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Will Grid Forming Inverters be the Key for High Renewable Penetration?

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Introduction

In regions such as Hawaii, South Australia, Tasmania, Texas, and Ireland, it is becoming common for power systems to experience instantaneous penetration levels of inverter-based power sources (IBPSs), such as wind, solar photovoltaics (PV) and battery storage, in excess of 50-60% relative to system demand.

New challenges arise when systems are operated with fewer synchronous generators (SGs) and more IBPSs. The penetration level of IBPSs at which these challenges occur is system-specific and depends on the amount of SGs in operation, their location and rating relative to IBPS production level, size of the largest credible contingency, stability of IBPS control systems, and availability of the interconnections. Analysis by system operators (SOs) such as EirGrid in Ireland and National Grid in Great Britain (GB), have shown that these challenges increase dramatically when IBPSs serve more than 65% of system load. Although large synchronous areas such as Continental Europe (CE) may not reach as high percentages in the next 10 years, parts of these synchronous areas (such as Germany or Denmark) are already experiencing situations when IBPSs serve a significant portion of their local load, in some cases in excess of 100%. Reliable operation of such systems currently depends on the support from the rest of the synchronous area. Following the occurrence of a low probability, high consequence event such as system separation (e.g. November 4th, 2006 event in CE), these smaller parts of the larger synchronous area require the capability to avoid a total collapse. As depicted in Figure 1, the forecast from 2016 shows that by 2025 the highest IBPS penetration level in 8 out of 33 countries in Europe would reach 100% of the load. These highest instantaneous penetration levels could be typically 3-5 times higher than the annual average penetration levels.

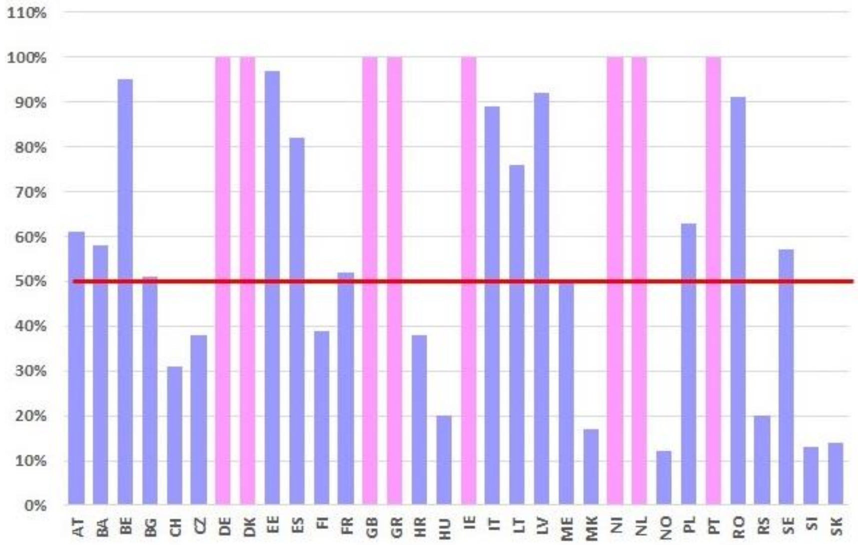

Fig. 1. Highest hourly penetration levels of IBPSs in Europe by 2025 (2016 forecast).

A large presence of online SGs inherently slows the overall system dynamic changes, thereby allowing present grid-following (GFL) IBPSs (having fast and rigid controllers) to accurately track the gird voltage angle of the grid voltage and inject current at the correct phase angle and frequency. However, as SGs are replaced with IBPSs, the system dynamic changes become faster, resulting in the rigid fast inverter controllers potentially failing to adequately synchronize with the system. This can be deduced from control theory; a fast-moving reference can only be tracked by an even faster controller. At these fast response timescales and with rigid control, even a small perturbation can result in significant consequences (discussed in subsequent sections of the article). Thus, as the penetration of IBPSs increases, their controllers need to become more robust in responding to a system with faster dynamics.

