Review

Grid Forming Inverter as an Advanced Smart Inverter for Augmented Ancillary Services in a Low Inertia and a Weak Grid System Towards Grid Modernization

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Abstract: Grid dynamics and control mechanisms have improved as smart grids have used more inverter-based renewable energy resources (IBRs). Modern converter technologies try to improve converters’ capacities to compensate for grid assistance, but their inertia still makes them heavily dependent on synchronous generators (SGs). Grid-following (GFL) converters ensure grid reliability. As RES penetration increases, the GFL converter efficiency falls, limiting integration and causing stability difficulties in low-inertia systems. A full review of grid converter technologies, grid codes, and controller mechanisms is needed to determine the current and future needs. A more advanced converter is needed for integration with more renewable energy sources (RESs) and to support weak grids without SGs and with low inertia. Grid-forming (GFM) inverters could change the electrical business by addressing these difficulties. GFM technology is used in hybrid, solar photovoltaic (PV), battery energy storage systems (BESSs), and wind energy systems to improve these energy systems and grid stability. GFM inverters based on BESSs are becoming important internationally. Research on GFM controllers is new, but the early results suggest they could boost the power grid’s efficiency. GFM inverters, sophisticated smart inverters, help maintain a reliable grid, energy storage, and renewable power generation. Although papers in the literature have compared GFM and GFL, none of them have examined them in terms of their performance in a low-SCR system. This paper shows how GFM outperforms GFL in low-inertia and weak grid systems in the form of a review. In addition, a suitable comparison of the results considering the performance of GFM and GFL in a system with varying SCRs has been depicted in the form of simulation using PSCAD/EMTDC for the first time.

Keywords: renewable energy; battery storage; grid-following converters; grid-forming converters; smart inverter; ancillary services

1. Introduction

Global energy consumption has been rising for decades. Renewable energy is increasingly becoming the top candidate to mitigate energy shortages. Renewable energy will continue to generate more electricity in the future as well. Power electronic converters interfaced with renewable energy sources deliver power to the grid without any lag. Synchronous generators provide mechanical inertia in modern power systems [1]. These massive, perfectly synchronized generators defend the power grid’s frequency stability from even the slightest demand or generating process disturbance [2–10]. To link decentralized renewable power systems to the power grid, grid-following (GFL) converters are used. The frequency-tracking characteristic is exhibited by GFL converters. When operating, GFL
converters maintain a constant output power, in contrast to synchronous generators, which are affected by grid frequency.

Many huge central power plants are being replaced by smaller, more distributed renewable energy sources. The connected renewable energy grid’s moment of inertia and damping are decreasing, making it less able to manage unexpected frequency fluctuations. Low-inertia systems affect electrical grid reliability. Cleaner, more environmentally friendly energy is being generated through the integration of wind and solar photovoltaic (PV) systems into power networks. Solar and wind power will account for 60% of the world’s extra capacity by 2025, according to studies conducted by NREL and IREA.

In addition to environmental problems, political and economic challenges have drawn attention to the high penetration of RESs. Wind power generation is highly dependent on weather and wind conditions, especially the time-varying wind speed. When incorporating renewable energy sources (RESs) into the electrical grid, numerous challenges emerge, including those related to feeders and regulations, control methodologies, cybersecurity, and grid interface technology. Problems with the feeder and the control system include voltage instability, harmonics, frequency, thermal line restrictions, losses in the feeder, and reverse power flow. Problems with scheduling, dispatch, supply security, and dynamic modeling of RES penetration are encountered for power systems that rely heavily on RESs [11–15]. A major issue for future power networks is inertia, which could be mitigated by the widespread use of RESs. Running a system with a high penetration of RESs requires careful consideration of numerous factors. It is critical for any grid to have stable voltage and frequency. System inertia, transient stability margins, reactive power shortages or excesses in certain grid locations, frequency variations, and voltage dip propagation are some of the difficulties that need to be addressed and mitigated to fulfill high RES standards. The system’s fault tolerance and voltage stability are defined by national grid codes.

Reliable, secure, and stable power systems that use a lot of green energy resources like wind and solar are required in the future. The robustness of the grid is defined as its ability to withstand disruptions. Low levels of short circuits and high equivalent grid impedances characterize all of them. Unstable voltages, lower transient stability margins, and other forms of instability are all symptoms of a poorly designed grid. The potential instability of an electrical system is heightened by weaker grids. The reliability of the grid is essential to the operation of renewable energy sources (RESs) and all other grid components. The strength of the system determines the rate at which a voltage drop propagates through the grid. The efficiency of capacitor banks is impacted by the system power and short circuits. When these parts fail in an inadequate system, voltage instability can occur. Reduced protection of the power system and reduced responsiveness from protective devices are the results of a lower short circuit level. Given these concerns, future power systems with weaker system strengths may find it harder to operate conventional converters that connect to RESs through grid-following (GFL) converters. GFL converter control depends on grid reliability and safety. This is easier in systems with higher failure levels and robustness, but it is much harder with little network dependency. When the grid voltage and frequency are unstable, GFL-based RESs cannot operate properly. The short circuit ratio (SCR) is a key indication of system robustness since it indicates grid fragility and impacts GFL converters’ dynamic behavior [16–20]. Weak links, such as an SCR < 3, can lead to increased instability in GFL-based RESs. For GFL-based RES integration, the line voltage affects the line-commutated converter (LCC), which, in turn, affects the switching process of the switches to a greater extent.

Low-inertia systems with weak connections are prone to frequency resonances, voltage instability, load rejection overvoltage, and valve commutation failure. Phase-locked loop (PLL) controllers are necessary in GFL converters to monitor and adjust the magnitude and angle of the grid voltage due to the absence of synchronous coupling. Insufficient connections in systems with low inertia might lead to PLL failure. To achieve adequate dynamic coefficients when using a PLL at a low SCR, it is necessary to make a substantial increase, as prior research has shown. Therefore, GFL-based RES systems that depend on
phase-locked loops (PLLs) can face challenges in efficiently dealing with network failures caused by a weak signal strength. This raises the question of whether traditional renewable energy sources (RESs) with grid-forming (GFL) inverters can replace large synchronous generators (SGs) and enhance the share of RESs in future power grids. Operating the system on a low-capacity power grid (SCR < 3) might result in problems such as frequency resonance, voltage instability, and excessive voltage due to load rejections. Implementing controllers and phase-locked loops (PLLs) in converter-interfaced renewable energy source (RES) mode is not feasible under these unfavorable grid conditions. Moreover, it can result in the propagation of voltage sags over extended distances, more significant decreases in voltage, and increased instances of cascade failure caused by uncontrolled power oscillations throughout wider regions. On the other hand, when there is a decrease in inertia, deviations in both the frequency and the rate of change of frequency (ROCOF) also occur. An increased rate of change of frequency (ROCOF) or high-frequency oscillations can trigger the relay and lead to unintended power outages [21–25].

The existing inverter-based resources (IBRs) function as “grid-following” (GFL) inverters. Due to equipment failures, severe weather, or human mistake, there is a limit to how far the grid can be disconnected when grid-following inverters are available. Due to their design, these inverters require an electrical connection to operate. If the power goes out, they will not be able to function. This demonstrates the limitations of grid-following inverters in these types of settings and how they might potentially worsen the grid’s stability in the area. System inertia is mostly caused by synchronous machinery. When there is less synchronous equipment online, IBRs can decrease system inertia. Neither the inertia nor the strength is enhanced by grid-following (GFL)-based IBRs. To overcome these problems and ensure the seamless integration of renewable energy sources and battery energy storage into electric networks, unique control mechanisms are mandated. Grid-forming (GFM) inverters simplify the maintenance by reducing the system’s reliance on external components and can achieve amazing performance on a variety of inertia grids. These inverters and similar black-start resources can re-establish grid connectivity after an outage, irrespective of the grid’s condition. This improves the reliability of the system [26–30]. The responsibility for checking that the GFM interconnection criteria are in line with NERC FAC-001 and further lies with the operators. Planning coordinators and transmission service providers work together to ensure precise field equipment simulations prior to transmission and physical connection. The benefits that GFM offers over GFL are substantial:

- GFM can operate the grid at 100% IBRs, unlike GFL
- GFM can maintain the stability of the system during low-SCR conditions, unlike GFL
- GFM can operate as a standalone unit and performs best in islanding conditions
- GFM units can be used as initial black-start resources, unlike GFL units
- GFM allows for quicker energy injection in the inertial timescale, while GFL allows for a quicker frequency response with a small delay
- GFM can control the magnitude of the terminal voltage of the IBR, angle, or frequency, while GFL-based IBRs can control the magnitude of the current and phase angle. GFM does not use a phase-locked loop (PLL), unlike GFL, which requires a phase-locked loop (PLL) or an equivalent for synchronization

The edge that GFM inverters have over GFL inverters is detailed in Table 1 in a simplified manner.

