the associated switch command is set to "ON." Conversely, when the sinusoidal reference falls below the carrier, the command is set to "OFF." This continuous comparison generates a sequence of high-frequency switching pulses, which control the power electronic bridge composed of IGBTs or MOSFETs.

The switching frequency, typically several kilohertz, is chosen to be much higher than the fundamental grid frequency (50 Hz or 60 Hz). As a result, the inverter output consists of a rapidly switching voltage waveform that oscillates between the DC-link voltage levels. Although this raw output resembles a staircase or pulsed signal rather than a pure sine wave, its time-averaged value closely tracks the desired sinusoidal reference. The accuracy of this approximation improves with higher switching frequencies, though practical limits are imposed by device efficiency and thermal constraints.

To further refine the waveform and ensure compliance with grid standards, the inverter output is passed through an LCL filter before reaching the point of common coupling (PCC). This filter, composed of inductors and capacitors, plays a dual role:

- It attenuates the high-frequency harmonics generated by the PWM switching process.
- It smooths the staircase-like voltage into a clean, continuous sinusoidal waveform.

The result is an output that meets both the stringent power quality requirements of modern grids and the operational needs of sensitive electrical loads. In effect, the LCL filter bridges the gap between the discrete, high-speed switching domain of the inverter and the continuous sinusoidal domain of the AC power system.

Through this final stage, the GFM inverter achieves its ultimate goal: the synthesis of a stable, high-quality sinusoidal voltage that conforms to grid standards while embodying the voltage magnitude, phase, and frequency dictated by its internal control system. When viewed in totality, the cascaded control loops, PWM modulation, and LCL filtering collectively enable the inverter to perform as a reliable grid-forming unit, capable of both supporting and stabilizing power systems under a wide range of operating conditions.

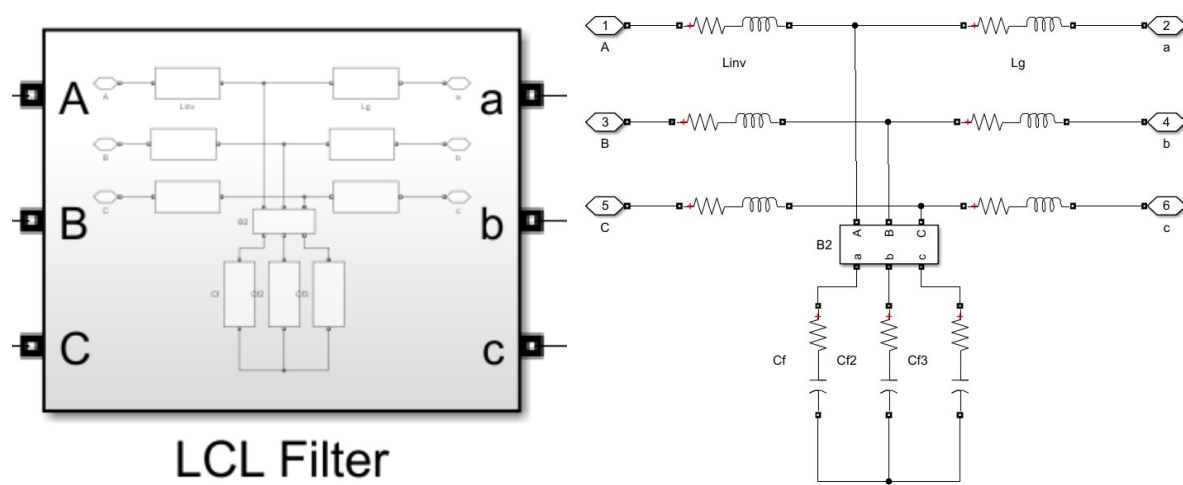


Figure 3.6: LCL Filter

A key advanced feature of many GFM inverters is the implementation of Droop Control. This algorithm allows multiple GFM inverters to share load without needing a direct communication link. It mimics the behavior of synchronous generators: if the active power demand increases, the inverter deliberately lowers its frequency slightly according to a predefined droop coefficient. Conversely, if the reactive power demand increases, it lowers the voltage magnitude. Other inverters on the same system see this change and respond by picking up more load, ensuring a fair and stable distribution. Some advanced GFMs also incorporate Virtual Inertia emulation, where their control algorithms are designed to temporarily absorb or release power to oppose rapid frequency changes, artificially replicating the inertia of a large rotating generator.

3.4 Structure of the Grid-Following (GFL) Controller

The GFL inverter's design is optimized for one primary goal: efficient and precise power injection into an existing grid. Its entire operation is contingent upon the presence of a stable voltage reference provided by a leader.

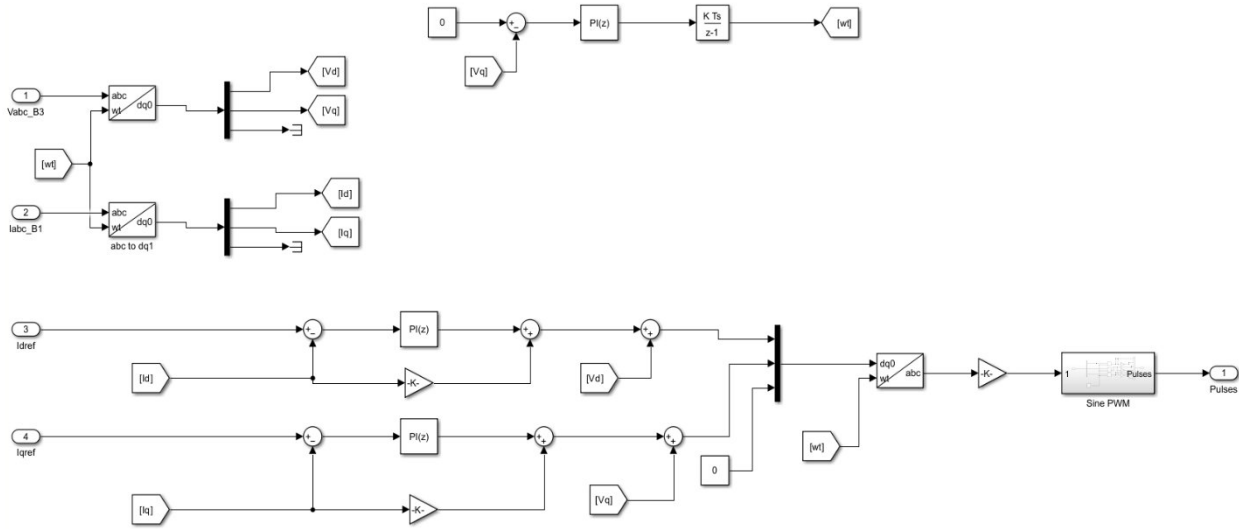


Figure 3.7: Grid Following Controller

At the heart of every Grid-Following (GFL) inverter lies the Phase-Locked Loop (PLL), which serves as its indispensable synchronization engine. Unlike Grid-Forming (GFM) inverters, which autonomously generate their own reference angle and frequency, the GFL inverter is entirely dependent on an externally existing grid signal. The PLL continuously measures the three-phase voltage at the point of common coupling (PCC), processing it through a sophisticated feedback algorithm to determine the instantaneous phase angle and frequency of the grid voltage. Once locked, the PLL provides a highly accurate and continuously updated angle reference, which becomes the cornerstone of all subsequent control actions. This synchronization mechanism enables the inverter to align its operation perfectly with the grid's waveform. However, this reliance also reveals the GFL inverter's most fundamental limitation: without a stable, pre-existing voltage waveform for the PLL to lock onto, the GFL inverter cannot function. In such scenarios—such as islanded operation or black-start conditions—the inverter is effectively “blind” and unable to contribute meaningfully to system operation. Having obtained a stable phase reference from the

