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Inverter-Based Resources and Grid Stability: A Comparative Study of Grid-Forming and Grid-Following Control

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ABSTRACT

The increasing penetration of renewable energy sources has accelerated the transition from synchronous generator–dominated power systems to grids heavily supported by Inverter-Based Resources (IBRs). Within this transformation, two distinct inverter control paradigms have emerged: Grid-Following Inverters (GFLs) and Grid-Forming Inverters (GFMs). GFLs synchronize to the existing grid voltage and supply controlled active and reactive power, while GFMs establish their own voltage and frequency references, thereby providing system-strengthening services traditionally delivered by synchronous machines. This paper presents an in-depth comparative analysis of GFL and GFM technologies, focusing on their control principles, dynamic performance, stability characteristics, and roles in renewable energy integration. A critical evaluation of their applications, limitations, and hybrid deployment strategies is also provided. The analysis highlights that GFMs are increasingly necessary to enable stable, resilient, and renewable-dominated future grids.

INTRODUCTION

In the past, synchronous generators powered by fossil fuels were the primary sources of electricity for the grid. (Boldea, 2020). The inertia properties of a synchronous generator (the ability of synchronous generators to remain in motion through stored kinetic energy in the rotor of the generators) generally serve to resist loss of power when the variables of the synchronous generator are disturbed. Historically, power system operation has relied on the physical inertia and frequency-stiffness of synchronous generators. As conventional generation retires, the grid must rely on inverter-based resources to provide similar or novel stability services. These inverter-based resources interface with the grid almost exclusively through power electronic inverters, making the characteristics of these inverters fundamental to grid stability (Hoke et al., 2021). Recent developments in the expansion of existing interconnected power grids have shown to include the integration of renewable energy resources. Such a grid is thus known as a renewable energy-integrated power system (Castillo & Gayme, 2014). Renewable energy resources, such as wind and solar, have been proven to be advantageous due to their self-replenishing attributes, thus making them cheaper to use when compared to fossil fuels. Unlike traditional energy resources, there is no emission of gases such as carbon monoxide, sulfur oxides, which are harmful and contribute to the greenhouse effect (Ellabban et al., 2014). The global push for decarbonization has triggered massive investments in renewable energy generation, particularly photovoltaic (PV) and wind power (Onodera et al., 2024).

Typical aims of renewable energy integration are usually to improve overall voltage profile and stability, power system reliability, optimize power-flow, and improve generation-load balance, cost reduction of power generation, reduce distribution losses, reduce carbon-emission produced by the use of synchronous generators that use fossil fuels, as well as achieve green–energy over time (Halim et al., 2023), (Ameur et al., 2019), (Melhem et al., 2016) and (Cerovac et al., 2014). Two primary paradigms for inverter operation are Grid-Following Inverters (GFLs) and Grid-Forming Inverters (GFMs). While GFLs dominate existing installations, GFMs are increasingly recognized as essential for ensuring voltage stability, black-start capability, and resilient operation in a high-renewable environment. (Du et al., 2021). Understanding the differences and complementarities of these two technologies is crucial for designing the next-generation power grid. The operational dynamics, interaction mechanisms, and stability margins of GFM and GFL control strategies under varying grid conditions remain insufficiently understood and quantitatively compared. This knowledge gap hinders optimal control design, stability assessment, and coordinated operation of hybrid inverter-based power systems. Therefore, a comprehensive comparative analysis of grid-forming and grid-following control approaches is essential to evaluate their impact on dynamic stability, transient behavior, and grid support capability in evolving low-inertia power systems. This paper, therefore, presents a comparative analysis between the GFLs and the GFMs as regards their operation and future trends. The remaining part of the paper is organised as follows. Section 2 describes the operating principles of the GFL and the GFM controls. Section 3 entails a transient stability assessment of the inverter-based renewables. The emerging trends as influenced by GFMs, along with some open research areas, are captured in Section 4. Finally, some conclusions are drawn in Section 5.

OPERATING PRINCIPLES OF INVERTER-BASED RENEWABLES

Grid-Following (GFL) and Grid-Forming (GFM) inverters represent two major control paradigms for inverter-based resources. This section outlines their control principles, dynamic behaviors, and implications for grid stability.

Inverter Control Paradigm of GFL

Grid-Following inverters (GFLs) are power electronic devices that operate by synchronizing their output current with the voltage waveform of the host power grid. Unlike grid-forming inverters, which establish voltage and frequency references, GFL inverters rely on an existing stiff grid to function properly. Their control architecture is designed to "follow" the grid, making them suitable for systems with a strong grid connection but less effective in weak or islanded grids (Aljarrah et al., 2024). A central component of GFL operation is the phase-locked loop (PLL). The PLL continuously estimates the grid's voltage angle. $\theta_g(t)$ and frequency ω_g from the measured terminal voltage. The inverter then aligns its internal reference frame with that of the grid. This ensures that the current injected into the grid remains synchronized with the grid voltage (Wen et al., 2016).

Also, the output power of a GFL inverter is primarily regulated through current control. In the dq-reference frame synchronized by the PLL. The d-axis current component (i_d) is controlled to regulate the active power P exchanged with the grid. The q-axis current component (i_q) is controlled to regulate the reactive power Q. The decoupled dq-axis control enables independent tuning of active and reactive power contributions. The reference currents are then enforced using an inner-loop current controller, typically implemented with PI controllers. By adjusting the i_d and i_q setpoints, the GFL inverter can deliver active power according to the available DC source (e.g., PV panels or energy storage). Since the inverter does not establish its own voltage reference, its power injection is entirely dependent on the strength and stability of the external grid voltage (Geng & Hiskens, 2022).

Limitations of GFL

Grid-following (GFL) inverters are the most commonly used control type in renewable energy systems such as photovoltaic and wind power plants. They are designed to synchronize with the grid voltage and inject active and reactive power according to reference commands. Although GFL inverters have proven effective in stable grid conditions, they exhibit several limitations that become more pronounced as the share of inverter-based resources increases in the power system. One fundamental limitation of GFL inverters is their dependence on a strong external voltage reference. These inverters rely on a phase-locked loop (PLL) to detect the grid frequency and phase, which allows them to synchronize with the grid. In weak or highly disturbed grid conditions, the PLL can become unstable, causing phase and frequency tracking errors. As a result, GFL inverters may lose synchronism, inject distorted currents, or trip offline during faults or severe voltage dips. This makes them unsuitable for providing grid support services in low-inertia or islanded systems where a stable voltage and frequency reference is not guaranteed.

Another major limitation is the lack of inertial and frequency support. Since GFL inverters operate as current-controlled sources, they do not inherently respond to frequency deviations or contribute to system inertia. During system disturbances, such as sudden load or generation changes, GFL inverters wait for the grid frequency to change before adjusting their output, which delays their contribution to frequency regulation. Consequently, high penetration of GFL-dominated renewable generation can lead to reduced system inertia, slower frequency recovery, and higher risk of instability following disturbances.

