Grid-Forming Inverter: A Review and Educational Perspective

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***Abstract*— This innovative practice full paper describes the response to significant climate changes, where power grids have increasingly integrated inverter-based resources (IBRs) within integrated power systems (IPS), leading to challenges such as reduced system inertia and** variable **power generation. Effective inverter control strategies are essential to maintain the stability and resilience of these systems. Among the various inverter control types, grid-following inverters (GFLIs) are prone to frequency and voltage instabilities with higher IBR integration. Conversely, grid-forming inverters (GFMIs) offer superior control by managing both frequency and voltage at their point of common coupling, emulating the performance of traditional synchronous generators. GFMIs have emerged as a pivotal technology, garnering significant interest from both academic and industrial sectors. This paper provides an extensive review of GFMIs, emphasizing their application in undergraduate electrical engineering education. By integrating theoretical understanding with practical simulations and experiments, students can gain a comprehensive understanding of GFMIs and their critical role in modern power systems.**

***Index Terms*— Micro grid, Gird forming inverter, grid following inverter, Virtual synchronous generator, islanded mode, and grid connected mode.**

I. Introduction

THIS work shows that power electronic based Renewable Energy Sources (RES) gradually replacing Synchronous Generators (SG) within the power system. The high penetration of RES changes the structure and operation mode of power system due to the less conventional SGs and more inverter-based control sources [1]. These changes resulting in the reduction of system inertia [2–4] and rapid growth in the intermittent power generation systems. In conventional power systems, SGs keeps system frequency stable via rotor physical or mechanical inertia, which plays a critical part in primary frequency control —repaid growth of inverter-interfaced RES results in a reduction of mechanical inertia in the power system. This may causes the large frequency swing, which in turn can cause unwavering quality or in some cases reliability and resilient issues, such as tripping of loads or generation of some busses or may cause complete blackout of the system [5].

Due to changes within the conventional electric power systems, progressively overwhelmed by distributed generation system (DG) based on RES, the concept of microgrids (MG)rises from integrating diverse sorts of RES [6–8]. Depending on the actualized control strategies or operation mode in AC MG, inverters can be classified into three bunches: Grid following (GFL also known as Grid-feeding inverter), Grid-forming (GFM) and Grid-supporting (GS) (also called Grid conditioning). GFL control is usually used when only active and reactive power injection in grid is concerned it acts like a current source in the system. GFM control is outlined for independent operation i.e. standalone operation or to work in island mode in micro grid scenarios, it works in system as a ideal AC voltage source and fix frequency. GS control can work both in grid connected and islanded mode, it can act both as a voltage and as current source as per need, giving fundamental support [9–12] to grid.

In a grid that relies 100% on inverters based renewable energy, Grid Forming (GFM) inverters play a crucial role, in establishing and maintaining the voltage and frequency of the grid. These inverters are considered components for the functioning of the power system [13–15]. Unlike Grid Following (GFL) inverters GFM inverters have the capability to actively contribute to frequency control [16,17]. To ensure performance a GFM inverter needs to be connected to an energy source. Since Energy Sources (RES) lack dispatchability it becomes necessary to combine GFM inverters with Energy Storage Systems (ESS). The size and strategic placement of these systems have an impact, on the GFM inverters ability to effectively regulate frequency and voltage within the power grid [18].

In power inverters, the control systems have fast dynamics response compared to the slower control mechanisms used in synchronous generators (SG) [19]. This speed advantage proves useful in power systems that face stability challenges. In situations the quick response of inverter controls becomes crucial, in preventing the need for load shedding [16]. However these faster dynamics also pose their set of difficulties, issues like transients can threaten the stability of inverter based power systems [20]. Additionally interactions between controllers can lead to instabilities such as resonance frequency and harmonics as seen in incidents. To address these problems it is vital to have an understanding of how grid connected inverters function and develop strategies, for their control [21]. Thoughtful planning regarding their sizing and placement is also necessary to ensure stability of power systems.

Within the last few years, research on GFM inverters has caught a lot of interest around the world [1, 4, 22–26]. Nevertheless, this noteworthy increase is still not sufficient for the large-scale implementation of GFM inverters, because it may be a moderately recent concept. Hence, certainty in this field has been picked up by working with them in littler MGs and islanded power systems [27–29]. Figure 1 [1,4] outlines the steps to be studied and the joined GFM controls over a long time until this innovation is implemented on most grids.