PLL, the inverter employs the dq-Transformation to convert both the measured three-phase grid voltage and its own output current into the rotating reference frame aligned with the grid. In this dq-frame, the inverter is able to decompose its electrical variables into two orthogonal components: the d-axis component, which is aligned with the grid voltage and represents active power flow, and the q-axis component, which is orthogonal to the grid voltage and represents reactive power exchange. This transformation greatly simplifies control, as it decouples the management of active and reactive power into two independent channels. The control objective of the GFL inverter is straightforward yet critical: to inject precisely controlled amounts of active power (P) and reactive power (Q) into the grid. Typically, these power commands are issued by an external supervisory controller, such as a plant-level energy management system or a grid operator. Using the real-time grid voltage information, the inverter translates these power references into corresponding current references. Thus, rather than attempting to control voltage or frequency directly, the GFL inverter focuses entirely on shaping its output currents to achieve the desired power exchange. At the core of the GFL controller lies the dual current control loop, consisting of two independent loops—one for the d-axis and one for the q-axis. Each loop is implemented with a fast-acting Proportional-Integral (PI) controller, which continuously compares the reference current with the actual measured current in that axis. The PI controllers then calculate the voltage commands required to drive the error to zero. To further enhance performance, decoupling feedforward terms are incorporated. These compensate for the natural cross-coupling that exists between the d and q channels due to the grid's inductive reactance. By mathematically canceling these coupling terms, the controller ensures that active and reactive power control remain independent, improving both speed and accuracy of the response. The calculated voltage commands are then transformed back into the three-phase AC domain through the inverse dq-Transformation, once again using the PLL-provided angle as the reference. This produces sinusoidal voltage reference waveforms in the abc frame, which are subsequently fed into the PWM generation stage. Similar to the GFM inverter, the PWM module compares the sinusoidal references with a high-frequency triangular carrier wave to produce switching signals for the semiconductor devices of the inverter bridge. The raw PWM-switched output contains high-frequency harmonics, which must be filtered before being injected into the grid. For this purpose, an LCL filter is employed at the output stage. The filter attenuates the switching harmonics and smooths the waveform into a clean sinusoidal current. The final result is an output current that is

perfectly synchronized with the grid's voltage waveform, with precisely controlled magnitude and phase angle to deliver the requested active and reactive power.

In summary, the GFL inverter operates fundamentally as a controlled current source, injecting power seamlessly into a grid that is already established by a leader such as a synchronous generator or a GFM inverter. It does not regulate the grid voltage or frequency, but rather depends on an externally provided reference to synchronize its operation. This makes GFL inverters highly efficient and well-suited for large-scale renewable energy integration into strong grids. However, their inability to function independently underscores their complementary role to GFM inverters in future power systems, where a balance between grid-forming and grid-following resources is essential for stability and reliability.

3.5 The Hybrid Paradigm: Combining GFM inverter with GFL Controller

Individually, both inverter types have significant limitations. A GFM inverter can operate alone but may suffer from reduced power quality and increased stress under large or fluctuating loads, as it bears the entire burden of both forming the grid and supplying power. A GFL controller, while efficient, cannot operate at all without a reference and is prone to instability in weak grids.

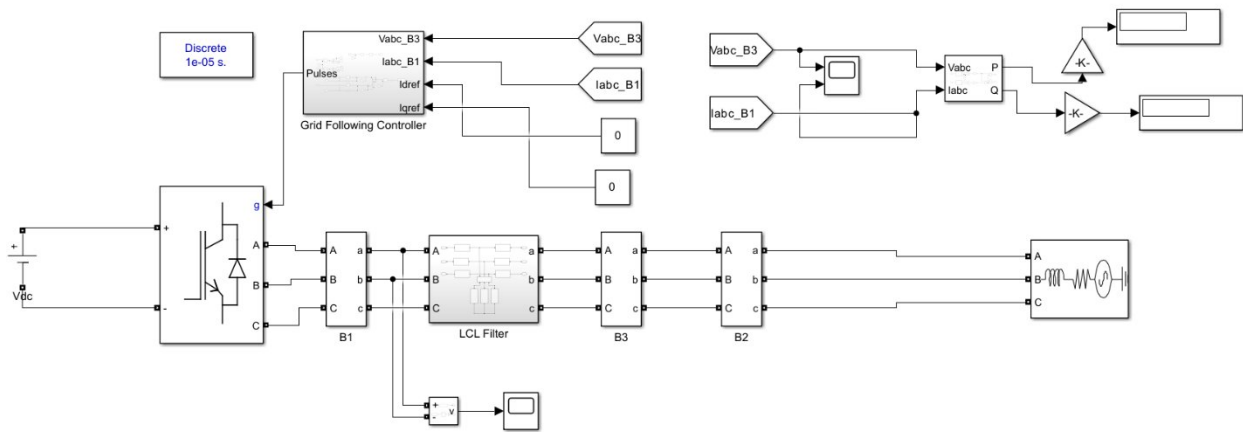


Figure 3.8: GFM inverter with GFL Controller

The hybrid inverter approach represents a strategic solution to the pressing challenges of modern power systems dominated by renewable generation. It combines the complementary strengths of

both Grid-Forming (GFM) and Grid-Following (GFL) inverters at a common interface known as the Point of Common Coupling (PCC). This architecture creates a system that is more robust, reliable, and efficient than one relying solely on either inverter type in isolation. At the PCC, the GFM inverter assumes the role of the leader. It is tasked with establishing and maintaining a stable grid reference, much like a synchronous generator would in traditional power systems. By autonomously generating a high-quality voltage waveform, the GFM inverter defines the system's frequency, voltage magnitude, and phase angle. This capability allows it to serve as the backbone of the hybrid configuration, ensuring that the PCC maintains grid-like characteristics even in the absence of a strong utility connection or under weak grid conditions. The GFL inverter, in contrast, functions as the follower. It relies on the clean sinusoidal voltage waveform generated by the GFM inverter. Through its Phase-Locked Loop (PLL), the GFL controller continuously detects and synchronizes to this reference, aligning its internal signals perfectly with the GFM-established grid. Once synchronized, the GFL inverter's primary function is to inject controlled active and reactive power according to external setpoints provided by higher-level controllers. In essence, it does not dictate system behavior but instead optimizes power delivery, ensuring that renewable energy resources feed into the system efficiently and reliably.

This division of labor between the two inverter types produces several transformative benefits for the stability and performance of inverter-dominated power systems:

- The GFM inverter focuses on maintaining a clean, stable sinusoidal voltage, while the GFL inverter complements it by delivering precisely controlled currents. Since the GFM is not overloaded with the entire task of power supply, it can sustain high-quality voltage regulation, reducing harmonic distortion and ensuring compliance with grid codes.
- Frequency regulation is a core service provided by GFM inverters via their droop control mechanisms. In a hybrid setup, frequency deviations are minimized because the GFM only needs to balance transient changes in load rather than the entire steady-state demand. The steady, continuous injection of power from GFL inverters further supports the frequency profile, ensuring smoother recovery after disturbances such as load fluctuations or renewable intermittency.

- The hybrid approach allows the system to allocate tasks intelligently. The GFM inverter responds quickly to transients and provides grid-supporting services (inertia, voltage regulation, frequency control), while the GFL inverter contributes the bulk of steady-state power. This complementary interaction ensures both operational efficiency and system reliability.
- One of the most compelling aspects of the hybrid model is its economic and technical feasibility. In large-scale renewable plants, it is neither cost-effective nor necessary to make every inverter grid-forming. Studies suggest that equipping 10–20% of inverters with GFM capability is sufficient to stabilize the network, while the majority can be simpler, cost-effective GFL units. This makes the hybrid configuration highly scalable and practical for real-world deployment.

By merging the grid-stabilizing capability of GFM inverters with the power delivery efficiency of GFL inverters, the hybrid architecture embodies the best of both worlds. It effectively bridges the gap between the inertia-rich stability of conventional synchronous machines and the renewable-driven flexibility of inverter-based resources. Thus, the hybrid GFM–GFL system is not merely a transitional solution but a blueprint for the future of inverter-dominated power systems, ensuring resilience, stability, and efficiency in the face of growing renewable integration.