GFL inverters also face limitations in fault ride-through and grid support capability. During voltage sags or short-circuit faults, they typically limit or shut down their current injection to protect power electronic components. This behavior reduces the available fault current in the system, complicating fault detection and protection coordination for grid operators. Although modern grid codes require low-voltage ride-through (LVRT) and reactive current injection capabilities, implementing these features in GFL control frameworks can be challenging and may still not fully replicate the response of synchronous machines.

While GFL inverters operate as current sources that simply track the existing grid voltage and frequency—making them poor candidates for generator coherency analysis due to their lack of inertia—GFM inverters are designed to actively synthesize and maintain a voltage at their point of connection. This means they can behave similarly to traditional synchronous generators, providing features essential for system stability. From a system-level perspective, the increasing dominance of GFL inverters can degrade overall grid strength and stability. Because they do not establish voltage or frequency, a grid composed mainly of GFL inverters becomes highly sensitive to disturbances and may experience voltage collapse or oscillations. GFL inverters also have limited ability to coordinate dynamically with other converters, leading to interactions that can amplify oscillations or cause control conflicts in weak networks. Economically, while GFL inverters are generally cheaper and simpler to implement than grid-forming (GFM) inverters, their limited dynamic performance and inability to operate independently reduce their long-term suitability in grids transitioning toward 100% inverter-based generation. The lack of standardization in modeling their control dynamics, particularly under weak grid conditions, further complicates accurate system studies and planning.

In summary, the main limitations of grid-following inverters include their reliance on strong grids, inability to provide inertia or frequency support, poor fault ride-through capability, PLL-induced instability, and restricted use in weak or islanded networks. As power systems evolve toward higher renewable penetration, these weaknesses highlight the need for complementary or alternative control strategies—such as grid-forming or hybrid inverter controls—to ensure system resilience and stability.

Inverter Control Paradigm of GFM

Grid-Forming inverters (GFMs) are advanced power electronic converters that establish the voltage magnitude, frequency, and phase of the connected bus, thereby "forming" the grid. Unlike grid-following inverters, which depend on an external voltage source for synchronization, GFMs act as voltage sources with built-in control mechanisms that enable them to operate stably in both grid-connected and islanded conditions (Babu et al., 2024).

A GFM inverter operates as a controlled voltage source. It synthesizes a sinusoidal output voltage of desired amplitude. V_{ref} and frequency ω_{ref}, which serves as the reference for other devices connected to the network. This behaviour makes GFMs comparable to synchronous generators in their ability to set grid-forming conditions (Du et al., 2019).

To enable power sharing and maintain grid stability in multi-inverter systems, GFMs commonly employ droop control. The principle is analogous to the frequency-power and voltage-reactive power characteristics of synchronous machines as described in equations (1) and (2), (Sadeque & Fateh, 2022).

$$\omega = \omega_0 - k_P(P - P_{ref}) \quad (1)$$

$$V = V_0 - k_Q(Q - Q_{ref}) \quad (2)$$

where:

ω is the inverter output frequency,

V is the inverter output voltage magnitude,

P and Q are the measured active and reactive power outputs,

ω_0 and V_0 are nominal frequency and voltage setpoints,

k_P and k_Q are droop coefficients.

Through this mechanism, active power variations influence frequency, while reactive power variations affect voltage magnitude. This ensures stable load sharing among parallel inverters (Pawar et al., 2021).

Limitations of GFM

Grid-forming (GFM) inverters play a crucial role in enhancing the stability and reliability of modern power systems with high penetration of renewable energy sources. However, despite their advantages, several limitations hinder their widespread adoption and practical implementation.

One major limitation lies in the control complexity of GFM inverters. Their control schemes—such as virtual synchronous machine (VSM), droop-based, and dispatchable virtual oscillator control—require careful tuning of parameters like virtual inertia, damping, and frequency droop. Improper tuning can lead to oscillations, poor dynamic response, or even system instability. Moreover, when GFMs operate alongside conventional synchronous generators and grid-following (GFL) inverters, complex dynamic interactions may occur, resulting in unintended coupling effects or small-signal instability, especially in weak grids.

Another significant limitation is associated with power and energy constraints. Unlike synchronous machines, GFMs cannot deliver large short-circuit currents during faults, which complicates fault detection and protection coordination. Additionally, their ability to provide inertial and frequency support depends on stored energy—typically in the DC-link capacitor or connected battery—which can be rapidly depleted during large disturbances. Their limited overload capacity also restricts the extent to which they can sustain transient power imbalances, making them less robust under severe system contingencies.

Integration of GFMs into existing grid infrastructure introduces further system-level challenges. The absence of widely accepted standardized dynamic models and testing protocols makes it difficult for system operators to assess performance consistently. Coordination between multiple GFMs and GFL inverters in hybrid systems also poses a challenge, as their control objectives can conflict, leading to suboptimal frequency and voltage regulation. Moreover, traditional protection systems designed for high short-circuit currents may not function reliably in grids dominated by GFMs. From an economic and practical perspective, GFMs are more expensive to implement than conventional GFL inverters due to their sophisticated control hardware, faster processors, and often the need for integrated energy storage. Field experience with large-scale GFM deployment is still limited, meaning that practical insights into long-term performance, maintenance, and reliability remain scarce. Furthermore, most existing grid codes and market frameworks are tailored for synchronous generators, which creates regulatory and interoperability challenges for GFM-based systems.

Finally, modeling and simulation limitations persist. GFM dynamics are inherently nonlinear, making analytical stability analysis and time-domain simulations computationally demanding. Simplified models often fail to capture essential interactions, while detailed Electromagnetic Transient (EMT) models can be too complex for large-scale studies. The ongoing development of standardized models such as IEEE REGFM_B1 aims to address these issues, but practical validation is still in progress.

TRANSIENT STABILITY ASSESSMENT OF GFL AND GFM

This study performs a comparative transient stability assessment between IBRs operating under the legacy GFL control (DER_A) and the advanced GFM control (REGFM_B1). The primary objective is to quantitatively analyze how the distinct operational principles of these two converter types—namely, current-source versus voltage-source behavior—influence the overall system transient stability and post-fault dynamic response. The findings will provide essential insights into the system-wide impact of substituting traditional GFL resources with GFM technologies in future low-inertia power grids.

GFL represented by the DER_A Model

The DER_A model (Distributed Energy Resource – Aggregated model) is a standardized dynamic model developed by the Western Electricity Coordinating Council (WECC) to represent the aggregate behaviour of Distributed Energy Resources (DERs) such as photovoltaic systems, battery energy storage, and other inverter-based technologies at the distribution level. Unlike detailed inverter models, DER_A simplifies complex device-level dynamics into a single equivalent model that can be integrated into transmission system stability studies. The DER_A model captures essential dynamic characteristics such as active and reactive power control**,** voltage and frequency regulation**,** and ride-through capabilities during grid disturbances. It includes control loops for real and reactive power, frequency response, voltage control, and protection logic, making it suitable for small-signal and transient stability analysis. The DER_A model is primarily designed to emulate the behaviour of Grid-Following (GFL) inverters, which is fundamentally modelled as a current source in bulk power system studies (Electric Power Research Institute (EPRI), 2019).

The numerous parameters of the DER_A model are parameterized based on IEEE category II-2018 data, which specifies connection standards for distributed energy resources [49]. The parameterization of the DER_A model is shown in Table 2.