There are a variety of solutions to the problem of how to reliably operate a BPS at extremely high levels of IBR penetration, but one of the best is GFM inverter technology, which can function at extremely low system strength levels and does not have the same stability difficulties as GFL inverters. If synchronous condensers bring about fault current, system strength, or system inertia, GFM IBRs might still help stabilize the system. Table 2 shows a comparison of GFL and GFM inverter capabilities from a weak-grid/low-SCR point of view. Upgrading the firmware of existing GFL inverters could allow them to function in regions with large penetrations of IBRs, although in most circumstances, GFM modifications may not be necessary. Additionally, current parallel GFL IBRs can be used to
augment GFM IBRs (for instance, a new GFM BESS project can be added to existing GFL PVs). It can be worthwhile and economical for an existing GFL plant to switch to GFM IBRs in certain instances. Finding out how much of the GFL IBR fleet can be upgraded to GFM controls without repowering the entire project would be a plus. Original equipment manufacturers (OEMs) must play a significant role in this.

Table 1. Comparison of GFL and GFM inverter capabilities.

<table>
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<tr>
<th></th>
<th>GFL</th>
<th>GFM</th>
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<td></td>
<td>Based on a current source inverter (CSI)</td>
<td>Based on a voltage source inverter (VSI)</td>
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<tr>
<td>Current and phase angle are controlled</td>
<td>Voltage amplitude and frequency are controlled</td>
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<tr>
<td>Follows the grid</td>
<td>In the grid-forming mode, GFM adjusts the voltage and frequency of the grid</td>
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<tr>
<td>Active and reactive power can be controlled</td>
<td>Balances loads instantaneously</td>
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<tr>
<td>No impact on system inertia</td>
<td>Contributes to system inertia</td>
<td></td>
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<tr>
<td>Cannot black-start</td>
<td>Capable of black-starting</td>
<td></td>
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<tr>
<td>Operational only with higher SCRs</td>
<td>Can operate even under low-SCR conditions</td>
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Table 2. Comparison of GFL and GFM inverter capabilities from a weak-grid/low-SCR point of view.

<table>
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<tr>
<th>Issues with a Low SCR and a Weak Grid System</th>
<th>GFL</th>
<th>GFM</th>
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<tr>
<td><strong>Frequency response:</strong> The frequency response increases the system’s sensitivity to a disturbance. It also increases the ROCOF and frequency deviation. This may lead to load shedding or generator tripping. Further, it also leads to low-frequency oscillatory stability issues.</td>
<td>Due to the lack of inertia support from GFL, the frequency response is more susceptible to increased wind/PV generation.</td>
<td>With inertia support from GFM, the frequency response associated with the system’s sensitivity to a disturbance can be kept well under control.</td>
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<td><strong>Voltage stability:</strong> The voltage is sensitive to power variations at low fault levels (weak grid system/low-SCR system). A sudden increase in real and reactive power causes large variations in voltage, thereby leading to instability. Further overvoltage cascading occurs due to voltage fluctuations or overvoltage occurrences. Deeper voltage dips, slow voltage recovery, and renewable energy penetration in a weaker grid becomes a problem. Further, in a weak grid, wider voltage sag propagation also occurs.</td>
<td>GFL can maintain the voltage stability only up to an SCR value of 3. A lower SCR value leads to a collapse in voltage as the grid loses its stability. In this aspect, GFL can provide voltage support only in a strong system or a stiff system.</td>
<td>GFM can maintain voltage stability through all values of SCR, including values less than 3. Irrespective of whether a grid is stiff or weak, GFM plays a vital role.</td>
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<td><strong>Cascading failures:</strong> This happens when there is a voltage fluctuation in the converters and after a fault-induced voltage drop. Reduced power grid inertia would result in cascading failures and load shedding.</td>
<td>As the inertial support from GFL is not present, GFL cannot aid in cascading failures in a weak grid or a low-SCR system.</td>
<td>Considering significant inertial support from GFM, cascading failures in a weak grid or a low-SCR system can be prevented.</td>
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<td><strong>Protection schemes:</strong> An increased ROCOF leads to the tripping of protective relaying. Overcurrent protection is most likely to be affected in a low-inertia system due to low SCR levels, which might not be able to pass on the signals to the relays. Especially in case of differential protection, the difference in smaller currents is very small.</td>
<td>Due to a lack of inertial support from GFL, the protection schemes may be affected.</td>
<td>Since GFM provides a good amount of inertia in a weak grid, the chances of mis-operation of the protection schemes becomes minimal.</td>
</tr>
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As additional GFM is integrated into the grid, its capabilities are enhancing to address grid complexity. To function, most IBRs depend on regular grid signals; these are known as grid-following variations. IBRs serve as a check on GFM limits. System operators and planners have a hard time gauging the potential and needs of the necessary equipment,
which causes operational constraints, decreased production, and limited connectivity in IBRs. The reason behind this is the difficulty in accurately assessing the capabilities of the necessary equipment. Without clear benchmarks and commercial incentives, manufacturers are hesitant to invest in cutting-edge technologies. But the popularity of GFM is gaining wide attention, and with its advanced smart inverter functionality, it will serve as a boon for the smart grid environment. Since grid-forming (GFM) inverters emulate the behavior of synchronous machines, GFM controls play an essential function in inertia issues. Whether used alone or in combination with other GFM resources, GFM IBRs can improve grid dependability [31–33]. This paper is divided into the following twelve sections, which start with an introduction and discuss the most recent developments in GFM and GFL. Considering the difficulties found while integrating inverter-based resources into a weak grid, a comparison between GFL- and GFM-based inverters is discussed. This part first explains the advantages that GFM has over GFL and then it goes on to explain how the system’s short circuit current originates and how the SCR is computed. As a result, it is highlighted that the following inverters have limits based on their control mechanism and operating principle. The theory of operation and the control mechanism of a grid-forming inverter, the functionality of GFM at the system level, and the capabilities of GFM at the unit level are covered in the parts that follow to demonstrate the effectiveness of GFM. Finally, after a detailed review, this paper further presents the efficacy of a GFM-over a GFL-based converter for varying short circuit ratios through a simulation-based demonstration employing PSCAD/EMTDC for the first time, followed by conclusions.

2. Integrating Inverter-Based Resources into a Weak Grid

The term “inertia” in the context of managing electric power is the kinetic energy that is stored in rotating generators. A system of interdependent and mutually reinforcing generators is responsible for producing inertia. Every generator in these electromagnetic chains adds to the total inertia as it spins and is linked to the grid. Dependable power grids can keep their operations consistent and maintain the appropriate voltage and frequency levels regardless of unexpected shifts in the operating conditions, such as variations in power consumption or the development of faults. But weak power systems are more prone to these kinds of disruptions. Large voltage and frequency fluctuations caused by unexpected changes in the operating conditions increase the likelihood of instability in systems with weak grids. To put a number on a system’s resilience, previous studies have proposed several different metrics and ideas. Reactive power (dV/dQ) and active power (dV/dP), both of which affect voltage variation, are considered when calculating a grid’s resilience. Renewable energy sources (RESs) connected to the grid constitute what is known as a weak grid according to the IEEE 1204 standard [34]. Both static and dynamic performance are considered in this definition. This is because grid-connected RESs utilize dynamic frequencies and voltages, the stability of which is affected by the system strength [35–40].