3.6 Conclusion

This chapter has outlined the core principles that govern the operation of modern grid-tied inverters. The Grid-Forming inverter emerges as an autonomous voltage source, essential for creating and stabilizing electrical networks, especially in isolated or weak grid scenarios. The Grid-Following inverter excels as a precision current source, designed for optimal power injection into strong, existing grids. Understanding this leader-follower dynamic is crucial. The hybrid control strategy, which leverages the strengths of both philosophies, presents a robust and practical solution for ensuring the stability, power quality, and reliability of the future renewable-rich power grid. The following chapters will use detailed simulation models based on these very principles to quantitatively validate these theoretical concepts.

Chapter 4:

Methodology

4.1 Introduction

The methodology adopted in this research was carefully designed to provide a step-by-step framework for modeling, validating, and analyzing inverter control strategies. The primary objective was to study how grid-forming inverters operate individually and then evaluate the impact of integrating a grid-following controller into the system to form a hybrid configuration. The chapter begins with the development of the grid-forming inverter model, followed by its validation under simple test conditions. Once validated, a grid-following controller was introduced and merged with the grid-forming inverter, creating a hybrid system capable of combining voltage and frequency control with active and reactive power injection.

The overall workflow of the research is illustrated in Figure 4.1, which summarizes the stages followed: from system modeling and validation, to controller design, hybrid integration, and finally simulation analysis. This figure serves as a visual guide for the methodology discussed in the subsequent sections.

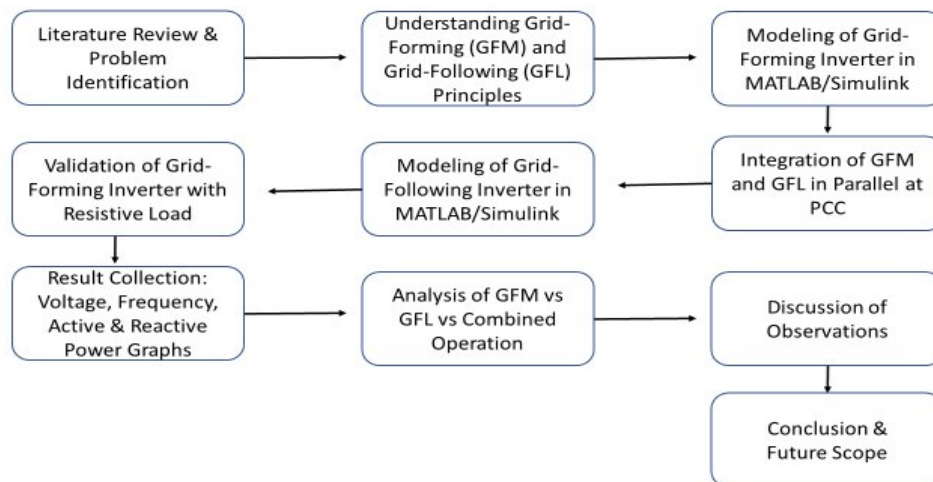


Figure 4.1: Workflow diagram

4.2 Development of the Grid-Forming Inverter

The first step in the methodology was the design of a grid-forming inverter model. A DC voltage source was connected to a universal IGBT-based bridge inverter, and the output was filtered through an LCL filter to reduce harmonics and produce a smooth sinusoidal waveform. The control system for the inverter was structured in two loops: an inner current loop and an outer voltage loop. The voltage loop ensured that the inverter maintained a steady reference voltage at the point of common coupling, while the current loop provided fast dynamic response and protection against sudden transients.

To emulate the behavior of synchronous generators, droop control equations were implemented. These equations linked the active power output to frequency and the reactive power output to voltage magnitude. By doing so, the inverter could naturally adjust its output in response to changes in load, forming the grid in a stable and autonomous manner. This design allowed the inverter to establish both frequency and voltage references without relying on any external signal.

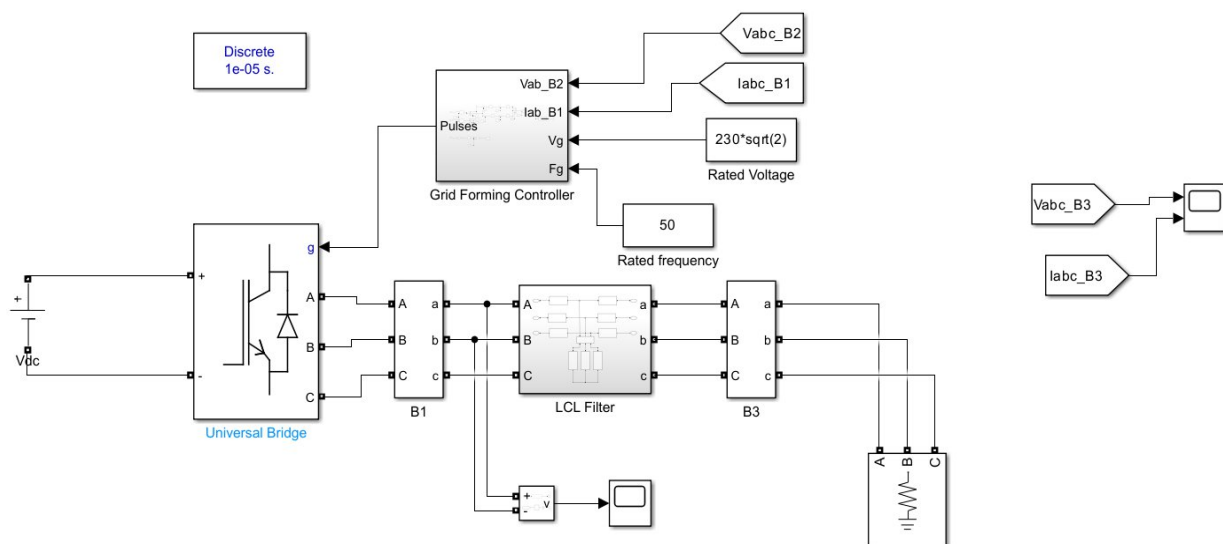


Figure 4.2: Simulink model of the grid-forming inverter

4.3 Validation of the Grid-Forming Inverter

Once the grid-forming inverter was designed, it was tested under a resistive load to validate its operation. The validation was essential to confirm that the inverter could form a stable grid independently. During this stage, the inverter's ability to maintain voltage and frequency within acceptable limits was observed. The results demonstrated that the grid-forming inverter successfully established a stable operating point, showing reliable performance under the given test conditions.

This validation step was critical in ensuring that the grid-forming inverter could serve as the reference unit in the later hybrid configuration.

4.4 Integration of the Grid-Following Controller

After the successful validation of the grid-forming inverter, a grid-following controller was designed and merged with the existing inverter model. The addition of this controller marked the transition from standalone grid-forming operation to a hybrid grid-forming and grid-following configuration.

The grid-following controller was designed to synchronize with the voltage established by the grid-forming inverter and inject controlled amounts of active and reactive power into the system. This was achieved through dq-axis control, where the d-axis current regulated active power and the q-axis current regulated reactive power. I_{d_ref} and I_{q_ref} reference values were used to set the desired power injections, while the actual inverter output currents were continuously measured and controlled to track these references.

The hybrid system therefore combined the stabilizing qualities of the grid-forming inverter with the precision and flexibility of the grid-following controller. This allowed the system to respond effectively to load changes while maintaining high power quality and stability at the PCC.