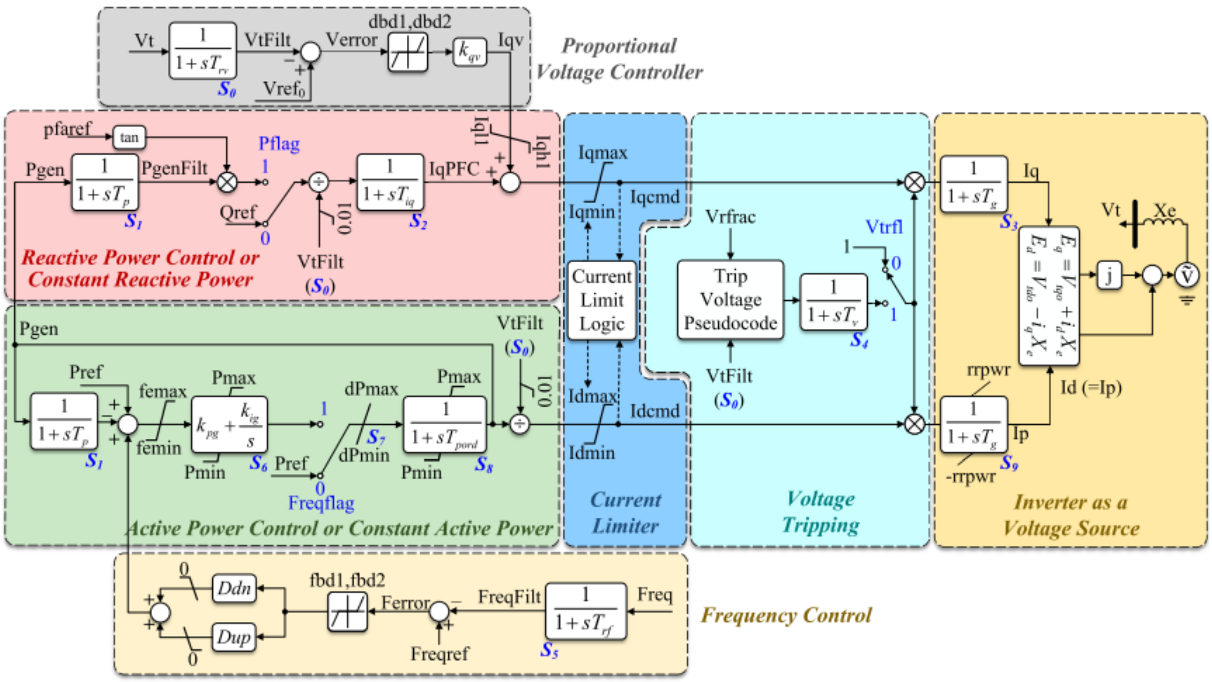

Figure 1: Schematic Diagram of the DER_A Model (Vasquez-Plaza *et al.*, 2023)

GFM represented by the REGFM_B1 Model

The REGFM_B1 model specification defines a standardized representation of a Virtual Synchronous Machine (VSM) type Grid-Forming (GFM) inverter. This model, which is represented as a voltage source, emulates the dynamic behaviour of a conventional synchronous generator, allowing inverter-based resources (IBRs) to contribute to grid stability through inertia, damping, and voltage regulation. In the REGFM_B1 specification, the inverter's control structure includes an emulated swing equation that governs frequency and active power dynamics, along with an internal voltage control loop to maintain reactive power and voltage levels. The parameters typically include virtual inertia (H), damping coefficient (D), droop gains, and voltage–frequency control settings, enabling the inverter to provide synthetic inertia, frequency support, and voltage regulation similar to synchronous machines. The REGFM_B1 model represents a standardized Grid-Forming (GFM) inverter developed under the WECC

Renewable Energy Modelling framework (Du et al., 2024).

Table 1: Parameterization of the DER_A Model Based on IEEE Category II-2018 Data

Parameter (DER_A)	description	chosen parameter
trv	transducer time constant for voltage measurement	0.02
dbd1	lower voltage deadband	-0.05
dbd2	upper voltage deadband	0.05
kqv	proportional voltage control gain	5
vref0	Vref0: voltage reference set-point (pu)	0
tp	transducer time constant (seconds)	0.02
tiq	Q control time constant (seconds)	0.02
ddn	down-side frequency control droop gain	20
dup	up-side frequency control droop gain	0
fbdb1	lower frequency control deadband	-0.0006
fbdb2	upper frequency control deadband	0.0006
femax	frequency control maximum error	99
femin	femin: frequency control minimum error	-99
pmax	Maximum power (pu)	1
pmin	Minimum power (pu)	0
dpmax	Power ramp rate up	99
dpmin	Power ramp rate down	-99
tpord	Tpord: Power order time constant (seconds)	5
Imax	Imax: Maximum converter current (pu)	1.2
Vfrac	fraction of device that recovers after voltage comes back to within vl1 < V < vh1	0
fltrp	frequency break-point for low frequency cut-out of the inverter (Hertz)	56.5
fhtrp	frequency break-point for high frequency cut-out of the inverter (Hertz)	62
tfl	frequency break-point for low frequency cut-out timer (seconds) (highly recommend that Tfl > Trf)	300
tfh	frequency break-point for high frequency cut-out timer (seconds) (highly recommend that Tfh > Trf)	300
tg	Current control time constant	0.02
rrpwr	Power rise ramp rate following a fault >= 0 (pu/s	2
tv	Tv: time constant on the output of the voltage cut-out	0.02
Kpg	active power control proportional gain	0.1

Kig	active power control integral gain	10
xe	Generator effective reactive (pu) > 0	0.25
vpr	voltage below which frequency tripping is disabled (pu)	0.3
iqh1	Maximum limit of reactive current injection, p.u.	1
iql1	Minimum limit of reactive current injection, p.u.	-1
pfflag	0 implies constant reactive power (Q) control, 1 implies constant power factor control	1
frqflag	0 implies frequency control disabled; 1 implies frequency control enabled	1
pqflag	PQFlag: 0 means Q priority; 1 means P priority for current limit (any number which is not 0 is treated as 1)	1
typeflag	0 means the DER_A model is a storage device and 1 means the DER_A model is a generator	1

Table 2: Parameterization of the GEGFM_B1 Model Based on IEEE Category II-2018 Data

Parameter (REGFM_B1)	**description**	**chosen parameter**
Re	Coupling resistance (pu)	0.03
Xe	Coupling reactance (pu)	0.15
kpv	Voltage-loop proportional gain	15
kiv	Voltage-loop integral gain(pu/s)	2.5
mp	Active power–frequency droop (pu/Hz)	0.05
mq	Reactive power–voltage droop	0.08
Mvirtual	Virtual inertia constant (s)	1.0
Dvirtual	Virtual damping coefficient (pu)	1.5
Dwmax / Dwmin	Frequency-related damping limits (pu)	± 0.5
Vtrip_U	Overe ride-through thresholds (pu)	High = 1.20
Vtrip_L	Undervoltage ride-through thresholds (pu)	0.45 pu
Ttrip_U /	Voltage ride-through durations	≥ 0.2 s below 0.45 pu
Ttrip_L	Voltage ride-through durations	≥ 10 s above 1.20 pu
Ftrip_U	Frequency trip thresholds	62 Hz (for 60 Hz system)
Ftrip_L	Frequency trip thresholds	58 Hz (for 60 Hz system)
Ttrip_F	Frequency ride-through time	≥ 300 ms
Imax_fault	Current limit during fault(pu)	1.2
Vdrpflag / Vdrp_deadband	Volt-VAR droop activation	Enable = 1; Deadband = ± 0.02 pu
kiPLL	PLL tuning for grid synchronization	10
kpPLL	PLL tuning for grid synchronization	100
filter time constant	Control measurement/filter time constant (ms)	15