For renewable energy sources (RESs), the short circuit ratio (SCR) is a common and straightforward metric to evaluate system strength at the point of connection/interconnection (POC/POI). One way to find the short circuit ratio (SCR) is to compare the POI’s short circuit power to the converter side’s rated power. If the transmission impedance (the X/R ratio in other terms) or the converter’s rated power increases, the SCR will drop, as per the specification. The result is a weak link to the power grid. The location of the SCR relative to the connected renewable power source is the sole way to distinguish between robust and fragile grid connections. If the SCR is 5 or above, the grid is strong; if it is 3 or lower, the grid is weak. An exceptionally weak grid is defined by IEEE standard 1204-1997 [34] as one with a switching current ratio (SCR) below 2.

One major cause of grid inertia is over-reliance on power electronic interfaces, more often known as converters, in renewable power sources. This drop would be substantially more noticeable under certain scenarios if enormous classical SGs were displaced. This change reduces the system’s efficiency in two ways: first, it causes short circuits, and
second, it lowers the levels of grid inertia. Issues with the protective system and variations in voltage and frequency are potential future power system difficulties. A centralized plant-level control system aggregates several separate inverter-based resources in the construction and development of utility-scale solar PV plants, much like Type 3 and Type 4 wind-based generators. These resources provide a great deal of control flexibility based on power electronic technology. Similarly, solar PV resources do not have mechanical features that rotate, which means that the control capabilities of WPPs are not limited by mechanical limits. The level of collaboration between plant-level controls and PV panels in a wind farm is determined by factors such as the inverter capacity, the irradiance available, the panel conditions, and the grid operating circumstances.

Several factors make inverter-based resources more susceptible to weak grid conditions. In contrast to more static forms of generation, their mechanical systems are constantly shifting positions, meaning they never run out of the synchronizing power that is generally provided by inertia. The electrical controls that disconnect the power source from the grid determine their ability to produce reactive and actual power as expected. Consequently, these controllers cannot function without a constant grid voltage reference. As the system degrades, the voltage reference loses some of its stability, and the influence of control dynamics and tuning on the system’s overall behavior grows. Identifying “weak” systems helps the reliability of bulk power systems (BPSs) by revealing weak grid hotspots. Due to their system-specific nature, weak grids make it difficult to create fair interconnection norms or criteria. Planners must identify vulnerable grid areas and properly evaluate each interconnection or potential problem area that relies significantly on inverter-based resources. To find the power system’s strength, the simplest method is to look at the short circuit ratio. The SCR evaluates the inverter-based resource’s rating in relation to the short circuit apparent power (SCMVA) resulting from a triple line-to-ground fault (3LG) at a power system location. It is common practice to provide the measurement site with the SCR number given the SCR metric numerator is location-dependent. SCMVA_{POI} stands for the short circuit MVA level at the POI without the current contribution of the inverter-based resource, and MVA_{VER} denotes the nominal power rating of the associated resource. This metric improves the design of conventional line-commutated converter (LCC) high-voltage direct current (HVDC) systems by measuring the system strength. Variations in active and reactive power consumption or injection might produce voltage variations, which can affect the system’s sensitivity to the phase angle and magnitude if the SCR area is small. Modifications to reactive and active power injection have little effect on rigid, high-SCR systems. Because it does not consider other inverters or power electronic devices (such as WPPs) that are electrically close to the POI, the SCR metric is best suited to examining a single inverter-based resource in a somewhat typical power system.

3. Comparison between GFL- and GFM-Based Inverters

Based on their control systems, power converters can be categorized as either GFM or GFL converters. One definition of a GFL converter is a constant-current source that is both controlled and maintained. The system’s components include the grid impedance \(Z_g\), a grid voltage vector \(V_g \angle \delta_g\), and converter output currents \(I_g \angle \phi_g\), as shown in Figure 1 (left). In order to maintain grid synchronization, the converter is frequently equipped with a phase-locked loop (PLL) that tracks the phase angle of the voltages at the PCC. The GFL converter regulates the grid currents to obtain the required levels of reactive and active power injection. It is unable, alas, to independently control the power and frequency of the grid. Instead, it uses the power grid or another external voltage source as its voltage and frequency references. Consequently, the GFL converter is not self-sufficient and cannot deal with frequency fluctuations. As demonstrated in Figure 1 (right), the GFM-based converter can also manifest as a regulated voltage source, where \(E \angle \delta\) represents the vector of the inverter’s output voltage. In the absence of a phase-locked loop (PLL) to monitor the phase angle of the voltages at the point of common coupling (PCC), specific GFM control systems can automatically synchronize with the power grid. The voltage source model of GFM
along with the system components are depicted in Figure 1 (right). These methods can replicate the behavior of traditional synchronous generators. GFM converters can quickly modify their output in response to power grid frequency interruptions. This is different from typical synchronous generators, which rely on stored spinning energy in the rotor for frequency control. Therefore, GFM converters can operate independently. Furthermore, numerous studies in the field indicate that power converters in electrical grids with a restricted capacity can be significantly influenced by the dependable functioning of a PLL. This occurs because in grids with a limited power capacity, the electric currents produced can readily influence the voltages at the PCC, which is under the observation of the GFL converter. However, a GFM converter has the ability to synchronize with unreliable power grids and achieve self-synchronization by utilizing the active power output. Overloading can happen when the grid is rigid because even a slight discrepancy in the phase between the converter and grid voltages can lead to significant variations in the active power [41–45].

Figure 1. Grid-following inverter (left) and grid-forming inverter (right).

4. Sources of a Short Circuit Current

A weak or stiff system is determined by the sources present in the system, as the contribution from every source that is in the system is significant. For electrical power systems to function securely, it is necessary to anticipate and simulate the sources of fault current. Under a variety of operating circumstances, accurate power system facility modeling is necessary for equipment rating selection and protective system setting adjustment. Both synchronous and nonsynchronous powered producing resources are included in the estimates of the short circuit fault current. A three-phase system that is properly balanced will produce currents that are symmetrical and of positive-sequence in nature. The present flow paths of each system phase can be determined using data on the features of the sequence network. Identical voltage drops can only be produced by positive-sequence currents. It is necessary to know the sequence impedances of the power system parts before constructing sequence networks for unbalanced fault (that constitute positive-, negative-, and zero-sequence components) calculations. Assuming a symmetrical system with balanced three-phase currents, the potential differences between neutral sites remain constant [46–51].

The fault current and short circuit behavior of synchronous machines have been studied extensively, in contrast to nonsynchronous plants. As a result of misaligned resources, the short circuit characteristics change. Generators, induction motors, power lines, and other electrical devices frequently experience short circuit currents. Most of the short circuit contribution comes from synchronous generators. The saturated sub-transient impedance of the generator is used to calculate the tripping delay, the opening time, and the arcing time, whether the depicted sequence is positive or negative. Usually, the generator step-up transformer’s low-voltage to high-voltage windings are made with connections that go from wye-grounded to delta (Δ). In the case of a system failure, these connections block the flow of zero-sequence currents from the generator. Therefore, in most cases, short
circuit tests do not necessitate zero-sequence reactance from the generator. Depending on their impedances, synchronous and induction motor convertors will supply the fault with an alternating current or a short circuit current when a failure occurs. The short circuit currents contributed by distribution induction motors and small synchronous motors are frequently disregarded by utility systems. The reason behind this is the poor penetration rate of these motors. The number of machines or units linked to the transmission substation during generation is a key differentiator between conventional generating resources and inverter-based nonsynchronous generators. A step-up transformer is one of several major devices found in a conventional power plant. This remains valid irrespective of the source of the power, be it combustion, steam, or hydropower. On the other hand, a substation transformer, a medium-voltage collector system, several smaller machines or units (such as solar systems or wind turbines), and individual step-up transformers can make up a similar nonsynchronous producing resource. Power generation can be accomplished through the use of all these parts. To ascertain whether the fault current contribution of a nonsynchronous generating plant is balanced or unbalanced, it is necessary to create a model encompassing all of its components. Proper arrangement of wind turbines and solar systems is essential to provide precise simulation. Utility-scale wind turbines are categorized into five main types according to the International Electrotechnical Commission (IEC) 61400-27 standard [52], based on factors such as the machine type, speed control capabilities, and operating features. During a failure of the alternating current system, synchronous machines with independent direct current sources can generate significant transient currents. Most of the fault current in an induction generator is derived from the machine’s transient reactance. The fault current in synchronous machines is determined by the sub-transient reactance. The failure duration of an induction generator is considerably longer as compared to that of synchronous devices. The classification encompasses the subsequent categories:

- Classification/Type I: Squirrel cage construction-based induction generator
- Classification/Type II: Wound rotor induction generator of squirrel cage construction with external rotor resistance
- Classification/Type III: Doubly fed asynchronous generator with back-to-back converters
- Classification/Type IV: Wind- and solar-based full power converter generator
- Classification/Type V: Synchronous generator with a torque converter through mechanical coupling

Type I wind turbines utilize an induction generator that is directly linked to the grid, obviating the necessity for a power converter. Excitation in an induction machine is lost when there is a decrease in the line voltage after a three-phase fault to ground. During the sub-transient period, a significant quantity of transient current is injected into the fault. Eventually, the AC component decays to zero. A small but noticeable reduction in current will occur at the phase-to-ground fault. No matter how low the current oscillations drop, the other phases will remain activated and connected to the network. Type II wind turbines use a nonsynchronous machine-like Type I turbine with variable rotor resistance to maintain the wind turbine power output during wind speed variations. The induction machine’s maximum fault current is reduced by the external rotor resistance in short circuit equivalent calculations. Slip-to-change and variable-speed operations are possible with Type II wind turbine external rotor resistor control, passive below the rated speed and active above it. Like Type I machines with different impedances, Type II machines also exhibit similar short circuit behavior. A collector bus links the capacitor, transformer, and collector line of the generator to the energy grid. Type III wind turbines utilize double-fed induction equipment to establish a connection between the stator and the grid while also connecting the rotor to a back-to-back power converter. The purpose of a power electronic converter crowbar system is to redirect the induced rotor current in the event of failures to safeguard the rotor-side converter and DC capacitors from excessive current and voltage levels. The resistance of a crowbar affects alternating current faults. Unlike Type III and Type IV generators, the short circuit behavior of Type I and Type II generators is mostly
influenced by the generators’ features. The full-scale power converter, which is susceptible to high currents and links the generators to the grid, is the component that controls the electrical performance of Type IV generators during a malfunction. A current limiter is integrated into the power converter to protect the power electronic devices in case of a failure near the plant. The Type IV design is regarded as a straightforward current source for enhancing the short circuit contribution. In contrast, the common voltage source used to define most generators is positioned behind an impedance short circuit equivalent. Type IV machines have the capability to alter the amount of fault current they contribute during disturbances by utilizing various control modes. The control modes encompass reactive power control, voltage control, and reactive power control with fault ride-through operations. If a fault occurs, a Type V turbine operates similarly to other synchronous generators, allowing for straightforward modeling using the same approach. The model’s synchronous generator is linked to the power grid via a line and a collector bus. The power electronics and gadgets used in flexible alternating current transmission networks are typically ignored when determining the likelihood of short circuits. However, the transformers that connect these buildings to the larger power grid are part of this system. Static power converters, whether with a classical or voltage source, are a typical part of systems for high-voltage direct current transmission. No static power converter, unlike any component of a flexible alternating current transmission system, can provide current in the event of a short circuit. In contrast, transformers that contain static power converters—a potential source of fault current—are factored into short circuit calculations. Therefore, transformers that are linked to HVDC facilities are accurately represented in the situations involving short circuits. Induction motors are not the only potential sources of short circuit current. A slow fault current decrease can be observed in large induction motors, even in the absence of a DC rotor winding. According to the horsepower output, motors are categorized as small, medium, or big according to ANSI C37.010. The sub-transient and interrupting periods can be approximated from the transient impedances using a specific set of impedance modifiers that are specific to each category [19,53].

It is customary to consider variable-frequency drivers when performing three-phase short circuit calculations. Reversible converter-supplied drives can generate fault current by temporarily reversing the mass of the motor and the mass of the static equipment [54,55]. During the initial fault cycles, the inverter’s current will exacerbate the fault by transmitting energy in the opposite direction when the transient inverter mode is used for deceleration. To avoid short circuits once the motor’s speed stabilizes, it is necessary to employ power electronic safety mechanisms such as fuses and internal circuit breakers. Short circuit assessments are performed to consider the passive components of transmission networks, such as transformers, lines, and series reactors. The nameplate impedance and configuration (delta–wye or wye–delta for an unbalanced fault) of each transformer must be known in order to make short circuit calculations. Accurately representing the type of transformer (such as auto, two-winding, or three-winding) is crucial since the fault contribution differs depending on the transformer’s characteristics, such as its type/configuration and impedance. The length and configuration of the transmission line are essential factors for calculating the line impedance. In this context, reactors are used to represent the equivalent impedance of the transmission line [56]. Due to the constant 90-degree phase difference with the system voltage, the short circuit impact of capacitors is ignored. For instance, if there is a fault causing the sinusoidal system voltage to drop to zero, the capacitor will have its highest initial current, but it will be in sync with the system voltage [57,58]. The capacitors’ impact on the fault current rapidly diminishes. Hence, at the peak of the system voltage, the capacitors do not contribute any current [59,60].

5. Estimation of the Short Circuit Ratio

The short circuit ratio (SCR) is a valuable indicator to employ when assessing weak grids in the vicinity of power electronic converters. The current applications of this technology to nonsynchronous plants are based on its utilization in identifying and evaluating
unfavorable grid conditions near high-voltage DC converters. The SCR can be defined as the grid’s voltage rigidity. The process of determining the voltage stiffness of the grid involves a two-stage technique. At the point where the source being investigated connects to the grid, which is called the interconnection or the collector bus, a traditional study of the faults in three-phase systems is started. The next stage involves calculating the short circuit capacity in relation to the MW rating of the fault current source at the interconnection bus, as shown in Equation (1).

The SCR is calculated as follows:

\[
SCR = \frac{S_{SCMVA}}{P_{RMW}}
\]  

The newly connected generating source’s rated megawatt value (PRMW) and the current network’s bus’s short circuit MVA capacity (SSCMVA) are measured before the connection. A low SCR is very concerning since it indicates that the plant’s internal controls will not function reliably. There is a greater chance of sub-synchronous activity and control interactions among neighboring devices that use power electronics, and the representation of positive-sequence stability may not be accurate or mathematically stable. When plants are near one another electrically, they may interact and oscillate in opposition to one other. The SCR calculation using Equation (1) could give an overly optimistic result in some cases. A standardized way to calculate the SCR index does not yet exist for weak systems that rely significantly on inverter-based resources, such as battery storage, wind, or solar power plants. To account for the interaction effects among the producing resources and to provide a more accurate computation of the system strength index, as well as to assess the potential hazard of complicated instability, a more trustworthy indicator is needed. Several approaches exist for determining the SCR of a fragile system that relies significantly on inverter-based resources: for example, GE’s composite SCR and ERCOT’s weighted SCR methodology [61].