The increasing interest, in Grid Forming (GFM) technology, has led to a surge, in projects and investments focused on examining how this innovative approach can be integrated with modified control systems and emerging technologies. The ultimate goal is to create a future where these various systems can seamlessly connect within the power grid.

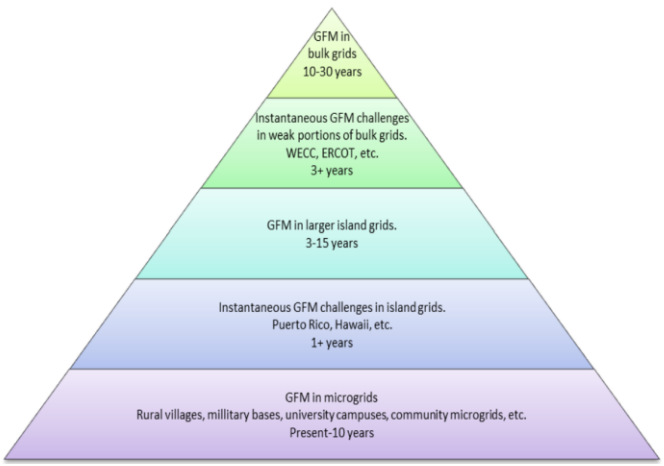

Figure 1. Study and implementation of GFM over the years [1].

Numerous reviews have already been conducted on strategies, for controlling inverters. One notable example referred to as [30,31] examines and categorizes types of inverter control techniques for operation such as master/slave control, current/power sharing control, and frequency/voltage droop control. However, these reviews do not specifically focus on the methods of controlling Grid Forming (GFM) inverters discussed in references [30-33].

In contrast, this work aims to provide a comprehensive review on the role of GFM inverters in power systems. It explores different topologies, control strategies, and current challenges as considerations for sizing and placement. To support research in this field the paper includes a review of existing literature and categorizes relevant studies while identifying gaps in research and suggesting areas for future investigation. Given the evolving nature of this field, this work is particularly focusing on research topics currently under study or in demand.

The need for this investigation arises not from the availability of consistent material on this topic in existing literature but also due to growing interest from both academic and industrial communities, for the bulk power system and specially in the MGs and rural communities neon grids [34, 35]. GFM inverters are capable of simulating power networks with penetration of renewable energy sources due crucial role of regulating its output voltage due to which can enhance the reliability and resilience of the system [1,4]. Despite the progress made, there is still room for research and development in this field it is still considered to be in the experimental stage.

As a result, this paper aims to examine the role of grid-forming inverters for reliability and resiliency within the framework of power systems. It will discuss aspects such as their structure, control strategies; operational challenges sizing considerations, and strategic placement and its effect on system.

The rest of the paper is organized as follows: Section II is subdivided into two parts: control objective and operation of inverters in grid tie and islanded mode, emphases the need and the goals of the GFM inverters. Section III presents distinctive topologies of the GFM inverters. Section IV describe different layers and widely used control strategies. In Section V, GFM invertor's attributes, such as their sizing for GFM reserve, and placement, are discussed. In Section VI, examine GFM challenges and research question still under experimental stage. Section VII is about grid-forming inverters as an undergraduate educational tool. Section VIII shows the conclusion and the work requirement and finally the references are provided in Section XI.

II. BACKGROUND OF GFMI

A. Classification of Inverter Operation Mode

Inverters are generally classified into three types [1,4]: grid-following, grid-forming, and grid-supporting, as depicted in Figure 2. The Grid-Following (GFL) inverter usually used for maximum power tracking, functions by transferring active power from an energy source, such as a Renewable Energy Source (RES), to the grid. Generally characterized by its rapid current control, it ideally acts as a controlled current source connected in parallel to the AC grid, with high output impedance. To ensure perfect synchronization with the AC voltage at the Point of Common Coupling (PCC), it necessitates a system to determine the frequency and phase at the PCC. This is often achieved using a Phase-Locked Loop (PLL) synchronization technique, vital for accurately regulating the exchange of active and reactive power with the grid. The grid's synchronism angle and angular frequency are crucial for system control. Significant advancements in state-of-the-art PLL algorithms for grid-connected systems are discussed in reference [3,4].