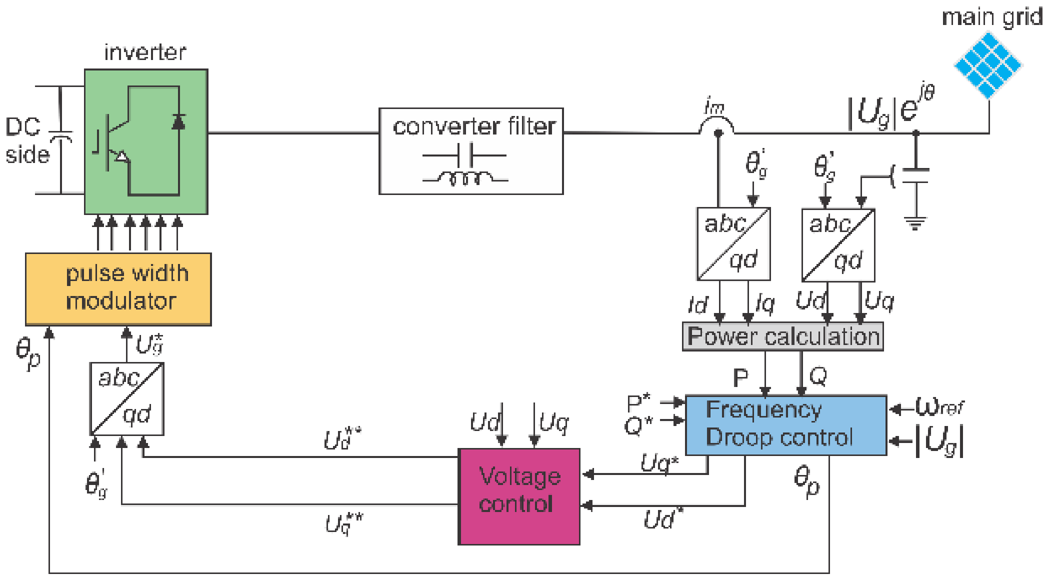

Figure 2: Simplified block diagram of grid-forming inverter block diagram from (Du *et al.*, 2024).

Case Study

The IEEE 9-Bus System is a standard test network used for power system studies. It consists of 3 generators, 3 loads, and 9 buses, representing a simplified version of a real transmission grid. Operating at 100 MVA and 60 Hz, it is commonly used for power flow, stability, and control design analysis. Its simplicity and well-documented data make it a popular benchmark model for validating algorithms and studying system dynamics. Simulations are conducted in Powerworld simulator using the IEEE 9 Bus System from the online repository in (Texas A&M University researchers, 2025). The IEEE 39 Bus System is further modified to a renewable energy integrated power grid by integrating the inverter-based resources on buses 5 and 6, each having an installed capacity of 100MVA and as shown in Figure

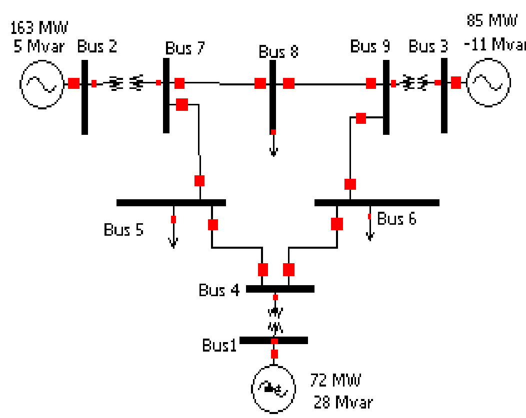

Figure 3: IEEE 39 Bus System the online repository in (Texas A&M University researchers, 2025).

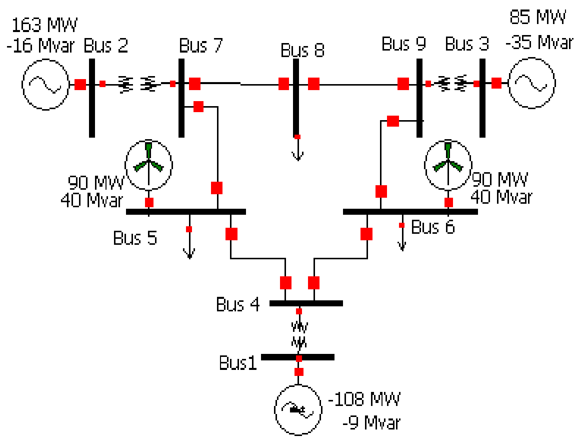

Figure 4: Inverter-based renewables installed at buses

5 at 6, 100MW each

SIMULATION RESULTS

The system is operating at its initial stable condition. The synchronous generators (usually at Buses 1, 2, and 3) are supplying power, and the inverter-based renewables at Bus 5 and Bus 6 are operating according to their initial settings—typically injecting a fixed amount of active power and maintaining their terminal voltage or injecting zero reactive power. DER_A model is configured for an extreme Low Voltage Ride True capability (LVRT), i.e., it does not trip under extreme system disturbances to enable proper comparison with the REGFM_B1. Simulations are conducted first by integrating the DER_A model on buses 5 and 6, after which a 3-phase bolted fault is implemented on Line 6-9, and a plot of the power system variables is presented. The DER_A models are then replaced with the REGFM_B1 model, after which the same 3-phase bolted fault is implemented on Line 6-9 of the modified IEEE 9 Bus System. Thus, 2 scenarios of the modified IEEE 9 bus system are presented. The first is with the DER_A model installed on buses 5 and 6. The second is with REGFM_B1 replacing the DER_A model on buses 5 and 6, each modification of the IEEE 9 Bus System having its voltage, rotor speed, and rotor angle dynamics captured as a plot. The application of a solid three-phase fault on the Line 6-9 at 1 second and cleared at 1.2seconds causes an immediate and significant disturbance on the system's bus voltage for the IEEE 9 Bus System modified with the DER_A and REGFM_B1 models respectively, according to Figures 5 and 6. Both scenarios show that the system's bus voltage experiences system disturbances.

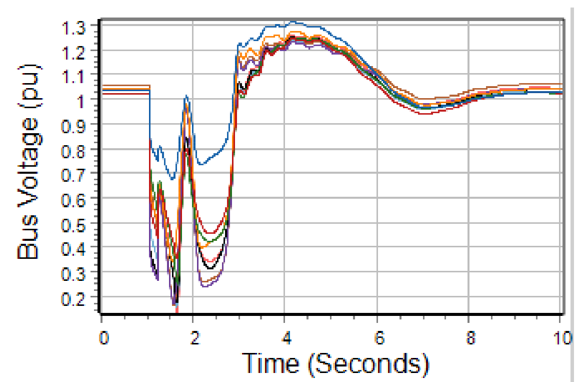

Figure 5: Bus voltages (pu) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with DER_A model integrated at buses 5 and 6.