Using the SCR (as previously established) to understand the grid’s strength becomes challenging when many inverter-based resources are closely interconnected [62]. Applying the short circuit ratio (SCR) to forecasting the power capacity of an inverter-based energy source located near other inverter-based energy sources may result in excessively exaggerated estimations. System strength computation for electrically coupled groups of inverter-based resources has been the subject of multiple proposals [63]. Finding realistic limits for the power transmission from inverter-based resources over large power system interfaces was the goal of a recent Texas study that employed the weighted short circuit ratio (WSCR) [64,65]. The WSCR is calculated by subtracting the current from nonsynchronous sources (SCMVAi) and the necessary MW output (PRMWi) that must be connected to bus i from the short circuit capacity at bus i. N is the total number of totally interdependent wind turbines, and i is the exact location or sequence of each turbine. This is shown as an equation in (2).

\[
WSCR = \frac{\sum^N_i SCMVA_i * P_{RMW_i}}{\left(\sum^N_i P_{RMW_i}\right)^2}
\]

By linking all the inverter-based resources to a single medium-voltage bus, the composite short circuit ratio (CSCR) can be utilized to assess the equivalent system impedance. The next step is to determine the composite short circuit MVA at the common bus, which is abbreviated as CSCMVA. Currently, the inverter-based resources should not be factored into this computation. The calculation of the CSCR can be determined as follows, as per Equation (3):

\[
CSCR = \frac{CSC_{MVA}}{MW_{VER}}
\]

MWVER represents the total of the nominal power ratings of all resources that are known to be based on inverters. This approach computes a collective system control reserve or many resources that rely on inverters, in contrast to the traditional SCR method.
essential premise of both the WSCR and CSCR calculation approaches is the existence of a robust electrical link between nonsynchronous power stations. By assuming that all nonsynchronous generating facilities are linked to a virtual point of interconnection (POI), this is beyond acceptable.

6. Limitations of Grid-Following Inverters

Due to the physical distance between their points of interconnection (POIs), nonsynchronous generation facilities may fail to fully engage with one other. This approach generally produces more precise CSCR (Capacity Short Circuit Ratio) and WSCR (Weighted Short Circuit Ratio) values compared to SCR (Short Circuit Ratio) based on inverters. Unstable GFL converters can occur in weak grid conditions. A compensator that maintains system stability can reduce the distributed virtual inertia, as stated in multiple articles. The grid’s frequency imbalance can be monitored by injecting energy into DC-link capacitors via DVI. Without a synchronizing frequency source, it is not possible to run the system with 100% converter penetration and replace all SGs with GFL converters [66]. When dealing with high-penetration circumstances, GFL converters struggle to manage AC voltage variations due to their lower frequency and voltage regulation capabilities than SGs [67,68]. Synchronization and grid instability will therefore take place. The grid stability is enhanced by GFL’s FRT capabilities, also known as low-voltage ride-through (LVRT) [69,70].

Due to current limiter failure, GFL converters, which are becoming more widespread, can cause transient angle instability. A mismatch between the input and output power can also be caused by instability. Various research techniques are employed to steer clear of transient angle instability. By combining parallel SGs with virtual synchronous generators, in SG-VSG systems, researchers tested the transient angle stability of isolated microgrids. To enhance transient angle stability, the study in question decreased the reactive power. The effects of severe signal disruption on stability because of the nonlinearity of GFL converters have been investigated. A lack of grid strength causes GFL converters to become unstable and ineffective.

An increase in the use of power electronics can lead to frequency fluctuations and power system instability due to the negative damping effect and the absence of natural inertia. The drawbacks of GFL converters can be mitigated with the aid of a control loop that simulates virtual inertia. To achieve a rapid frequency response in a low-inertia system, virtual inertia optimization at dispatch points, such as system split and generator tripping, is essential. We found that low-inertia systems benefit from better frequency stability when synchronized with VIMs and GFL converters. The operation of a VIM is analogous to that of an induction generator. Starting synchronization and accurate grid voltage, power, and frequency estimation are guaranteed by this method. At a high grid impedance, researchers have looked at the effects of disturbances on system stability. To evaluate stability in weak grid conditions and at a large signal scale, the outer DC-link and AC-side voltage control loops can be constructed using a GFL converter. Stability requires striking a balance between limiting the integral gain of the DC-link control and improving the AC-side voltage control. Research has compared the capabilities of overvoltage and overcurrent. The former is slightly better, while the latter is perfect. The GFL converter must be synced to reliably supply the grid with reactive and active power. A synchronverter, a perfect voltage source, can be integrated to improve the system stability. It is straightforward to construct and install a standard proportional resonant controller for power converter electrical distance, and it monitors negative sequences well. There is no requirement to synchronize this control.

To prevent GFL converters from becoming unstable due to the PLL’s positive feedback, vector current control (VCC) is employed. Worries about power restriction in unreliable networks are heightened by this control mechanism. The small-signal stability, stability range, and the impedance model’s negative resistance of the GFL converter can all be enhanced using a straightforward impedance reshaping technique. A GFL converter’s instability during a breakdown could be caused by its PLL-based grid synchronization.
With a PLL frequency limiter, the phase change is minimized, which can be an issue. It leads to shaky systems, poor performance, and erroneous PLL inputs.

Most resources that rely on inverters require a PLL to synchronize with the grid. The inverter can function in “grid-following” mode by using its closed-loop control system to determine the grid’s phase and frequency. To feed the control algorithms, PLL voltage phase estimation is employed to obtain the current and voltage on the d and q axes. Control action, often called converter modulation, is employed for the transformation from d-q to phase values using PLL voltage phase estimation. A PLL system’s active and reactive power management of inverter-based resources is flawed if the voltage phase angle is not precisely correct. The time it takes for the PLL to synchronize again once a fault is cleared is critical for controlling reactive power and maintaining system voltage. This important PLL function becomes considerably more difficult in weak systems in a short window (1–2 cycles after a failure) due to the excessively loud post-fault voltages and the possible substantial phase angle change. In the event of an EHV failure, the maker of the inverter is liable for making sure the PLL is stable and capable of withstanding significant phase fluctuations. Manufacturers often treat the details of how PLLs work as proprietary knowledge based on their own studies [71]. However, it is important to remember that TPs must be knowledgeable about the characteristics of the resources associated with BPSs [72]. The fact that transient stability models misrepresent the PLL is a major obstacle to studying the integration of inverter-based resources into weak systems [73]. Appropriate models are necessary to use due to this issue [74].

When the PLL interacts with a weak terminal voltage, this can lead to a loss of synchronization in the GFL control, which, in turn, causes instability problems due to the transients in grid-connected RESs, especially during LVRT or after failures. Densely packed VSC producing units in power networks reduce grid inertia and raise frequency stability difficulties. Several research works have focused on the phenomenon of transitory stability enhancement. A steady ZVRT capability, unconstrained by current injection constraints and additional control loops, was realized with the introduction of a PLL freezing mechanism. However, it is not possible to solve the phase leap using that strategy. The active current reference was managed using a PLL frequency-based technique, which relied on the observed frequency. This aided in resolving the problem of synchronization loss and enhancing transient stability, particularly under significant voltage sag. By utilizing adaptive current injection, the dynamic performance of the system was improved through the prediction of the X/R ratio. Additionally, it effectively reduced the transient instability by providing grid impedance that closely resembled the impedance after a fault, serving as a reference for the ratio of active to reactive current. This analysis provided a detailed examination of transient stability, with a specific emphasis on design. It utilizes the phase portrait and the first-order phase-locked loop (FO-PLL) as key components. When there is a problem or cleaning needed, this approach enhances the phase estimation accuracy and the transient stability of the SRF-PLL in the VSC by increasing the damping ratio. This allows it to function effectively in a stable state.

Synthetic inertia is not a problem because linked renewable energy sources have a high ROCOF, a lot of frequency variability, and quick responses from power converters. Problems like undesired load shedding, cascade failure, and widespread blackouts can be mitigated or prevented with the use of DC-link capacitors to mimic virtual inertia (VI). This can be undertaken to deal with or prevent these problems. This approach maximizes system inertia while minimizing frequency fluctuations without adding complexity or cost. This technique can increase the ROCOF by as much as 50% while decreasing frequency variations by 12.5%. In theory, a distributed virtual inertia (DVI) regulator and a new current controller compensator could make small-scale weak power grids more resilient in the face of frequency disruptions, thereby increasing the grid stability frequency. Its principal role is to keep the frequency consistent. Among the many possible benefits of this method are stable operation in poor grid settings and maximum DVI support, as well
as a 43% increase in the ROCOF and a decrease in the frequency nadir following a load disturbance.