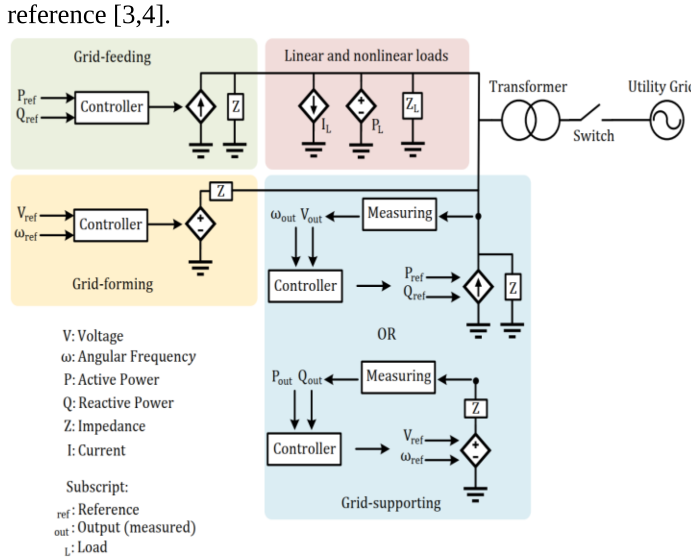

Figure 2. Grid-connected power electronics inverters modes [4].

On the other hand, the GFM inverter, which is optimized for islanded operation, controls the voltage amplitude and frequency to establish a stable local grid. It can be likened to an ideal AC voltage source with low output impedance [2]. While synchronization is a common feature of grid-connected inverters, GFM inverters require an exceptionally precise synchronization system for parallel operation with other inverters, typically achieved by integrating the set angular frequency. Grid-Supporting (GS) inverters are designed to offer ancillary services and control the AC grid's voltage amplitude (reactive power) and frequency (active power), whether in a stand-alone system or interconnected grid. They ensure power sharing for balance and can support the grid either independently or alongside other GS inverters [1-6].

An alternative perspective focuses on the services provided to the grid, which are central to system analysis. From this viewpoint, inverters can feed the grid, establish the grid, deliver ancillary services, support the grid, or perform a combination of these roles. In reference [3], the author distinguishes various control strategies based on four criteria: the nature of the source (current or voltage source); grid contribution (like feeding, voltage or frequency support, or virtual inertia emulation); synchronization method (droop or grid-synchronized); and operational mode (grid-connected or island mode). A notable distinction between inverters acting as Voltage Sources (VSI) or Current Sources (CSI) lies in their transient behavior. VSIs naturally regulate power following a disturbance (i.e., quick response time), whereas CSIs respond to disturbances through control dynamics (i.e., slower response time), as elaborated in references [1, 4].

B. *Control Objectives for GFM Inverters*

As previously mentioned the detailed definitions and classifications of various inverter control strategies. Additionally, the operational mode of an inverter can differ based on the specific requirements of the power system. For instance, a Grid-Forming (GFM) inverter within a microgrid has the capability to operate in both Grid-connected (GC) mode, where it synchronizes with the main grid, and in island mode. In GC mode, the voltage vectors of the microgrid are determined by the main grid, with the GFM inverter playing a supportive role. It adjusts its operation to either inject or absorb power, transitioning into a Current Source Inverter (CSI) mode, similar to a Grid-Following (GFL) inverter, as noted in references [1, 6]. Alternatively, it can continue operating as a Voltage Source Inverter (VSI), taking on a Grid-Supporting (GS) role, as seen in reference [5].

Operating as a CSI in GC mode offers a simpler control structure since it doesn't necessitate voltage control at the Point of Common Coupling (PCC) - the voltage is set by the main grid. In this mode, the inverter's role is mainly to manage power flow from a Renewable Energy Source (RES) or for charging/discharging an Energy Storage System (ESS), a task that is more efficiently handled in CSI mode, as discussed in reference [7]. However, transitioning to island mode adds complexity, as the inverter must switch its operating mode, as detailed in the reference [7, 8, 23]. In scenarios where the inverter is part of a weak grid and needs to provide voltage support, VSI has been found to be more effective, as shown in reference [18, 19].