However, it can be seen from Figure 6 that the system bus voltages in the IEEE 9 Bus System withREGFM_B1 reached steady state far quicker than the IEEE 9 Bus System with DER_A models. The rotor speeds of the generators can also be seen to have a sharp response, with the largest rotor speed deviation being experienced by the generator at bus 3, exceeding 1.04Hz in the IEEE 9 Bus System integrated with the DER_A model, according to Figure 7. Whereas, the rotor speeds of the generator connected to bus 2 of the IEEE 9 Bus System, integrated with REGFM_B1, barely exceed 1.017pu. Moreover, the scenario of the IEEE 9 Bus System with REGFM_B1 can be seen to recover quickly from frequency disturbances according to Figure 8.

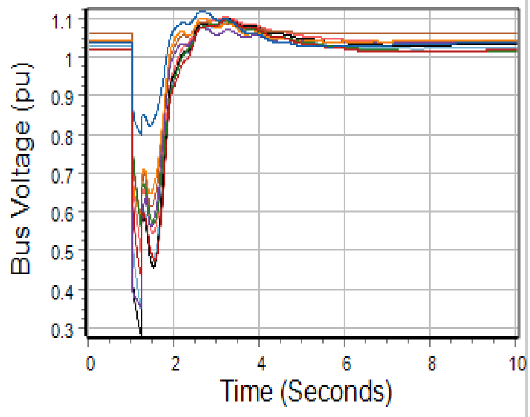

Figure 5: Bus voltages (pu) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with REGFM_B1 model integrated at buses 5 and 6.

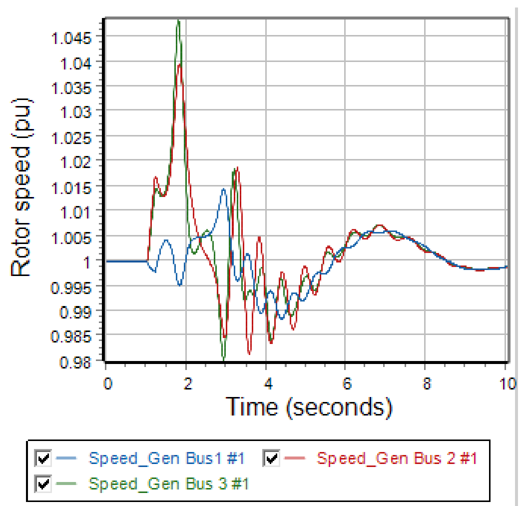

Figure 6: Rotor speeds (pu) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with DER_A model integrated at buses 5 and 6

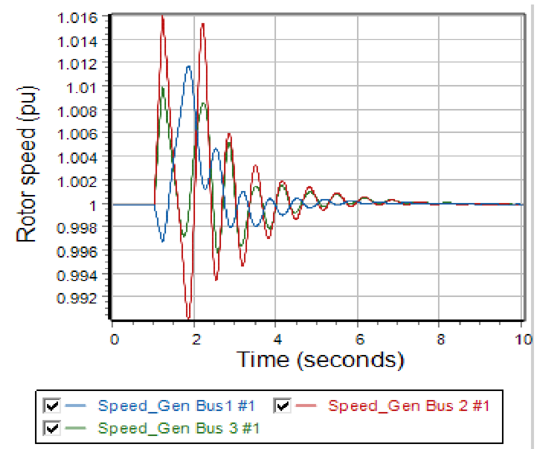

Figure 7: Rotor speeds (pu) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with REGFM_B1 model integrated at buses 5 and 6.

The implementation of a 3-phase bolted fault on the IEEE 9 Bus System modified respectively with DER_A and REGDM_B1 is also seen to cause the rotor angles of the generators connected at buses 1,2, and 3 to experience disturbances and consequently, settle at new steady state values according to Figures 9 and 10. The new steady state values reached by the rotor angles in the IEEE 9 Bus System integrated with DER_A models are seen to be much farther away from their original positions before the implemented fault, according to Figure 9.

Whereas, the rotor angle deviations in the IEEE 9 Bus System integrated with REGFM_B1 can be seen to be a lot closer to their original steady state values before system disturbances, according to Figure 10. This therefore implies that the presence of the REGFM_B1 tends to support rotor angle stability of synchronous generators far better than the DER_A model.

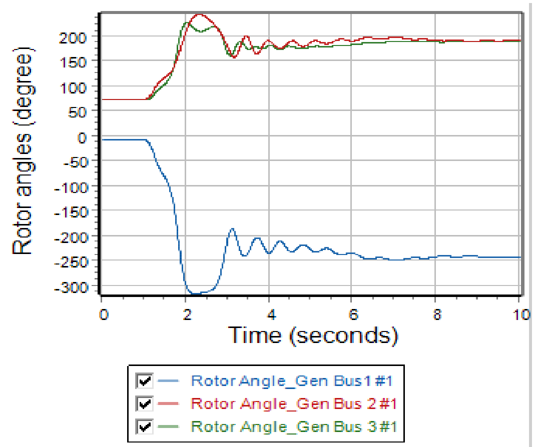

Figure 8: Rotor angles (degrees) after implementing 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with DER_A model integrated at buses 5 and 6.

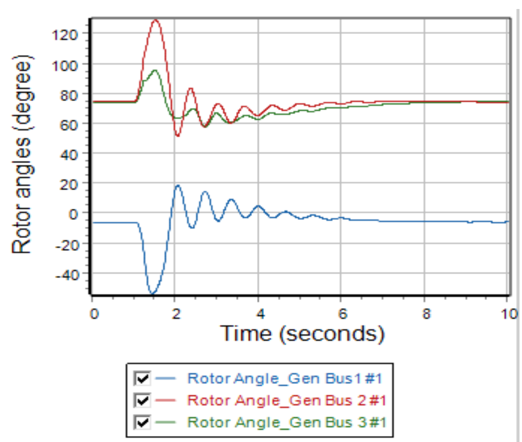

Figure 9: Rotor angles (degrees) after implementing 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with REGFM_B1 model integrated at buses 5 and 6

With LVRT enabled, DER_A MW output does not trip during system disturbance as shown in Figure 11. Its ts instantaneous MW output falls in proportion to the reduced terminal voltage and any current limiting. The MW trace for DER_A exhibits a sharp drop at fault onset, followed by a recovery whose speed depends on PLL tracking, current-limit recovery strategy, and any active curtailment logic.