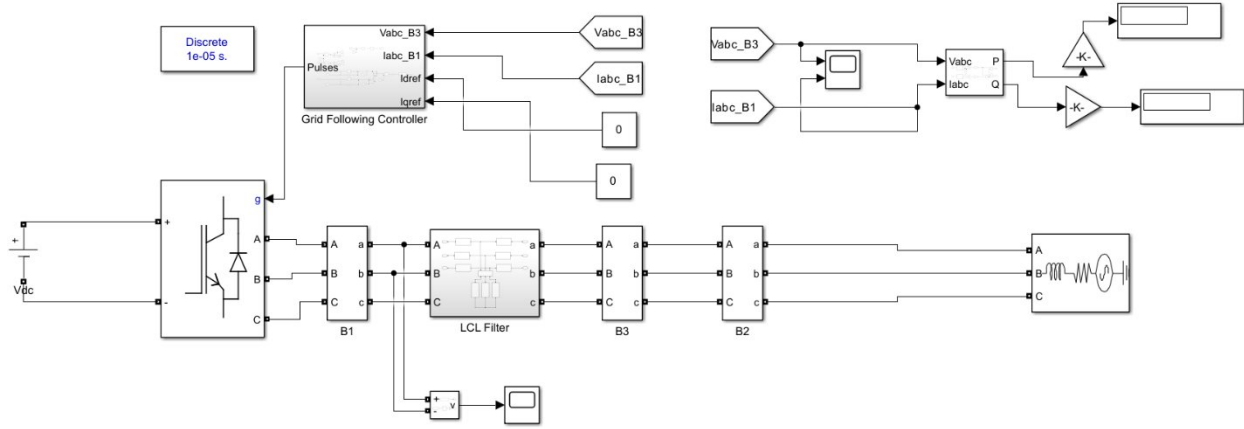


Figure 4.3: Simulink model of the hybrid inverter system

4.5 Simulation Test Cases

To systematically evaluate the hybrid inverter system, a series of simulation test cases were defined. These test cases provided a structured way to analyze how the system behaved under different operating conditions, particularly in response to variations in I_{d_ref} and I_{q_ref} . Each test case was designed to highlight specific performance aspects, such as voltage stability, frequency response, harmonic distortion, and power-sharing capability.

Table 4.1: Simulation Test Cases

Case No.	Configuration	Reference Settings	Disturbance Applied	Inputs Recorded
Case 1	GFM only	D r o o p - b a s e d frequency and voltage control	Step change in load	PCC voltage, current, active and reactive power
Case 2.1	Hybrid (GFM + GFL)	$I_{d_ref} = 0$, $I_{q_ref} = 0$	Step change in load	PCC voltage and frequency, power graphs, THD
Case 2.2	Hybrid (GFM + GFL)	$I_{d_ref} = -100$ A, $I_{q_ref} = 40$ A	Step change in load	PCC voltage and frequency, active and

				reactive power sharing
Case 2.3	Hybrid (GFM + GFL)	$I_{d_ref} = +100 \text{ A}$, $I_{q_ref} = 0$	Step change in load	PCC voltage, frequency, harmonic spectrum, load sharing

4.6 Result Inputs for Analysis

During the execution of each test case, several critical inputs were recorded. These inputs were not analyzed in this chapter but were preserved for detailed discussion in the results and analysis chapter. The recorded inputs included waveforms, power values, and frequency data that directly reflect system performance.

Input Variable	Purpose of Measurement
PCC Voltage Waveform	To analyze waveform quality and measure THD
Frequency Deviation	To study stability, overshoot, and settling time
Active Power (P)	To evaluate power injection and sharing dynamics
Reactive Power (Q)	To examine voltage support capability
Id/Iq Tracking	To check accuracy of GFL controller response
Harmonic Spectrum	To evaluate distortion and harmonic content

4.7 Summary of Methodology

In summary, the methodology followed a clear progression: first, the grid-forming inverter was designed and validated as a standalone system; second, a grid-following controller was developed and merged with the grid-forming inverter to form a hybrid system; third, a series of test cases were defined to evaluate hybrid operation under different power reference conditions; and finally, the key inputs were recorded for later analysis. Figures and tables placed throughout this chapter provide a comprehensive description of the modeling process, hybrid integration, and simulation framework.

This structured approach ensured that the study not only established the capabilities of grid-forming inverters but also demonstrated the advantages of hybrid operation when coordinated control strategies were applied. The next chapter builds on this methodology by presenting the recorded results, analyzing the system's performance across test cases, and interpreting the findings in light of the research objectives.

Chapter 5:

Result and Analysis

The performance of the proposed inverter system was evaluated in two stages. First, the Grid-Forming (GFM) inverter was simulated in isolation to assess its standalone capability in establishing voltage and frequency at the Point of Common Coupling (PCC). Following this, the Grid-Following (GFL) controller was integrated with the GFM inverter, forming a hybrid system in which both inverters operated in coordination. This hybrid arrangement was further tested under three distinct scenarios defined by different reference current settings (I_{dref} and I_{qref}). The following sections present a comprehensive analysis of these cases, supported by corresponding graphs and simulation outputs.

5.1 Result of Case 1: Standalone GFM Inverter

In the standalone case, the GFM inverter assumed full responsibility for both generating a sinusoidal voltage waveform and regulating frequency. The voltage waveform observed at the PCC demonstrated that the inverter was capable of forming the grid independently. The signal was largely sinusoidal, validating the effectiveness of the GFM's cascaded voltage and current control loops. However, closer inspection revealed distortions and harmonic ripples superimposed on the sinusoidal envelope. These imperfections can be attributed to two primary factors: the switching ripple from the Pulse Width Modulation (PWM) process and the control burden placed on the GFM, which was forced to handle all active and reactive power requirements without parallel support.

The frequency response confirmed the theoretical behavior of droop control. For most of the simulation period, the inverter maintained a frequency close to 50 Hz. Nevertheless, when subjected to load changes, the system exhibited small oscillations and slow recovery, underscoring the absence of physical inertia that synchronous machines traditionally provide. Similarly, the active and reactive power graphs demonstrated that the GFM adjusted its power outputs effectively, yet the entire burden of both P and Q fell upon this single inverter, resulting in stress on its control loops.

Overall, this case highlights the indispensable capability of a GFM inverter: it can indeed form a grid autonomously. Yet, the waveform distortions, harmonic presence, and slower transient recovery emphasize its limitations when operating alone. This case serves as the baseline for comparison with hybrid configurations.