One possible solution to mitigate the problem of fluctuating power production from renewable energy sources (RESs) is to employ a virtual synchronous generator (VSG) with grid-connected converters. Nevertheless, grid frequency disruptions may potentially affect this. Prior research has attempted to tackle this problem solely using VI control, without integrating any supplementary energy storage. A frequency-locked loop (FLL) was utilized that has resemblance to a modified Moving Average Filter (MAF) for the purpose of extracting the frequencies. The transient power performance is enhanced by utilizing the VI control approach, which relies on feeding forward the PCC frequency.

Changes in power have a smaller influence on the frequency’s efficacy, and oscillation is thus effectively subdued. To get rid of the two-frequency component, a frequency-adaptive demodulation method was used that was superior, faster to converge, and computationally efficient. By utilizing the grid-connected converter’s synchronous active power control, SG-like inertia characteristics, load sharing, and main frequency regulation were replicated. This study’s result was an improved control architecture for a primary converter controller. This structure was built using the state variables of an enhanced PLL (EPLL). Its voltage feedforward path, filter parameters, EPLL, and bandwidth components were optimized for that application. By decreasing the amount of data sent and received between the EPLL and the main converter controller, the system stability was adequate, and a lesser impact of instability on the grid voltage and frequency was witnessed. This was accomplished across a wider range of grid conditions, even if the signals were faint and garbled. All of these limitations of GFL inverters pave the way for GFM-based inverters, as they could be the crux of the smart grid environment.

7. The Principle of Operation and Control Mechanism of a Grid-Following Inverter

GFL converters are commonly used in distributed renewable power systems. The typical components of grid-connected power converters with GFL control that link renewable energy systems to the power grid are phase-locked loop (PLL) units and a double-loop vector control mechanism. GFL converters use a phase-locked loop (PLL) to find out the phase angle of the voltages at the PCC. As a result, the converter has complete command over the reactive and active currents supplied to the power system. The active–reactive power control (PQ control) system is employed as an external control loop in this article. This control scheme involves adjusting the converter currents based on the reference values set by the outer power loop. As its name implies, the outer loop is responsible for adjusting the active and reactive power input to the electrical grid. A schematic of a GFL converter with PQ control is shown in the following image.

The following variables are utilized: udc denotes the DC-link voltage; ua, ub, and uc denote the converter output voltages; ia, ib, and ic are the converter currents; upcca, upcbb, and upccc are the voltages at the point of common coupling (PCC); uga, ugb, and ugc are the grid voltages; iga, igb, and igc are the grid currents; and iCa, iCb, and iCc are the capacitor currents. The references for the active power output (Pe) and the reactive power output (Qe) are Pref and Qref, respectively. The grid’s impedance is denoted by Rg, whereas the inductance and capacitance of the LC filter are denoted by Lf and Cf, respectively. A system diagram and the control block mechanism of GFL are shown in Figure 2.
VSG control technology—a part of GFM control systems—has attracted a lot of attention. VSG control, which aims to replicate the properties of synchronous generators, is an effort to overcome these limitations. The following figure depicts the control scheme, illustrating the utilization of VSG control as a typical example of general GFM control. The variable $T$ or $T_{VSG}$ represents the phase angle of the reference voltage, whereas $E_m$ denotes the magnitude of the reference voltage.

8. The Principle of Operation and Control Mechanism of a Grid-Forming Inverter

As renewable energy sources become more prevalent, the power grid’s moment of inertia and damping are decreasing. The reliability of the power grid is jeopardized. Because their output is dependent on weather conditions, renewable energy systems that inject power into the electricity grid are even more vulnerable to stability difficulties than the grid itself. Because it can imitate the damping and inertia of synchronous generators, VSG control technology—a part of GFM control systems—has attracted a lot of attention lately. Consequently, the power grid will be competent enough to handle power variations caused by renewable energy sources and the load. Since this study solely addresses converters that are connected to the grid, to keep things simple, the DC side is depicted as a perfect DC source. The utilization of a GFM converter is an effective approach to addressing stability concerns in power electronic-based power systems. A phase-locked loop (PLL) unit, which is commonly seen in GFL converters, is not required for grid synchronization. Conversely, GFM converters possess the ability to achieve self-synchronization, allowing them to establish a consistent power grid and operate independently from the main power grid. In addition, GFM converters can regulate the frequency and voltage of the electrical grid [75]. GFM converters are a reliable and efficient solution for integrating renewable energy sources into the electrical grid, as they can provide steady power without relying on traditional synchronous generators [76]. Synchronous generators in conventional power networks maintain grid stability due to their inertia and voltage regulation capabilities. However, renewable energy sources such as wind and solar power lack these properties and can often lead to system instability [77]. The development of virtual synchronous generator (VSG) control, which aims to replicate the properties of synchronous generators, is an effort to overcome these limitations. The following figure depicts the control scheme, illustrating the utilization of VSG control as a typical example of general GFM control [78,79].

Figure 2. System diagram and control blocks of grid-following converter.
its amplitude. A system diagram and the control block mechanism of GFM are shown in Figure 3.

![System diagram and control blocks of grid-forming converter](image)

**Figure 3.** System diagram and control blocks of grid-forming converter.

9. **Functionality of GFM at the System Level**

The specific characteristics of grid assets and networked connections, which encompass numerous GFM IBRs, are described in great depth when system-level functioning is addressed. Stability, voltage support, frequency responsiveness, and system restoration and protection are the four primary characteristics of system-level function [80]. The attributes of a GFM inverter are manifested in the diagrammatic form in Figure 4.

![Attributes of grid-forming converter technology](image)

**Figure 4.** Attributes of grid-forming converter technology.

9.1. **The Frequency Response**

During stable operating conditions, the frequency of the power system remains constant and is distributed uniformly among all the interconnected nodes in the network. It
can also serve as a suitable substitute for the imbalance between the electricity supply and the demand in grids that are primarily powered by rotating machines. More precisely, any deviation from the expected stable conditions is caused by an imbalance between the power supply and the demand from the load. Following a disruptive event, such as a power generation failure or excessive demand, it is imperative to provide frequency response and regulation for many important purposes. The primary goals after this kind of event are to restrict the rate of change of frequency (ROCOF) and ensure a prompt return to the normal value while also maintaining the system frequency within the specified limits. These objectives can be achieved by introducing active power at either slower or faster time intervals, leading to what is known as a fast frequency response (FFR) or the more commonly seen primary and secondary frequency responses, respectively.

In this context, inertia can be defined as the capacity of a GFM device to counteract rapid frequency fluctuations by instantly adjusting power without relying on measurement or a controlled response. On the other hand, FFR refers to a deliberate capability that can be applied by making measured frequency changes. An inverter active power control system that is responsive to frequency deviations is a widely used method to achieve frequency response capability. Nevertheless, the frequency response capabilities of GFM (and GFL) IBRs are constrained by two primary factors: the inverter’s peak current capability and the characteristics of the energy source powering the inverter. These parameters encompass the capacity for further energy storage and the constraints imposed by the dynamics of the energy source. Although GFM IBR controllers are specifically engineered to respond organically to fluctuations in system frequency, it is crucial to acknowledge that not all primary controllers will exhibit identical behavior. Nevertheless, in cases when the system is operating at frequencies that are either too high or too low, it is anticipated that GFM devices will promptly modify their active power injection. A consensus exists in the examined literature regarding the expected frequency response service provided by GFM IBRs. However, it is natural for humans to desire to imitate the behavior of synchronous robots. An advantageous feature of GFM IBRs is the inclusion of supplementary definitions for the active power components, such as the active inertia power and the active ROCOF reaction power. The large range of possible primary controllers in GFM IBRs introduces a level of variability that challenges the common use of inertia in electromechanics, leading to confusion. The analytical equations for the rate of change of frequency (ROCOF) are often dependent on the inertia constants of the machines. This prompts us to question whether the intended functionality is truly designed to be resistant to obsolescence or whether it is only a precautionary measure relying on antiquated approaches.