In island mode, the responsibility of the GFM inverter shifts to forming the voltage vectors, operating as a VSI in GFM mode [1, 4, 9]. This necessitates a synchronization system capable of rapidly aligning with the main grid during reconnection and establishing grid frequency in island mode. Reference [19] proposes a general approach towards standardizing the control objectives of inverters in a microgrid, recommending local power-sharing, frequency, and voltage control in island mode, and active/reactive control in GC mode. For the purposes of this paper, the essential functions of the GFM inverter are identified as:

- Forming voltage amplitude and frequency during island operation,
- Synchronizing with the main grid in GC mode, functioning either as a VSI or CSI GS inverter,
- Detecting transitions between island and GC operations,
- Maintaining connection during transient events, which requires an effective current limiting strategy.

III. GFM Inverter Topologies

In microgrid systems, integrating Renewable Energy Sources (RES) and Energy Storage Systems (ESS) with the AC grid necessitates the use of an inverter as a power interface. However, the use of Pulse Width Modulation (PWM) techniques by these inverters can potentially impact the power quality at the Point of Common Coupling (PCC). To enhance power quality and simultaneously reduce the size and cost of the output filter, along with simplifying control, improving reliability, and increasing availability, selecting the right inverter configuration becomes a significant challenge, as discussed in reference [4]. Different inverter topologies, varying in aspects like the number of legs, PWM levels, and types of filters used, are summarized in reference [3-6].

Figure 3 presents a generic depiction of the Grid-Forming (GFM) inverter, applicable in both single-phase and three-phase configurations. The most frequently used semiconductor in GFM topologies is the Insulated Gate Bipolar Transistor (IGBT), though Silicon Metal-Oxide-Semiconductor Field-Effect Transistors (Si-MOSFETS) are also viable for certain applications, as indicated in reference [4, 9-11].

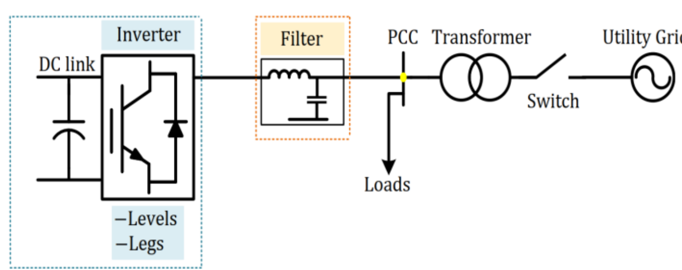

Figure 3. Block diagram of a typical GFM inverter and associated topology variations [1-4]

Three-phase inverters are widely used in industrial systems and electricity supply. However, the popularity of single-phase inverters has been increasing, notably due to their unique characteristics and the resulting reduction in production costs. References [11, 17] explore the implementation of a Flyback inverter in an isolated photovoltaic system employing a hybrid Maximum Power Point Tracking (MPPT) method under various environmental conditions.

A. Number of Legs

The inclusion of an additional leg in GFM inverter topologies, while offering distinct advantages, also presents an impasse in terms of usage and application. The standard three-leg/three-phase inverter, as seen in Figure 4b, is well-established in the literature. However, the emergence of single-phase full-bridge inverters, depicted in Figure 4a and widely recognized as the most common form of single-phase inverter referenced in [4, 12], marks a shift in inverter design.

Research interest has expanded to four-leg GFM inverter configurations Figure 4c, evolving from the traditional three-leg models. This fourth leg's primary function is to manage neutral point currents, which is particularly beneficial for addressing unbalanced and nonlinear loads, as discussed in references [13-15]. This feature enhances the inverter's utility in microgrid applications.

An added benefit of this four-leg approach is the feasibility of applying Space Vector Pulse Width Modulation (SVPWM), which contributes to lower DC-link voltage. Despite these advantages, the introduction of an additional leg entails more complex hardware requirements and sophisticated control strategies, posing challenges for practical implementation and usage, as outlined in reference [4, 16]. This complexity can create a barrier to the widespread adoption and efficient utilization of these advanced inverter designs in various applications.