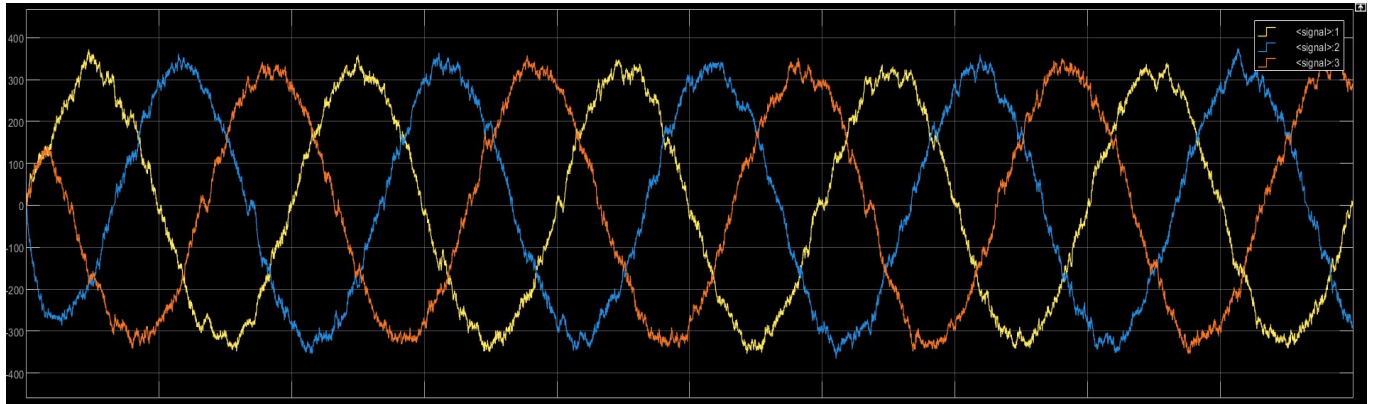


Figure 5.1 : Voltage Graph of GFM

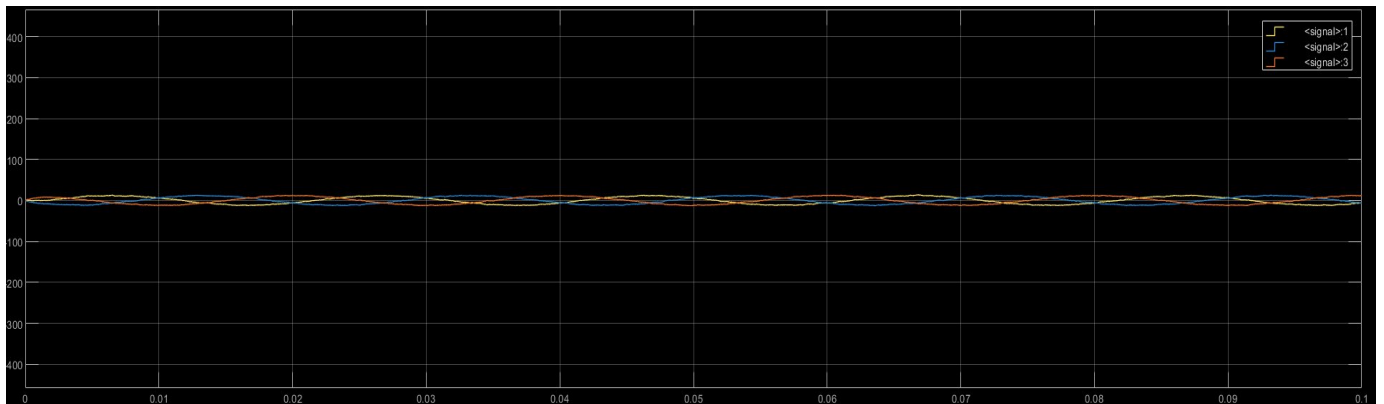


Figure 5.2 : Current Graph of GFM

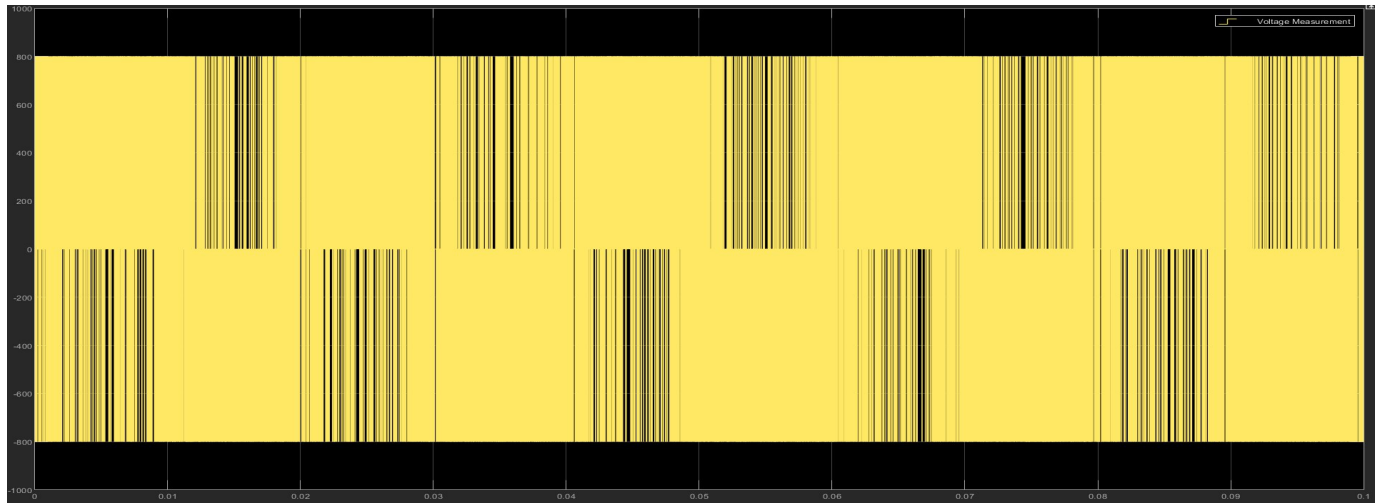


Figure 5.3: Terminal Voltage of GFM

5.2 Result of Case 2: Hybrid GFM + GFL System

When the Grid-Following controller was merged with the Grid-Forming inverter, the results improved significantly. In this configuration, the GFM inverter continued to provide the voltage and frequency reference, while the GFL inverter synchronized itself to this reference via its Phase-Locked Loop (PLL) and injected controlled amounts of active and reactive power into the system.

The combined operation resulted in a much smoother voltage waveform at the PCC, with notable reductions in Total Harmonic Distortion (THD). Frequency deviations were quickly corrected, with oscillations damped more efficiently compared to the GFM-only case. Moreover, the sharing of active and reactive power between the two inverters reduced the stress on the GFM, thereby improving overall system stability. This hybrid arrangement proved to be the most practical and efficient strategy for modern renewable-dominated grids.