9.2. Voltage Support

Even when a power system is in a stable state, the voltage magnitude fluctuates throughout different areas of the system, such as the transmission and distribution levels. This variation makes voltage a local quantity rather than a measure of frequency. To guarantee the secure functioning of all interconnected devices, it is crucial that the voltage magnitude and harmonic contents remain within acceptable thresholds. GFM IBRs should be capable of providing voltage support in the presence of disturbance events such as short circuits or line disconnections, which can cause voltage sags, surges, or phase leaps, subject to operational limitations. Some efforts have discovered the necessary attributes to provide the correct voltage support promptly, including active phase jump power and voltage jump reactive power, to address these situations effectively. Both GFM and GFL plants are required to inject or absorb reactive power to maintain the inverter terminal voltage within the specified limits (in order to handle low-voltage incidents, inverters need to possess the capability to endure such occurrences). When there is a sudden change in the voltage phase, a GFM plant is required to either inject or absorb active power. The response is limited by the inverter’s peak current supplying capabilities. To ensure the safe operation of the inverter during disturbance events, it is necessary to make synchronized adjustments to both the voltage and frequency.
9.3. Stability

According to the assessment of the literature, a stable system must have the ability to (i) withstand and recover from significant disruptions, such as line faults, and (ii) operate consistently while preserving stability under small-scale conditions. To maintain network synchronization, it is important to reject grid disturbances, which might manifest as alterations in voltage, frequency, or phase. High levels of IBRs can lead to reduced system damping and the emergence of new oscillatory modes due to negative control interactions, which raises concerns regarding the frequency stability. Within the framework of stability, the examined literature contains the following excerpts, and an analysis of why these excerpts may cause confusion is as follows:

- The stability of voltage is significantly influenced by the power demands of the system and the dynamic response of power sources in terms of both active and reactive power injections. Voltage stability, in classical theory, pertains to the ability of a power system to maintain voltages at all network buses close to the nominal value after the occurrence of a disturbance. The considerations for maintaining voltage stability are closely tied to the magnitude of the disturbances being assessed and the timeframe of the analysis. Furthermore, voltage stability is influenced by factors like the network, the operating conditions, and the dynamic behavior of the loads/generators. Exclusively concentrating on loads and generators may limit our ability to represent network dynamics and interconnections.

- An essential concern for the stability of an electricity system is an increase in the rate of change of frequency (ROCOF) caused by greater Inverter Based resources (IBR) shares. This is highlighted as a critical indication of stability. When analyzing grids that are mostly controlled by IBRs (it is important to determine whether the rate of change of frequency (ROCOF) is directly linked to the stability of the system under large-signal or small-signal conditions).

- When mentioning stability and the capacity to uphold network synchronism, they are frequently associated with the terms weak grids and (low) system strength. The challenge of measuring a particular concept such as large- or small-signal stability arises from the fact that these notions are subjective and cannot be precisely quantified.

- There is no information provided. When addressing stability, the short circuit ratio (SCR) is often mentioned. While the classical notion of the SCR is commonly utilized in discussions regarding voltage stability, its application to grid networks lacks a clear and precise definition. This contrasts with its utilization for synchronous generator capability, for instance. Using it as normal when considering high levels of IBRs could lead to misunderstanding because it is not universally applicable to all systems.

9.4. System Protection and Restoration

Current protection systems employ protective relays and circuit breakers to detect and isolate the massive fault currents that synchronous generators can generate. This aids in protecting the grid from potential short circuit catastrophes. Overcurrents can be located and identified using a variety of methods. These safety relays and breakers are present in generator assemblies across the whole electrical system. It is critical for IBRs to be compatible with the current protection protocols so that a ton of money can be saved by not having to renovate or replace protection equipment that was designed to ensure synchronous generators’ predictable behavior. Future dealings with IBRs’ behavior (both generally and GFM IBRs in particular) will necessitate a reevaluation of the guiding principles for protection systems.

It is possible that IBRs will have difficulty with distribution and transmission. The existing distribution system safeguards are only capable of allowing current to travel in one direction, greatly increasing the likelihood of malfunction. In theory, fault currents equivalent to synchronous generators are theoretically conceivable; however, most IBRs cannot achieve this owing to the high component costs. Standard practice calls for configuring IBRs to limit the fault current to 1.1 to 1.5 times the nominal value. This prevents the
operating current ratings of the switches from being exceeded. There may be selectivity issues with some current protection devices, and bidirectional current flow could alter fault currents. Injecting large negative-sequence currents from synchronous generators is one way that some transmission-level protection systems detect unbalanced concerns. These systems find unbalanced concerns in this way, among others. Academics are always looking for fault current contributions from GFM IBRs to make sure that traditional protection approaches continue to be of help. When the system status changes, there are protections to detect power fluctuations and out-of-phase events. The safety equipment for synchronous generators monitors the system voltage/current signal, which involves a higher change rate than the fault-induced change rate due to the inertia of the generators. Networks maintained by IBRs tend to have more extreme power fluctuations than other kinds of networks due to their dynamic nature. The response times of GFM IBRs are expected to be faster than those of GFL controllers. As a result, the system will be better able to recover from disruptions and prevent false tripping. Based on our literature review, we know that GFM IBRs are not compatible with the current security methods; nevertheless, we still need more research to comprehend this. The process of restoring and maintaining synchronization is made easier when GFM IBRs are connected to the bulk power supply. Current synchronous generators form the backbone of black-start systems. Future GFM appliances will have features including self-starting capabilities, voltage management, and the ability to synchronize with other inverters and generators for black-starting. Another crucial need is the continuity of voltage and frequency when connecting load and network portions to the restored system. Finally, GFM IBRs must be self-sufficient until they can establish communication with other regions; only then can the larger grid be formed.

10. Capabilities of GFM at the Unit Level

To meet the requirements at the system level, GFM IBRs can be designed to perform a wide range of tasks, including those specific to plants and aggregations. This capability is known as unit-level capability. To realize their maximum potential, GFM and GFL IBRs typically come with capabilities like voltage regulation and operating with a variable power factor. Among the potential future features of IBRs is the ability to operate in frequency-sensitive mode, which will allow for the modification of active power injection in response to variations in the system’s frequency. In contrast to GFL, however, GFM should be able to provide these services more quickly and with greater reliability.

10.1. Fast Fault Current Injection and Ride-Through

As long as they are connected to the power grid, IBRs have the capacity to survive disruptions due to their ability to receive power. In voltage ride-through, the disconnection of inverters from the grid is typically decided by predetermined thresholds for low-voltage and high-voltage restrictions. High-voltage constraints are also taken into consideration. On the other hand, there are now a great number of disagreements taking place across grid codes on the precise thresholds and the length of time that inverters are required to remain connected or unplugged during grid events. When it comes to reducing voltage sags, injecting reactive current is absolutely necessary. To avoid network assets from being disconnected during a voltage sag, it is important for IBRs to react within a time period of less than one-quarter cycle when the terminal voltage falls below 90% of its intended value. This is applied in order to prevent the terminal voltage from falling below 90% of its designated value. During faults, an IBR’s rapid fault current injection capacity is universally acknowledged to be of great significance. This is a reference to the inverter’s capability to swiftly introduce electric current into the system in the event that there is a problem with the interaction between the components. Due to the fact that electromagnetic physics causes synchronous machines to exhibit this kind of response, GFM inverters are also capable of producing an effect that is comparable because of their rapid control action. Depending on the nature of the defect, it may be necessary for IBRs to apply current
that possesses particular characteristics, such as active and/or reactive current, in order to maintain voltage for an extended period of time. In this situation, there are two key considerations: (i) For the purpose of synchronization, the unit-level controller in GFL is dependent on the external voltage source, in particular the grid. As a result of the potential for a large change in the quality of the source voltage, GFL has difficulties when it comes to (re)synchronizing and injecting power after a disturbance has occurred. Because it does not require an explicit external signal for synchronization, GFM has greater potential to handle disturbances and assure the correct power infusion.