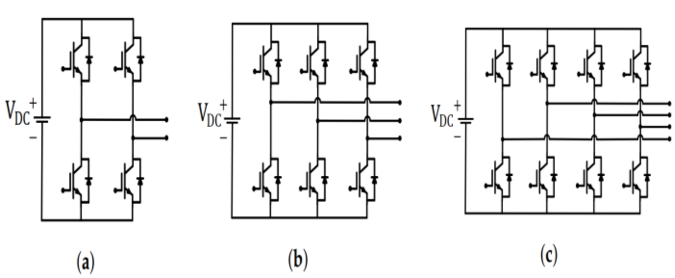

Figure 4. Inverter classification according to the number of legs. (a) Topology with two-leg [1] (b) Topology with three-leg [5] (c) Topology with four-leg [15]

B. Levels

Inverters come in two primary configurations: two-level (2L) inverters, as shown in Figure 4, and three-level Neutral Point Clamped (3L-NPC) inverters, depicted in Figure 5 and discussed in reference [17]. The 2L inverters, which are more commonly used according to references [15-18], operate on a straightforward principle: each leg of the inverter has two switches that must switch in a complementary manner. This is crucial because activating two semiconductor switches on the same leg simultaneously would result in a short circuit of the DC source, as highlighted in reference [19]. As a result, each leg of a 2L inverter has only two states.

In contrast, 3L-NPC inverters, as their name implies, introduce an additional voltage level compared to 2L inverters, thanks to the incorporation of clamping diodes that facilitate current flow. This extra level allows 3L-NPC inverters to achieve superior power quality and enable smaller filter components for higher power applications, typically over 30 kW, compared to 2L H-bridge inverters, as noted in reference [4, 20, 25]. The advantage of a multilevel inverter lies in its ability to produce a smoother waveform and utilize multiple lower DC-link voltages. However, increasing the number of levels also complicates the control circuit and the components involved. While two levels are sufficient for most applications, multilevel inverters become particularly beneficial when there's a need for low distortion in the output voltage.

Modular Multilevel Converters (MMC) represent another class of inverters capable of providing more than two levels in each phase voltage. This approach involves arranging inverters in series and parallel, with the primary idea being to distribute the total voltage or current of the inverter among several smaller units. This distribution enables the creation of intermediate voltage or current levels, which are key to synthesizing alternating waveforms with minimal harmonic distortion. MMCs are especially favored in high-power systems, as indicated in reference [1, 26], due to their effectiveness in handling large-scale power requirements.

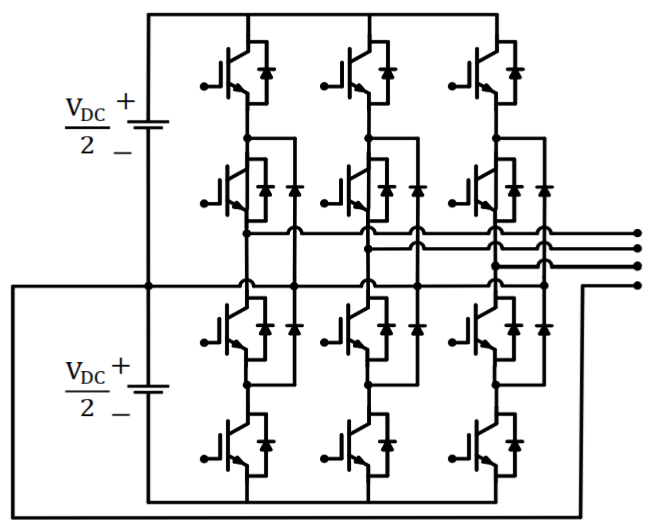

Figure 5. Three phase three-level modulation configuration [4]

IV. GFM Control Approaches

The control strategy for Grid-Forming (GFM) inverters is designed to ensure stable and efficient system operation. This strategy focuses on maintaining the system's nominal voltage and frequency values and managing the distribution of active and reactive power. In grid-connected mode, the system adopts the grid's nominal voltage and frequency values. However, in islanded mode, the control strategy itself takes charge of these parameters. The control framework for GFM inverters is structured into three distinct levels: current and voltage control, and primary, secondary, and tertiary control, as illustrated in Figure 6 [4, 27].

At the first level, often referred to as the inner loop in literature, lies the cascade control strategy, which encompasses both voltage and inner current control. This level is tasked with the immediate tracking of the system's nominal voltage and addressing power quality concerns [28, 35]. The primary control, positioned at the second level, deals with overall system stability, including voltage and frequency steadiness and equitable power sharing among connected loads, be they linear or non-linear [29-34].