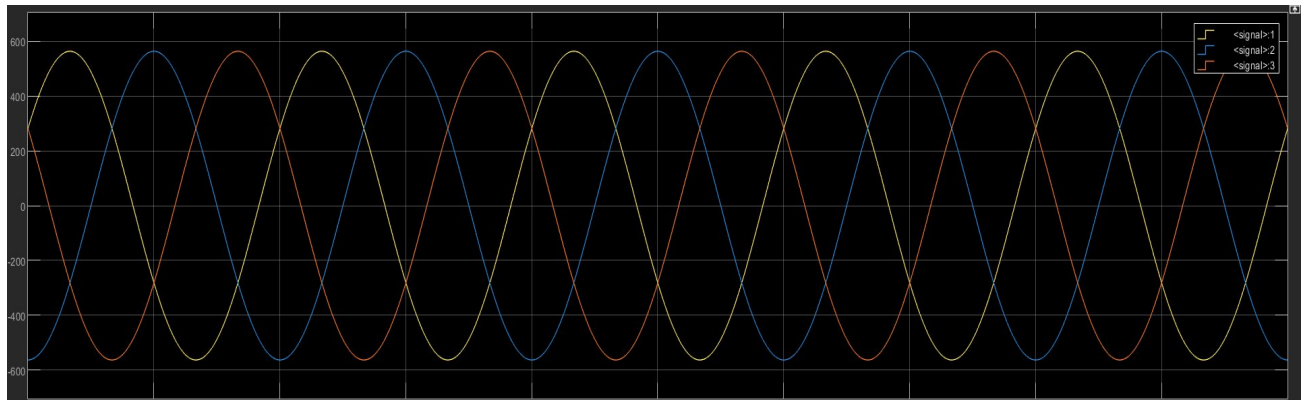


Figure 5.4: Voltage Graph of Hybrid System

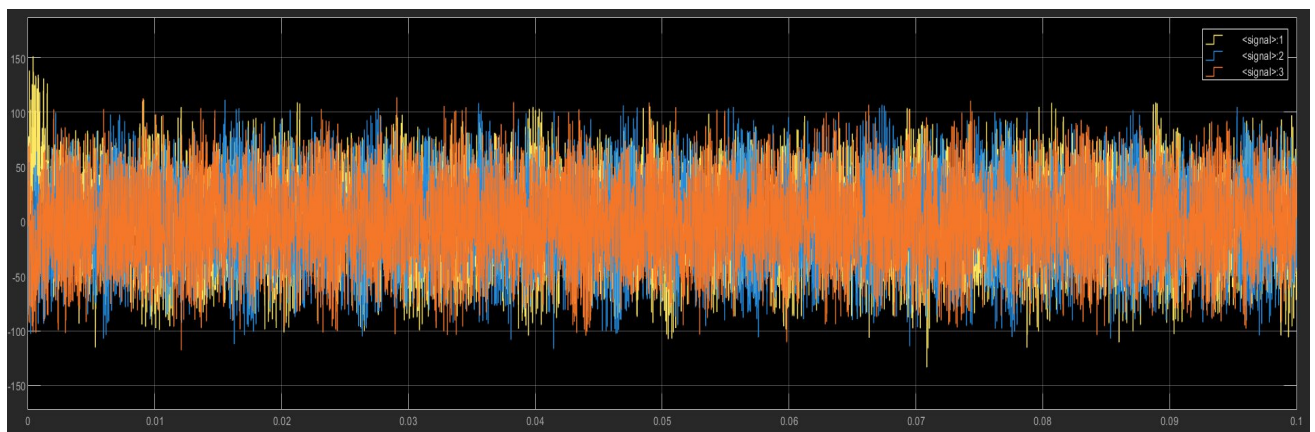


Figure 5.5: Current Graph of Hybrid System

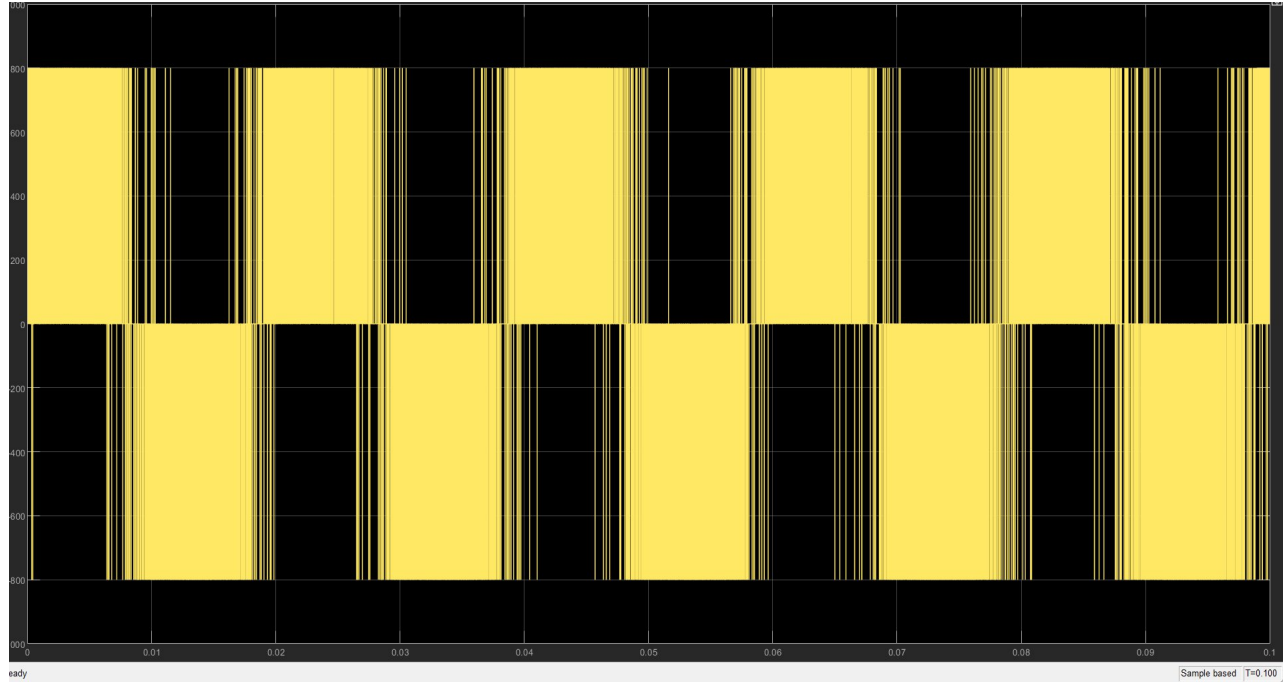


Figure 5.6: Terminal Voltage of Hybrid System

5.2.1 Test Case 1: $I_{dref} = 0$; $I_{qref} = 0$

In the first test case, the GFL inverter was synchronized with the GFM inverter but was instructed not to deliver any active or reactive power. Consequently, the GFM continued to shoulder the full responsibility of voltage and frequency regulation, with the GFL remaining effectively idle. The results were therefore similar to the GFM-only case: the voltage waveform displayed sinusoidal behavior with minor distortions, and the GFM carried both active and reactive loads.

This test case served as a baseline to confirm that the GFL could synchronize successfully with the GFM reference without introducing instability, even when its power output was set to zero.

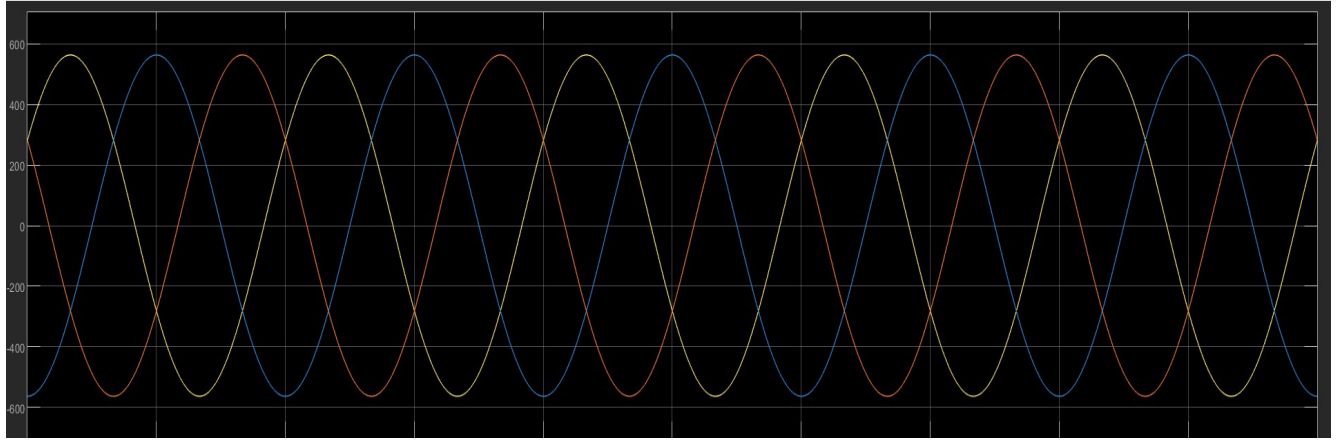


Figure 5.7: Voltage Graph for Test Case 1

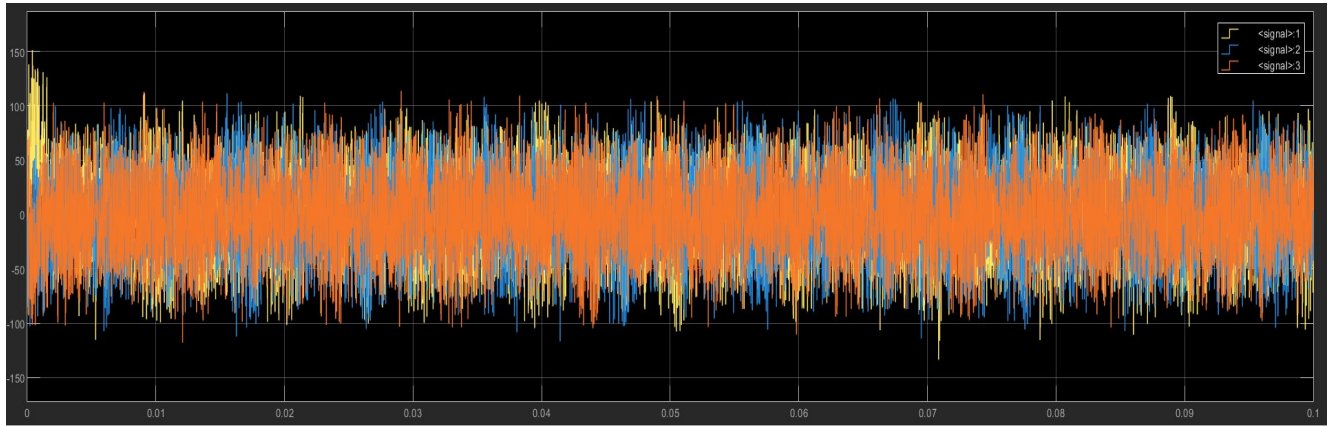


Figure 5.8: Current Graph for Test Case 1

5.2.2 Test Case 2: $I_{dref} = -100$; $I_{qref} = 40$

The second test case represented the most favorable condition for the hybrid system. Here, the GFL inverter was commanded to deliver both active and reactive power, with $I_{dref} = -100$ and $I_{qref} = 40$. Under these conditions, the GFL injected approximately +76.68 W of active power and +30.82 VAR of reactive power into the grid.