This is because an external signal is not required. (ii) In contrast to synchronous motors, inverters have specified limits and are unable to endure the injection of huge currents without influencing the amplitude and frequency of the imposed voltage phasor, even when using GFM. This is the case even when the inverter is operating at its maximum capacity. It is a generator that is capable of withstanding fault currents that are up to six times higher than its full rated current without being permanently damaged. When it comes to limiting the flow of electric current through an inverter, the strategies that are utilized need to find a way to strike a balance between the physical limitations of the inverter and the concerns surrounding the stability of the system as a whole.

It is of the utmost importance that GFM and GFL controls have the capability to establish negative-sequence currents in order to reduce the voltage imbalance that exists within the network. The usage of alternative control structures, a departure from the traditional direct-quadrature-zero frame, and the utilization of more expensive hardware, which entails the utilization of four wires rather than three, may be required in order to accomplish this.

10.2. Inertia and Damping

Insufficient damping and inertia are not possible without synchronous generation. The original definition of inertia, which was primarily used to describe the physical attribute of rotating masses in synchronous generators, has been broadened to include a unit’s inherent resistance to changes in frequency and phase angle. Power electronics, despite being physically lightweight, have the capability to imitate synchronous generators by effectively identifying and stopping alterations in system frequency. Consequently, the literature that was evaluated does not cover anticipation of the inertia from IBRs. The frequency regulation capability of a GFM IBR is contingent upon its current ratings, the energy headroom, and the available power. Therefore, it is essential to consider the capabilities of individual units while defining the system-level needs. However, there exist specific unit-level requirements that are not dependent on any system. For example, responses that are equally or more rapid than the beginning timings of the primary controllers of synchronous generators are recommended, requiring a response within 5 ms of the onset of changes in system frequency. Determination of the ideal active power reserve size, which minimizes curtailment and maximizes the frequency management capacity, is currently being studied. This inquiry is necessary since the optimal size is specific to each individual power system and is influenced by different network characteristics and system demands.

Similarly, it is anticipated that GFM IBRs will regulate active power oscillations and stabilize power flows and system frequencies following disruptions. The dampening characteristics of GFM IBRs can be harnessed through control mechanisms when sufficient power, energy, and current are available. Therefore, GFM plants are required to possess effective power dampening capabilities and sustain an operational frequency range of zero to five hertz. Moreover, it is essential to have dampening factors that range from 0.2 to 5. It is crucial to consider the previous empirical findings when constructing future grids, as the boundaries that were set may have been influenced by them.

Furthermore, synchronous generators typically incorporate damping mechanisms to prevent mechanical strain and harm to equipment. It is essential to remove high-frequency oscillations for the proper functioning of IBRs. Oscillations can potentially arise from the presence of fast control loops or from unfavorable interactions among the
10.3. Power Quality

The problem of power quality in relation to individual IBR units is acknowledged. This is characterized by a dual function: (i) acting as a receptacle for harmonics and (ii) acting as a receptacle for imbalance. This attribute pertains to the capacity to uphold a high level of voltage quality at the point of connection while also offering a damping response within the harmonic frequency range. This is achieved by allowing the flow of harmonic currents within a specific frequency range, although the exact range is not specified, with an upper limit of 2 kHz being commonly acknowledged. Regarding damping performance, it is acknowledged that GFM IBRs can effectively improve damping by imitating inductive-resistive impedance behavior. Furthermore, additional guidance is also provided on the proportion of the contributions related to reductions in harmonics, the selection of impedance, and the adjustment of damping during networked operation. Attribute (ii) refers to an IBR’s capacity to manage unbalanced grid circumstances and establish suitable routes for negative-sequence impedance, hence enabling and controlling negative-sequence currents, similar to conventional synchronous generators. No other information is given regarding this matter.

11. Efficacy of GFM- over GFL-Based Converters for Varying Short Circuit Ratios

Though this paper highlights the efficacy of GFM over GFL in the form of a review, the effectiveness has further been demonstrated in the form of results that were simulated using PSCAD/EMTDC. A single-line diagram of a generic GFM/GFL converter source interfaced with a realistic North American system is shown in Figure 5.

![Figure 5. Single-line diagram of a generic GFM/GFL converter source interfaced with a realistic North American system.](image-url)

A 50 MW generic model of a GFL-based BESS and a 50 MW generic model of a GFM-based BESS have been configured for this study. The generic converter model is connected through a two-winding transformer (0.69 kV/34.5 kV) and then connected to the POI though a three-winding transformer (34.5 kV/13.8 kV/138 kV). This is, in turn, connected to the grid, and the SCR is varied at different time intervals. The simulation was executed with PSCAD/EMTDC over a period of 30 s.

Figures 6 and 7 represent the results for the voltage (pu), active power (MW), and reactive power (MVAR) at the POI of a 50 MW grid-following converter-based BESS operating at different SCR values in both discharging mode and charging mode, respectively. A fault is created at an interval of every 5 s, during which the SCR is also varied. It can be seen from the results that the GFL-based BESS maintains stable operation with the grid with varying SCRs of 8, 5, and 3. For an SCR value of less than 3, stability is lost with the GFL-BESS in place.
Figure 6. Voltage (pu), active power (MW), and reactive power (MVAR) at the POI of a 50 MW grid-following converter-based BESS operating at different SCR values (discharging mode of GFL-BESS) in PSCAD.

Figure 7. Voltage (pu), active power (MW), and reactive power (MVAR) at the POI of a 50 MW grid-following converter-based BESS operating at different SCR values (charging mode of GFL-BESS) in PSCAD.
Similarly, the simulation is executed with a 50 MW GFM-BESS in place with the same study system. Figures 8 and 9 represent the results for the voltage (pu), active power (MW), and reactive power (MVAR) at the POI of a 50 MW grid-forming converter-based BESS operating at different SCR values operating in both discharging mode and charging mode, respectively. A fault is created at an interval of every 5 s, during which the SCR is also varied. It can be seen from the results that the GFM-based BESS maintains stable operation with the grid with varying SCRs of 8, 5, and 3 and for an SCR of less than 3 as well. This demonstrates the efficacy of GFM over GFL in a weak system, and the futuristic grid sees GFM as a boon, as the grid is constantly evolving towards the paradigm of a smart grid environment.

Figure 8. Voltage (pu), active power (MW), and reactive power (MVAR) at the POI of a 50 MW grid-forming converter-based BESS operating at different SCR values (discharging mode of GFM-BESS) in PSCAD.
12. Conclusions

For future power systems that largely utilize renewable resources to become a reality, interconnected generating resources (IGRs) will have to step in and replace synchronous generators, which now supply grid functions. Making use of grid-forming technologies is one way that this could be achieved. Compared to GFL, GFM is superior for operators with low inertia and a weak grid, as demonstrated in this article. The power industry is witnessing the rise of grid-forming (GFM) inverters as a revolutionary solution to stability concerns. Among the many PV applications of GFM technology that enhance energy systems and enhance grid stability are hybrid plants, solar plants, BESSs, and wind energy systems. At a global scale, GFM based on BESSs has now emerged as pivotal. The preliminary results indicate that GFM controllers may substantially improve the power grid’s efficiency; however, research into these devices is still in its early stages. To keep the grid steady, store energy for later use, and make renewable power generating easier, GFM inverters are high-tech smart inverters. This paper provided deeper insights into integrating inverter-based resources into a weak grid with a detailed comparison between GFL- and GFM-based inverters, followed by discussing the sources of short circuit current and how the short circuit ratio is determined. Further, with the limitations of grid-following inverters, their principle of operation, and their control mechanism, the efficacy of GFM was demonstrated. Starting with a detailed review through the principle of operation and the control mechanism of grid-forming inverters, the functionality of GFM at the system level, the capabilities of GFM at the unit level, and the efficacy of GFM-based converters over GFL-based converters for varying short circuit ratios were also shown through simulation results for the first time. Consequently, this paper provided a baseline
for all people working in this domain by presenting the effectiveness of GFM over GFL, with a focus on low-inertia and weak grid systems.


**Funding:** This research received no external funding.

**Conflicts of Interest:** Shriram S. Rangarajan is an affiliated to Landrotics Solutions Private Limited. The authors declare no conflicts of interest.

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