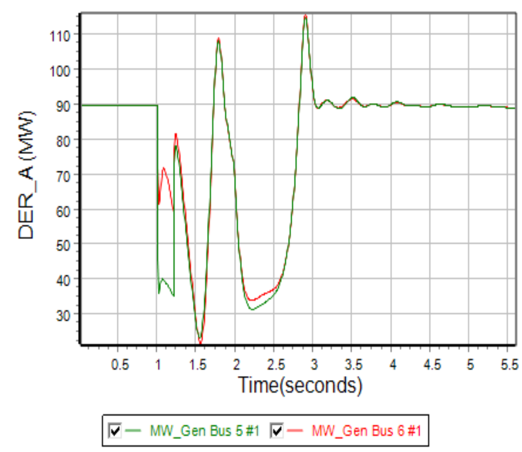

Figure 10: Power output (MW) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with DER_A model integrated at buses 5 and 6.

DER_A model primary objective remains to track the grid reference, so its contribution to arresting frequency decline is limited by how much active power it can inject while respecting voltage/current constraints. Consequently, the presence of the DER_A model in the IEEE 9 Bus System tends to increase the Rate of Change of Frequency (ROCOF) on the buses, as shown in Figure 12.

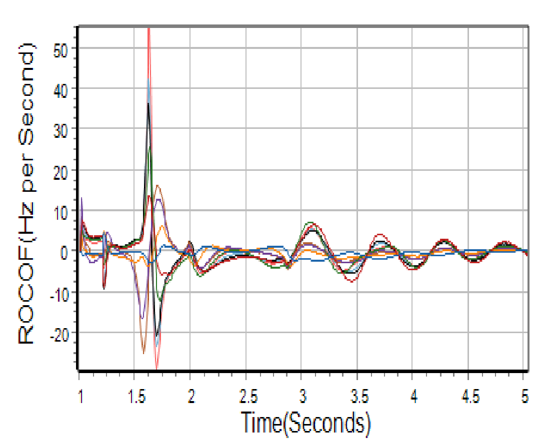

Figure 11: ROCOF (Hz per Second) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with DER_A model integrated at buses 5 and 6

During the implementation of the 3-phase bolted fault on Line 6-9 of the IEEE 9 Bus System modified with REGFM_B1, the REGFM_B1 MW output also temporarily reduces, as shown in Figure 13.

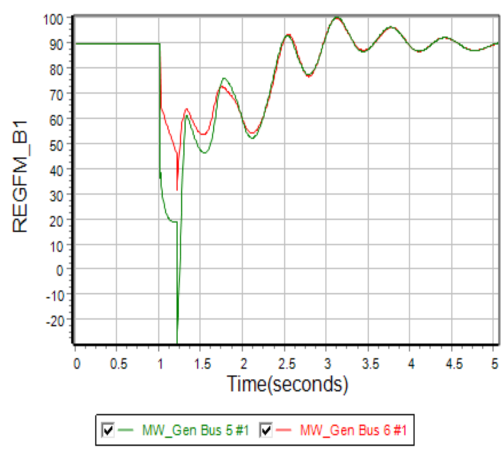

Figure 12: Power output (MW) after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with REGFM_B1 model integrated at buses 5 and 6.

After an initial transient from the 3-phase bolted fault on the Line 6-9 of the IEEE 9 Bus system modified with REGFM_B1 , the REGFM_B1 typically supplies a more sustained increase in MW relative to DER_A. The REGFM_B1, as a grid-forming resource, remains online, and contributes inertial response immediately thereby reducing the system's overall ROCOF far better than the DER_A modified IEEE 9 Bus System, according to Figure 14. To better understand the operational distinctions between inverter-based resources, it is important to highlight the fundamental differences between Grid-Following (GFL) and Grid-Forming (GFM) control strategies. The GFL inverter relies on an existing grid voltage to synchronize and inject power, while the GFM inverter establishes voltage and frequency references, contributing actively to grid stability.

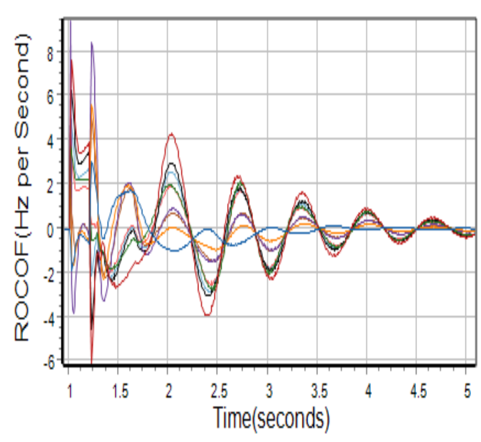

Figure 13: ROCOF (Hz per second after implementing a 3-phase bolted fault on line 6-9 of the modified IEEE 9 Bus System with REGFM_B1 model integrated at buses 5 and 6.

Table 3 presents a comparative summary of the key features, control principles, and dynamic characteristics of both inverter types, emphasizing their roles, advantages, and limitations in modern power systems with high renewable penetration.

Emerging Applications of GFM

The transition towards renewable-dominated power systems has accelerated the deployment of grid-forming inverters (GFMs). Their ability to establish voltage and frequency references, emulate synchronous machine behaviour, and support system stability makes them central to the future of power grids. Beyond their traditional role in microgrids, several emerging applications of GFMs are gaining attention in both academia and industry.

Black-Start Capability

GFMs can energize de-energized networks by establishing voltage and frequency without reliance on synchronous machines. This enables black-start capability, allowing renewable-based microgrids or islanded regions to recover from complete system outages (Jain et al., 2020).

Table 3: Comparison Between GFL and GFM Inverter-based Renewables

Aspect	Grid-Following (GFL) Inverters	Grid-Forming (GFM) Inverters
Control Objective	Track and inject current synchronized to the grid voltage	Establish and regulate grid voltage and frequency
Synchronization Mechanism	Phase-Locked Loop (PLL) used to detect grid phase and frequency	Self-synchronizing; does not require PLL
Grid Dependence	Requires a strong grid or voltage reference to operate	Can operate independently or in weak grids
Power Reference	Operates in PQ control mode (controls active and reactive power)	Operates in VF control mode (controls voltage magnitude and frequency)
Inertia Contribution	Provides no inherent inertia; responds based on control loop dynamics	Can emulate virtual inertia and provide fast frequency response
Fault Ride-Through Capability	Limited; may disconnect under severe voltage/frequency deviations	Enhanced; capable of supporting voltage and frequency during faults
Dynamic Behaviour	Fast current control but limited support during transients	More robust transient response; supports grid recovery
Grid Support Functionality	Reactive power control, voltage support through current injection	Frequency and voltage regulation; black-start capability
Typical Applications	Grid-connected PV and wind systems in strong grids	Microgrids, weak grids, islanded operation, and system restoration
Stability in Weak Grids	Poor; prone to oscillations and instability	Superior; stabilizes weak or islanded networks
Communication Requirements	Often relies on external grid signals	Can operate autonomously or in decentralized setups
Implementation Complexity	Simpler and widely commercialized	More complex control design and ongoing research development

Hybrid Renewable Power Plants

Inverter-based renewable power plants (e.g., solar PV and wind) increasingly incorporate GFMs to provide grid-forming services. GFMs enhance the plant's resilience, allowing it to operate stably in weak-grid conditions and to contribute to system restoration during disturbances (Dykes et al., 2020).