The results were highly encouraging. The PCC voltage waveform was the smoothest among all cases, with minimal harmonic distortion. The frequency response was stable, with negligible

oscillations during transients. Most importantly, the GFM inverter no longer carried the entire burden of active and reactive power supply. Instead, the workload was shared, allowing the GFM to focus primarily on maintaining voltage and frequency while the GFL supported the grid through precise power injection.

This case is particularly significant because it reflects the real-world application of hybrid systems, where renewable energy sources such as photovoltaic arrays operate through GFL inverters while a GFM inverter ensures overall grid stability.

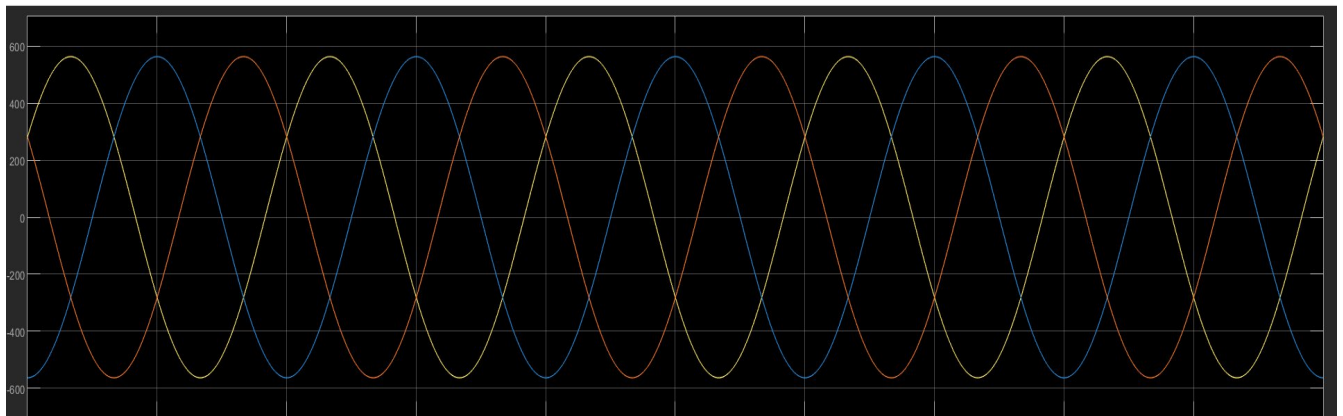


Figure 5.9: Voltage Graph for Test Case 2

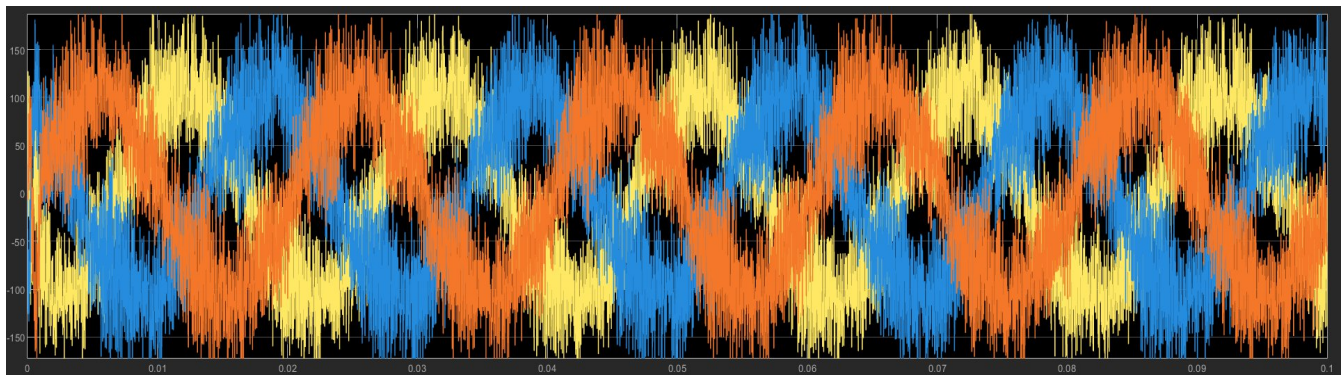


Figure 5.10: Current Graph for Test Case 2

5.2.3 Test Case 3: $I_{dref} = +100$; $I_{qref} = 40$

In the third test case, the GFL inverter was commanded to absorb active power while injecting reactive power ($I_{dref} = +100$; $I_{qref} = 40$). As a result, the GFL absorbed approximately -76.68 W of active power but continued to inject around $+30.74$ VAR of reactive power.

The PCC voltage remained sinusoidal, but minor distortions were observed, particularly during transients, due to the reversal of active power flow. The GFM inverter was required to compensate for the absorbed power, thereby taking on a greater share of active power supply. Despite this increased burden, the system maintained stability, with only minor deviations in frequency.

This case demonstrates the flexibility of the hybrid system. While it may not represent the most efficient operating condition for all scenarios, it has practical applications in systems involving Battery Energy Storage Systems (BESS) or Vehicle-to-Grid (V2G) technologies, where inverters must occasionally absorb power for charging purposes while still providing reactive power support.

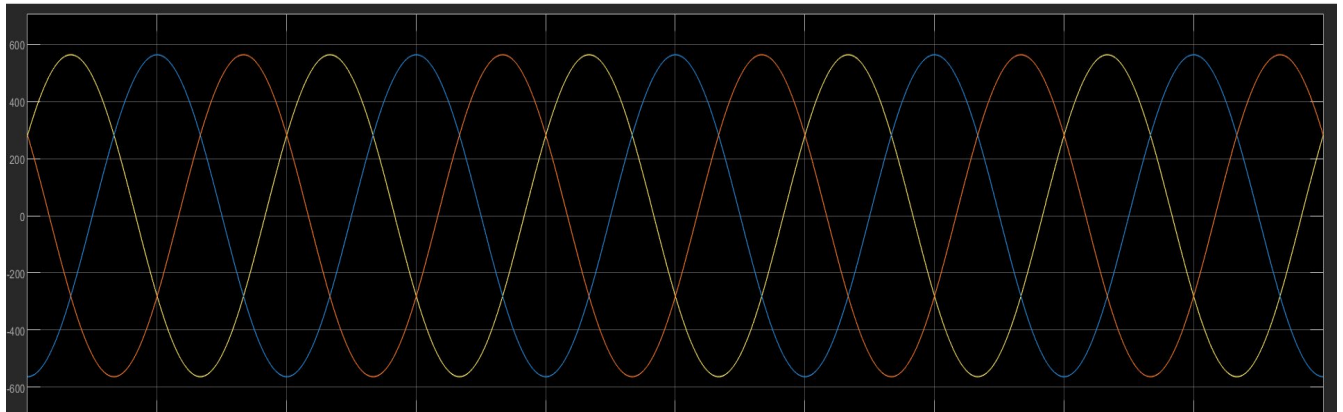


Figure 5.11: Voltage Graph for Test Case 3

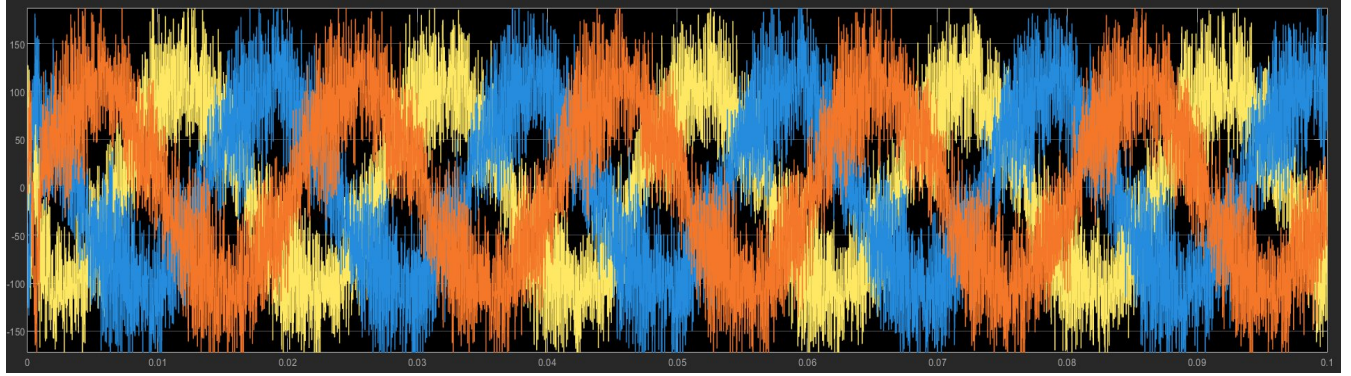


Figure 5.12: Current Graph for Test Case 3

5.3 Comparative Results Table

The outcomes of all cases are summarized in the following table, which provides a comparative perspective on inverter performance under different conditions.