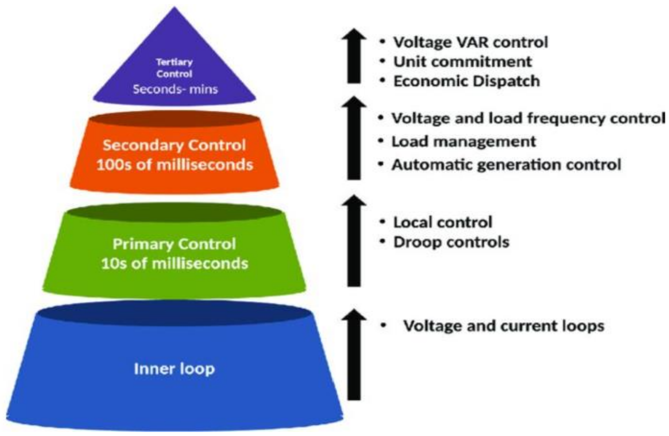

Figure 6. A hierarchical grid-forming control levels [1,4]

The third and fourth levels, secondary and tertiary controls, primarily focus on restoring and maintaining voltage and frequency values to their desired levels. Additionally, these controls play a crucial role in determining the optimal operating points for Distributed Generation (DG) units within the system, calculating necessary generation and demand values. The design of secondary and tertiary controls often incorporates optimization algorithms to enhance efficiency and performance [4, 30-33].

Figure 7 depicts a typical islanded system with these various layers of control. The normalization stage generates modulation signals. At the device level, the inner control loop manages current and voltage control, aiming to stabilize the inverter, for example, by protecting it from overcurrents. Meanwhile, the primary control sets parameters for the inner controller based on broader system-level requirements. These requirements may include ancillary services such as scheduling and dispatch, reactive power and voltage control, or the provision of virtual inertia.

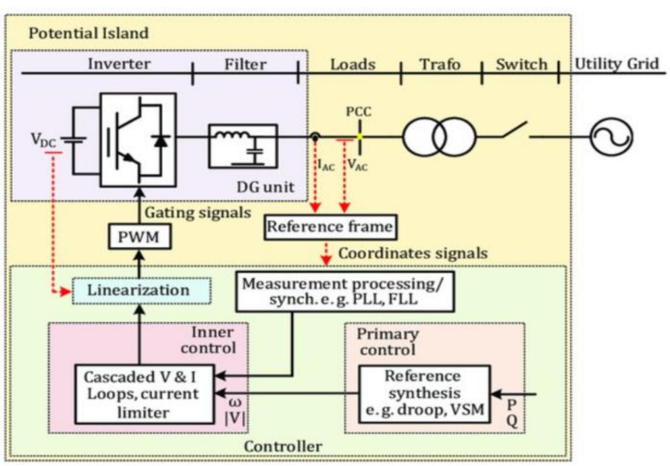

Figure 7. Potential islanded system and control layers [1-4]

V. GFM Inverters in the Power System

The sizing, placement, and planning of Grid-Forming (GFM) inverters within power systems are recognized as key challenges, especially in future low-inertia grids dominated by inverter-based resources, as noted in [15]. A GFM inverter requires a dispatchable energy source to regulate voltage and frequency efficiently and precisely. Considering the intermittent nature of many primary Renewable Energy Sources (RES), the integration of Energy Storage Systems (ESS) becomes imperative. These ESS can be paired with various types of RES to enhance system stability, which is inherently a non-linear phenomenon dependent on factors like available energy, power rate, and inertia of components. Different ESS types impact these stability parameters differently. For instance, a study in [18] found that ultracapacitors more effectively mitigate frequency deviations than a Battery Energy Storage System (BESS) due to fast charging and discharging, whereas BESS had a more significant effect on reducing oscillation durations compared to ultracapacitors due to steady supply.

There is extensive research on optimizing the placement, sizing, operation, and power quality of ESS in distribution networks, thoroughly reviewed in [18–19]. These reviews focus on optimization algorithms, objectives, and decision variables, as optimal solutions are highly system-specific. Efforts to apply optimization algorithms, like genetic algorithms for ESS location and sizing, are discussed in [19, 23]. However, direct comparisons between different studies are challenging due to varying objectives, constraints, and decision variables [29]. Despite the high costs associated with ESS, maximizing their applications across various uses is crucial to justify the investment [18, 19].

From a GFM inverter perspective, optimization involves determining the ideal bus location, power rating, and energy capacity of the ESS. Effective management of storage devices, alongside load-shedding strategies, is vital for successful microgrid operation in island mode, as indicated in [19-21]. A proposed approach is to size the ESS based on the needs of critical loads that cannot be shed during unintentional islanding, as suggested in [17]. This approach ensures that essential services remain operational, even in scenarios where the MGs is isolated from the main grid.