Virtual Synchronous Machine (VSM) Applications

Advanced GFM controllers often emulate the dynamics of synchronous machines described in equation (3). This approach, termed the Virtual Synchronous Machine (VSM) concept, introduces virtual inertia and damping into the inverter control (Wang et al., 2025).

$$J\frac{d\omega}{dt} = P_{ref} - P - D(\omega - \omega_0) \quad (3)$$

Where J represents the virtual inertia and D is the damping factor. The inclusion of these dynamics enhances frequency stability and improves system resilience against disturbances. The reference power commands are achieved by shaping the inverter output voltage. Inner control loops (typically voltage and current regulators) enforce the desired voltage waveforms at the inverter terminals, while outer loops (droop or VSM-based) determine the steady-state operating point. On the other hand, GFMs are being explored for integration within FACTS devices, providing advanced voltage regulation, synthetic inertia, and damping control. This enhances the stability of transmission networks under high renewable penetration (Adetokun & Muriithi, 2021).

Isolated and Remote Microgrids

GFMs are particularly suited for remote or islanded microgrids where synchronous machines are impractical. They ensure autonomous operation, stable load sharing among distributed generators, and reliable integration of variable renewable resources (Silvanus D'silva et al., 2020).

Electric Vehicle (EV) Integration

Vehicle-to-grid (V2G) charging systems are evolving from grid-following to grid-forming control modes. GFMs enable electric vehicles to contribute to voltage and frequency regulation, forming mobile and distributed energy resources capable of supporting local grid resilience (Barsali et al., 2017).

Open Research Areas

Although significant progress has been made in understanding the operational differences between grid-following (GFL) and grid-forming (GFM) inverters, several open research areas remain. Addressing these challenges is essential for achieving stable, secure, and well-coordinated operation of inverter-dominated power systems.

Coordinated Operation of Hybrid GFL–GFM Systems:

Modern power grids will operate with both GFL and GFM inverters for the foreseeable future. However, the dynamic interactions between these two control types are not yet fully understood. Further research is needed to develop adaptive coordination frameworks and control hierarchies that allow GFL and GFM inverters to coexist without introducing oscillatory modes or instability, particularly in weak and low-inertia systems (Huang et al., 2025).

Parameter Tuning and Stability Evaluation:

The control parameters of GFM inverters—such as virtual inertia, damping, and droop coefficients—strongly influence system dynamics, while GFL inverters depend heavily on PLL tuning and current control bandwidth. Establishing systematic and standardized tuning approaches, including small-signal and transient stability assessment under mixed inverter operation, remains an open problem.

Modelling and Experimental Validation:

Although standard dynamic models such as REGFM_B1 and DER_A provide a foundation, they still require validation under diverse system conditions. The lack of universally accepted Electromagnetic Transient (EMT) and RMS models for both GFL and GFM inverters limits the accuracy of wide-area dynamic studies. Future work should focus on high-fidelity modelling and Hardware-In-The-Loop (HIL) testing to bridge this gap.

Protection and Fault Management:

Inverter-based resources contribute limited fault current and respond differently during faults compared to synchronous machines. Traditional overcurrent-based protection schemes may therefore operate abnormally in systems dominated by GFL and GFM inverters. Research is needed to develop adaptive protection strategies that account for inverter control modes, current limits, and grid-forming capabilities (Nagaboopathy et al., 2025).

Coherency Detection and Dynamic Grouping of Generators:

The increasing integration of GFL and GFM inverters challenges conventional methods for identifying coherent generators—a critical step in oscillation analysis, stability control, and controlled islanding (Vincent et al., 2025). Classical coherency detection techniques assume synchronous machine dynamics dominated by electromechanical modes, which may no longer hold in inverter-based systems. The presence of fast inverter controls, synthetic inertia, and grid-dependent phase-locking complicates the identification of coherent areas. Future research should explore data-driven, adaptive, and frequency-dependent coherency detection methods that can accurately group both synchronous and inverter-based sources in evolving grid conditions.

Inertia Emulation and Energy Management:

While GFM inverters can emulate inertia, sustaining this support requires careful energy management, particularly when the DC energy source is limited. Research is needed to design optimal control strategies that balance stability support with energy constraints and prevent depletion of stored energy during prolonged disturbances

Market and Grid Code Integration:

Existing grid codes and ancillary service markets are primarily designed for synchronous machines. It remains an open area of research to determine how GFM inverters can participate in frequency regulation and stability markets, and how both GFL and GFM controls can be standardized within evolving compliance frameworks such as IEEE 2800 and ENTSO-E standards.

Cyber-Physical and Communication Considerations:

As inverter-based systems become more networked, they introduce vulnerabilities related to communication delays, data integrity, and cyber-attacks. Future studies should investigate resilient control and communication architectures for wide-area coordination of inverter-based resources to ensure both stability and security.

CONCLUSION

Grid-Following Inverters (GFLs) and Grid-Forming Inverters (GFMs) represent two fundamentally different paradigms for renewable integration. While GFLs are simple, mature, and suitable for today’s grids with abundant synchronous generation, GFMs are indispensable for tomorrow’s inverter-dominated, renewable-centric power systems. Future grids will likely require a synergistic coexistence of both technologies, gradually transitioning toward widespread GFM deployment. Continued research in advanced controls, coordination strategies, and standards will determine the pace of this transformation. In summary, emerging applications of GFMs extend beyond conventional grid support to include black-start capability, renewable plant integration, microgrid stability, EV-to-grid interaction, and critical infrastructure resilience. As the share of inverter-based resources increases, GFMs are poised to become the backbone of future low-inertia power systems. Future research on Grid-Following (GFL) and Grid-Forming (GFM) inverters should focus on developing unified control frameworks that enable seamless coordination and interoperability between both inverter types in hybrid power systems. Ultimately, future work should aim at establishing standardized guidelines for inverter interoperability, stability assessment, and ancillary service provision in converter-dominated power systems.

REFERENCE

Adetokun, B. B., & Muriithi, C. M. (2021). Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review. In *Heliyon* (Vol. 7, Issue 3). Elsevier Ltd. https://doi.org/10.1016/j.heliyon.2021.e06461

Aljarrah, R., Fawaz, B. B., Salem, Q., Karimi, M., Marzooghi, H., & Azizipanah-Abarghooee, R. (2024). Issues and Challenges of Grid-Following Converters Interfacing Renewable Energy Sources in Low Inertia Systems: A Review. *IEEE Access*, *12*(January), 5534–5561.https://doi.org/10.1109/ACCESS.2024.3349630

Ameur, A., Berrada, A., Loudiyi, K., & Aggour, M. (2019). Analysis of renewable energy integration into the transmission network. *The Electricity Journal*, *32*(10), 106676. https://doi.org/10.1016/j.tej.2019.106676

Babu, V. V., Roselyn, J. P., Nithya, C., & Sundaravadivel, P. (2024). Development of Grid-Forming and Grid-Following Inverter Control in Microgrid Network Ensuring Grid Stability and Frequency Response. *Electronics (Switzerland)*, *13*(10). https://doi.org/10.3390/electronics13101958

Barsali, S., Bojoi, R., Ceraolo, M., Mallemaci, V., Mandrile, F., Mocci, S., & Pasini, G. (2017). *Grid forming inverters for electric vehicle charging stations to enhance distribution grid resilience*. *1*. https://doi.org/10.1109/ACCESS.2024.Doi