Table 5.1: Comparative table of GFM and Hybrid System

Case	Idref	Iqref	GFL Role	P Contribution	Q Contribution	Voltage Quality	Conclusion
GFM Only	—	—	Inactive	GFM supplies all	GFM supplies all	Distorted sinusoid	GFM can form grid alone but with stress
Test Case 1	0	0	Idle	~0 W	~0 VAR	Similar to GFM-only	Confirms synchronization without power sharing
Test Case 2	-100	40	Delivering P & Q	+76.68 W	+30.82 VAR	Smoothest sinusoid	Best scenario for PV/microgrids
Test Case 3	+100	40	Absorbing P, injecting Q	-76.68 W	+30.74 VAR	Slight distortion	Useful for BESS/V2G charging

5.4 Overall Conclusion

From the analysis, it is clear that the GFM inverter can successfully establish and regulate grid voltage and frequency independently. However, its operation in isolation results in waveform distortions and increased stress on its control mechanisms. The GFL inverter, on the other hand, cannot function alone due to its reliance on an external reference.

The hybrid configuration, in which the GFM and GFL inverters operate in coordination, represents the most effective solution. It combines the grid-forming ability of the GFM with the efficient power injection capabilities of the GFL, thereby improving waveform quality, enhancing frequency stability, and allowing flexible control of both active and reactive power.

Among the three test cases, Test Case 2 ($I_{dref} = -100$, $I_{qref} = 40$) emerged as the most favorable condition, offering the smoothest sinusoidal waveform and the most balanced power-sharing arrangement. This result makes it the most practical for real-world applications such as photovoltaic microgrids, where both active and reactive power contributions are required.

Chapter 6:

Conclusion and Future work

6.1 Conclusion

This study set out to investigate the performance and interaction of Grid-Forming (GFM) and Grid-Following (GFL) inverters, both as standalone units and within a coordinated hybrid system. The motivation for this research stemmed from the growing penetration of renewable energy resources, which increasingly replace conventional synchronous machines in modern power systems. With this transition comes the challenge of maintaining voltage stability, frequency regulation, and overall system resilience in the absence of inherent mechanical inertia.

The results obtained in this work provide clear insights into the operational strengths and limitations of both inverter types. When simulated in isolation, the GFM inverter successfully established a stable sinusoidal voltage waveform and maintained nominal frequency through droop-based control. This validated its ability to operate independently, a feature that makes GFMs indispensable in weak grids, islanded systems, and black-start scenarios. However, the results also revealed that the GFM inverter, when operating alone, is burdened with the entire responsibility of power supply. This led to waveform distortions, harmonic content, and slower transient recovery, particularly during load disturbances. These findings confirm that while GFMs are powerful tools for grid support, their efficiency and power quality are compromised when deployed as the sole source.

By contrast, the GFL inverter failed to operate independently. Its dependency on an external voltage reference, provided through a Phase-Locked Loop (PLL), rendered it unstable in isolation. The distorted and irregular waveforms observed in the GFL-only case reaffirmed the theoretical understanding that GFL inverters are fundamentally followers. Without a leader (synchronous machine or GFM inverter), their operation collapses, making them unsuitable for standalone use.

The most significant contribution of this research lies in the hybrid operation of GFM and GFL inverters. When combined at the Point of Common Coupling (PCC), the GFM established a stable

voltage and frequency reference, while the GFL accurately injected controlled active and reactive power. This division of roles resulted in improved waveform quality, reduced harmonic distortion, enhanced frequency stability, and balanced power sharing. Among the three test cases studied, Test Case 2 ($I_{dref} = -100$, $I_{qref} = 40$) emerged as the optimal condition, producing the smoothest voltage waveform and demonstrating effective power-sharing. This case highlights the synergy between GFM and GFL inverters: while the GFM provides the backbone of stability, the GFL relieves its burden by injecting active and reactive power in a controlled manner.

The results collectively demonstrate that coordinated GFM–GFL operation represents a robust strategy for renewable-dominated grids. By combining the independence of GFMs with the efficiency of GFLs, hybrid systems can address the limitations of each inverter type. Such coordination offers a practical pathway toward maintaining voltage stability, frequency resilience, and power quality in modern inverter-based power systems.

6.2 Future Work

While the findings of this study are significant, the scope of the research was limited to simulation-based analyses in MATLAB/Simulink. Future work can extend this project in several directions to enhance both technical depth and practical applicability:

- **Hardware-in-the-Loop (HIL) Implementation:** The immediate next step is to validate the proposed hybrid control strategy using real-time digital simulators (RTDS) or dSPACE platforms. HIL implementation would allow testing the control under realistic conditions and provide insights into practical challenges such as switching delays, noise, and computational limits.
- **Experimental Prototyping:** Building a small-scale laboratory prototype of the hybrid GFM–GFL system would bridge the gap between theory and practice. Such an experimental setup would enable the study of electromagnetic interference, component thermal ratings, and hardware protection schemes that were not considered in this study.
- **Integration with Renewable Sources and Energy Storage:** The hybrid system can be extended by connecting it to photovoltaic arrays, wind turbine models, and battery energy storage

systems (BESS). In such scenarios, the GFL inverter can represent renewable energy injection while the GFM ensures grid stability, offering a realistic demonstration of microgrid operation.

- **Advanced Control Strategies:** This project employed conventional droop control for the GFM inverter and dq-current control with PLL synchronization for the GFL inverter. Future work could explore more advanced techniques, such as:
 - Virtual Synchronous Machine (VSM) and virtual inertia control for enhancing dynamic stability.
 - Adaptive or nonlinear droop methods for improved transient response.
 - Predictive and model-based control for reducing delay and overshoot.
 - Fault Ride-Through and Protection Studies

Further investigations should examine the hybrid system's performance under grid faults, sudden disconnections, or voltage sags/swells. These fault-ride-through capabilities are critical for compliance with IEEE 1547 and IEC standards.

- **Communication-Assisted and Distributed Coordination:** Future microgrids may require multiple GFMs and GFLs operating in parallel. Coordinated strategies with limited communication or decentralized control can be studied to improve scalability and resilience.
- **Application in Bangladesh and Developing Countries:** Finally, this research has particular relevance for Bangladesh and similar regions where renewable integration is rapidly growing. Future studies can explore how hybrid inverter strategies can support rural electrification, off-grid solar solutions, and the national grid transition toward 40% renewable penetration by 2041.

6.3 Final Remarks

The transition to inverter-based resources represents one of the most profound changes in power system history. As synchronous machines are gradually retired, the stability and resilience of modern grids will depend increasingly on the intelligent coordination of GFM and GFL inverters. This research demonstrated, through detailed simulations, that while neither inverter type is sufficient on its own, their coordinated operation provides a practical and powerful solution. The

hybrid approach ensures grid stability, enhances power quality, and prepares the foundation for a renewable-dominated energy future.

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