A. Sizing of GFM Inverter Reserve

The efficacy of a Grid-Forming (GFM) inverter in providing frequency support doesn't solely hinge on the power rating of its components. It also depends significantly on the power supply capability (measured in MW) and the energy storage capacity (measured in MWh) of the accompanying Energy Storage System (ESS). The intricacies of sizing ESS for frequency regulation are explored in [11], and the dynamics of power systems with high proportions of Renewable Energy Sources (RES) are discussed in [16].

In complex power systems that integrate a mix of power sources, including GFM and Grid-Following (GFL) inverters and synchronous generators, the allocation of reserves is influenced by factors beyond penetration ratios and droop percentages. The location of loads and sources, as well as the distribution of impedance, play a crucial role. While communication networks could enable a more tailored distribution of reserves, the complexity of such an arrangement escalates rapidly in larger systems. Autonomous operation of inverters, sidestepping intricate communication setups, relies on each GFM inverter being equipped with sufficient ESS reserve capacity. However, considering the substantial investment required for ESS, an alternative discussed in the literature involves reducing the output of RES, i.e., operating them below their maximum power potential. This approach allows RES to contribute to frequency control without needing ESS or with a smaller-sized system. As demonstrated in [17], this method can be more cost-effective for systems like photovoltaic arrays, compared to using a BESS solely for frequency control. However, it does increase power losses since RES often operate below their optimal capacity.

B. Location of GFM Units

The positioning of Distributed Generation (DG) units significantly impacts the grid's reliability and flexibility, as noted in [4, 19, 30]. There has been considerable research on the strategic placement of Distributed Energy Resources (DERs) and Energy Storage Systems (ESS). Key goals of this research include optimizing voltage profiles, enhancing reliability, and ensuring adequate short circuit levels. While this paper does not delve into them, other critical considerations in such allocation include reducing energy costs, minimizing copper losses, and cutting down emissions [14].

In [11], the concept of optimal inertia placement is explored. This study reveals that the resilience of a power system doesn't just depend on the total system inertia but is also heavily influenced by the location of disturbances and the positioning of virtual inertia units. For instance, during a fault, the proximity of the fault to the Grid-Forming (GFM) inverter, which acts as the primary power source, has a notable effect on transient stability [17]. Faults occurring nearer to the main source tend to induce greater instability in the system.

VI. Research Challenges for GFM

Micro-grid projects are increasingly exploring diverse topologies and configurations, particularly focusing on the application of Grid-Forming (GFM) inverters [14, 28, 29]. However, before GFM inverters can fully replace synchronous machines at the transmission level, many challenges need to be addressed. These include the development of appropriate hardware, software, and controls for network formers, the standardization of inverter models, and ensuring system integration with high levels of renewable energy penetration. Additionally, considerations like energy storage, distribution and subtransmission protection, fault path analysis, stability analysis, and networking capabilities for black-start operations are crucial. Dynamic islanding solutions, unintentional islanding in distribution classifications, advancements in detection and communication systems, comprehensive system cost analysis, and economic dispatch strategies also form part of these challenges [22].

Addressing these issues involves not just technical solutions but also a reevaluation of existing standards, particularly those related to inverters connected to the electrical network. The properties of synchronous generators differ significantly from those of inverters, necessitating a revision of standards to reflect these differences. These challenges underscore the need for a comprehensive and multifaceted approach to integrating GFM inverters into modern power systems, ensuring they meet the demands of both the support system voltages and load requirements effectively [1-6].

VII. Grid-Forming Inverters as an Undergraduate Educational Tool

A. Accreditation Board for Engineering and Technologies

As part of an ABET accredited engineering program, this work can yield the following outcomes [1 -8]:

- The ability to identify, formulate and solve complex engineering projects using engineering sciences, and mathematical principles. Students identify issues that increase the use of renewable energy to reduce pollution from fossil fuels. Taking this as a starting point, by researching and designing GFMIs to extract maximum power from renewable energy and feed it into the grid as a voltage source, a system that helps to improve the utilization of renewable energy.
- The capability to design and to provide solutions to specific needs, taking into account public health, safety and welfare, as well as global, cultural, social, environmental and economic factors. Through the procedures performed in this project, students will be able to propose solutions that can reduce the impact of global warming as renewable energy increases.
- The ability to communicate effectively with a wide range of audiences. This research work will aid students in conveying developed mathematical models of GFMIs and other renewable energy devices to a wide range of scientific audiences.
- The capability to realize ethical and professional responsibilities and exercise sound judgment in engineering situations, which must identify the impact of engineering solutions in global, economic, environmental, and social contexts.
- The skills to develop and perform relevant experiments to interpret and analyze data and use engineering codes to draw conclusions. Through this research after students design and simulate GFMIs using *MATLAB/Simulink*, they will be able to test the system in a hardware-in-the-loop platform to experimentally validate the functionality.
- The capabilities to acquire and use the emerging knowledge as required, using comprehensive learning strategies. Students that work on this project will gain the skills and knowledge to design other systems for the improvement of renewable energy systems, utilizing power system optimization.

B. Courses Suggested in this Project

Table I illustrates some Electrical Engineering courses in the field of power systems control and stability with the IBR on modern power electronics system to possibly enter in the field of GFMIs [6].

Table I: University of Puerto Rico-Mayagüez Courses

Courses name and codes	Descriptions
INEL 3105: Electrical circuit Analysis I	Analysis of direct current and alternating current linear electric circuits; laws and concepts that characterize their behavior
INEL 4102: Electrical Systems Analysis II	Networks functions; Circuit analysis by Laplace Transforms and Fourier series; Two-port Networks; Butterworth and Chebyshev Filters; Computer aided Analysis of these System.
INEL 4103: Electrical Systems Analysis III	Analysis of magnetics circuits and polyphaser balanced systems; transformers; power transmission lines; computer-aided analysis of these systems
INEL 4415: Power System Analysis	Formulation of bus admittance and bus impedance matrices; symmetrical component; symmetrical and unsymmetrical faults; load flow; economic operation of power systems.
INEL 4201: Electronics I	Semiconductor Device characteristics; semiconductor diodes, bipolar junction transistors and field effect transistors; analysis of basic digital circuits; analysis and design considerations of transistor amplifiers; introduction to integrated circuits
INEL 4416: Power Electronics	Design of circuits for rectification, inversion, frequency conversion, direct current (D.C.) and alternating current (A.C.) machines control, and other non-motor applications using solid state power devices.
INEL 4418: Power Electronics Laboratory	Design, control and practical experience in power electronics.
INEL 5417: Power Electronics Applied to Renewable Energy System	Design of interfaces using topologies based on power electronics for photovoltaic and wind applications. Use of algorithms for maximum power point tracking; control of photovoltaic and wind systems, and its applications.
INEL 5496: Design Projects in Power Electronics	Application of power electronics fundamentals to the design of a system incorporating engineering standards and realistic constrains.
INEL 4505: Introduction to Control Systems	Analysis of control systems and their mathematical models; analysis and design of control systems for single input single output plants; computer solution of problems will be emphasized.
INGE 3016: Algorithms and Computer Programming	Development of algorithms and their implementation in a structured high level language. Programming techniques applied to the solution of engineering and mathematical problems.
INEL 4206: Microprocessors	Architecture, organization and operation of microprocessors and their supporting devices; design of microprocessor based systems.
ICOM 4015: Advanced Programming	Advanced programming techniques applied to the solution of engineering problems; extensive use of subprograms, logical and specification statements. Principles of multiprogramming, multiprocessing, and real-time systems.
INEL 4998: Undergraduate Research	Participation, under the supervision of a faculty member acting as an investigator, in a research project.

VIII. CONCLUSIONS

This article briefly discusses the IBRs and the usage of GFMIs in modern power systems as a potential tool for undergraduate education. As claimed in literatures that integration of Inverter-Based Generators (IBGs) in power systems intensifies, new stability challenges emerge for electrical grids. In recent years, Grid-Forming (GFM) methods have been recognized as a viable solution to address these stability issues in modern power systems due to its ability to regulate frequency and voltage mimicking synchronous generator. This paper aims to provide a thorough analysis of the stability challenges associated with GFM-based IBGs, considering perspectives from academia and vendors. The importance of undergraduate student engagement in the use and understanding of renewable energy through a power electronics and power system projects. These types of projects can be used as a foundation for future research at university.

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IX. REFERENCES

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