Boldea, I. (2020). Electric generators and motors: An overview. *CES Transactions on Electrical Machines and Systems*, *1*(1), 3–14. https://doi.org/10.23919/tems.2017.7911104

Castillo, A., & Gayme, D. F. (2014). Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, *87*, 885–894. https://doi.org/10.1016/j.enconman.2014.07.063

Cerovac, T., Cosić, B., Pukšec, T., & Duić, N. (2014). Wind energy integration into future energy systems based on conventional plants - The case study of Croatia. *Applied Energy*, *135*, 643–655. https://doi.org/10.1016/j.apenergy.2014.06.055

Du, W., Achilles, S., Ramasubramanian, D., Hart, P., Rao, S., Wang, W., Nguyen, Q., Kim, J., Zhang, Q., Liu, H., Santos, P. A., Weber, J., Sanchez, J., Chen, M., Senthil, J., Pourbeik, P., Nwaneto, U., Bloemink, J., Wang, S., … Zhu, S. (2024). *Virtual Synchronous Machine Grid-Forming Inverter Model Specification (REGFM_B1)*.

Du, W., Schneider, K. P., Tuffner, F. K., Chen, Z., & Lasseter, R. H. (2019). Modeling of Grid-Forming Inverters for Transient Stability Simulations of an all Inverter-based Distribution System. *2019 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2019*, 1–5. https://doi.org/10.1109/ISGT.2019.8791620

Du, W., Tuffner, F. K., Schneider, K. P., Lasseter, R. H., Xie, J., Chen, Z., & Bhattarai, B. (2021). Modeling of Grid-Forming and Grid-Following Inverters for Dynamic Simulation of Large-Scale Distribution Systems. *IEEE Transactions on Power Delivery*, *36*(4), 2035–2045. https://doi.org/10.1109/TPWRD.2020.3018647

Dykes, K., King, J., Diorio, N., King, R., Gevorgian, V., Corbus, D., Blair, N., Anderson, K., Stark, G., Turchi, C., & Moriarty, P. (2020). *Opportunities for Research and Development of Hybrid Power Plants*. https://www.nrel.gov/docs/fy20osti/75026.pdf.

Electric Power Research Institute (EPRI). (2019). *The New Aggregated Distributed Energy Resources (DER_A) Model for Transmission Planning Studies: 2019 Update*. 35.

Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, *39*, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

Geng, S., & Hiskens, I. A. (2022). Unified Grid-Forming/Following Inverter Control. *IEEE Open Access Journal of Power and Energy*, *9*, 489–500. https://doi.org/10.1109/OAJPE.2022.3217793

Halim, M. A., Akter, Mst. S., Biswas, S., & Rahman, Md. S. (2023). Integration of Renewable Energy Power Plants on a Large Scale and Flexible Demand in Bangladesh's Electric Grid-A Case Study. *Control Systems and Optimization Letters*, *1*(3), 157–168. https://doi.org/10.59247/csol.v1i3.48

Hoke, A., Gevorgian, V., Shah, S., Koralewicz, P., Kenyon, R. W., & Kroposki, B. (2021). Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges. *IEEE Electrification Magazine*, *9*(1), 74–91. https://doi.org/10.1109/MELE.2020.3047169

Huang, S., Yao, J., Yang, D., Zhao, L., & Xie, H. (2025). Coupling Mechanism Analysis and Stabilization Improvement for Hybrid System With GFL and GFM Converter Under Grid Faults. *IEEE Transactions on Power Delivery*, 1–12. https://doi.org/10.1109/TPWRD.2025.3614982

Jain, H., Seo, G. S., Lockhart, E., Gevorgian, V., & Kroposki, B. (2020). Blackstart of power grids with inverter-based resources. *IEEE Power and Energy Society General Meeting*, *2020-Augus*. https://doi.org/10.1109/PESGM41954.2020.9281851

Melhem, F. Y., Moubayed, N., & Grunder, O. (2016). Residential energy management in smart grid considering renewable energy sources and vehicle-to-grid integration. *2016 IEEE Electrical Power and Energy Conference, EPEC 2016*. https://doi.org/10.1109/EPEC.2016.7771746

Nagaboopathy, M., Pandu, K. D. R., Selvaraj, A., & Velu, A. S. (2025). Improved Fault Resilience of GFM-GFL Converters in Ultra-Weak Grids Using Active Disturbance Rejection Control and Virtual Inertia Control. *Sustainability*, *17*(14), 6619. https://doi.org/10.3390/su17146619

Onodera, H., Delage, R., & Nakata, T. (2024). The role of regional renewable energy integration in electricity decarbonization—A case study of Japan. *Applied Energy*, *363*(February). https://doi.org/10.1016/j.apenergy.2024.123118

Pawar, B., Batzelis, E., Chakrabarti, S., & Pal, B. (2021). Grid-Forming Control for Solar PV Systems with Power Reserves. *IEEE Transactions on Sustainable Energy*, *12*(4), 1947–1959. https://doi.org/10.1109/TSTE.2021.3074066

Sadeque, F., & Fateh, F. (2022). On Control Schemes for Grid-Forming Inverters. *2022 IEEE Kansas Power and Energy Conference, KPEC 2022*, *July*. https://doi.org/10.1109/KPEC54747.2022.98147

74

Silvanus D'silva, Mohammad Shadmand, & Haitham Abu-Rub. (2020, February 6). Microgrid Control Strategies for Seamless Transition Between Grid-Connected and Islanded Modes. *2020 IEEE Texas Power and Energy Conference (TPEC)*.

Texas A&M University researchers. (2025, October 29). *WSCC 9-Bus System*. https://electricgrids.engr.tamu.edu/electric-grid-test-cases/wscc-9-bus-system/

Vasquez-Plaza, J. D., Scarpetta, J. M. R., Hansen, T. M., Tonkoski, R., & Rengifo, F. A. (2023). Smooth Mathematical Representation of the DER-A Aggregated Model. *IEEE Access*, *11*(September), 101398–101408. https://doi.org/10.1109/ACCESS.2023.3315245

Vincent, M., Alayande, A. S., Adetona, S., & Balogun, A. (2025). Alternative Framework for Generator Coherency Analysis and Controlled-Islanding for Grids with High Penetration Levels of Inverter-Based Renewables. *ABUAD Journal of Engineering Research and Development (AJERD)*, *8*(3), 189–211. https://doi.org/10.53982/ajerd.2025.0803.18-j

Wang, Y., Chen, S., Yang, M., Liao, P., Xiao, X., Xie, X., & Li, Y. (2025). Low-frequency oscillation in power grids with virtual synchronous generators: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *207*(September 2024), 114921. https://doi.org/10.1016/j.rser.2024.114921

Wen, B., Boroyevich, D., Burgos, R., Mattavelli, P., & Shen, Z. (2016). Analysis of D-Q Small-Signal Impedance of Grid-Tied Inverters. *IEEE Transactions on Power Electronics*, *31*(1), 675–687.
https://doi.org/10.1109/TPEL.2015.2398192

.