Presently, for operational security reasons, some synchronous areas (e.g. Ireland, Texas, and South Australia) need to either frequently limit (curtail) output of IBPSs, or require a sufficient number of must-run SGs. The installation of synchronous condensers (SCs), to provide necessary characteristics supporting reliable operation with very high IBPSs penetration, has also been pursued as it is often difficult and expensive to maintain a sufficient number of SGs online. In the long run, operational constraints and the need for additional investments into SCs could significantly affect further development of IBPSs.

In recent years, the concept of grid-forming (GFM) IBPS technology has been pursued by the research community as an alternate robust IBPS controller. Constructing an exact definition of a "grid-forming" IBPS is complex, as the characteristics are still being shaped in concert with the changing needs of the power systems around the world. However, for the purpose of this article, a GFM IBPS broadly refers to IBPS capable of supporting operation of an ac power system under normal, disturbed, and emergency conditions without having to rely on services from SGs or SCs. This includes system conditions when 100% of the electricity demand is being supplied from IBPSs as well as situations with very low IBPS penetration, and transitions between the two. More specifically, it would be desirable for a GFM IBPS to have the following functionality:

a) Under normal conditions (small signal) it behaves as an ac voltage source (voltage behind impedance), while respecting its internal physical limitations. Control and associated settings of this voltage source should be designed depending on the power system to which it is connected.
b) It works autonomously if it is isolated from the bulk power system.
c) Under transient conditions it behaves as described in (a), but it may fall temporarily into a specific operation regime in order to respect its own limits. However, as soon as the limits are not at risk of being violated it must return to the behavior described in (a).
d) Similar to select SGs contracted to provide black start services at present, it is expected that some GFM IBPSs will have sufficient energy buffer (battery storage, possibly, coupled with a super-capacitor) to initiate system restoration after a blackout, while others should be capable of supporting the grid restoration process.

This article attempts to describe GFM functionality needed for secure grid operation with high penetration of IBPSs without being overly prescriptive on how this functionality is achieved. The functionality is also subject to physical limitations of an inverter, such as short-term current carrying capability and availability of an energy buffer. The necessity for, and amount of these capabilities must be determined based on specific system needs confirmed by simulations.

The functionalities listed above are required in addition to the capabilities of the existing GFL technology, typically mandated by grid codes. This includes operating in a stable and coordinated manner with other

IBPSs as well as SGs, not causing adverse control system interactions, and maintaining industry-standard characteristics such as fault-ride-through capability, fault current injection to support grid voltage, and active power-frequency control.

Some of the functionalities that may be expected from GFM IBPSs may not be provided even by SGs in today's power systems. However, this does not preclude one from recognizing the capabilities that could be harnessed from IBPSs of the future and may be necessary under high IBPS penetration levels.

In order to achieve a high penetration of IBPSs, it is not enough to just resolve the operational issues mentioned above. Broader system resiliency must be considered, covering resource adequacy, reserve availability, and managing uncertainty due to weather dependent generation, among other issues. This article focuses on system security from a SO's perspective; particularly, stability, while operating at high penetration of IBPSs, and then on grid-forming IBPSs as one of the possible solutions, including manufacturers' perspective along with a summary of ongoing research.

Operators' Perspective

This section describes eight key challenges encountered by SOs in synchronous areas with high penetration of IBPS. These challenges are expected to worsen as the IBPS penetration level increases unless adequate system-specific solutions are developed and implemented. Existing practices adopted by some SOs to address these challenges include maintaining sufficient amount of SGs, constraining total output of IBPSs, or applying constraints to reduce the largest credible contingency. Other solutions such as installing SCs, GFM IBPSs, or a combination of both also have been discussed in recent years. At the time of writing this article, however, no grid code mandates a GFM capability, although a draft of such requirement was considered in GB in 2018 and revised proposals are expected in 2019.

1. System strength
    - Sufficient system strength needs to be maintained at all times under normal and contingency system conditions. System strength has been traditionally represented by the fault level available at a specific node in the power system in relation to the rating of an IBPS connecting at this node, or short circuit ratio (SCR). More recently SOs started using versions of an aggregated SCR recognizing that electrically close IBPSs have a cumulative effect on the system strength of that entire part of the grid. Historically, system strength issues have been primarily associated with connection of IBPSs electrically remote from SGs. In several jurisdictions a significant increase in IBPS penetration along with a decline in number of online SGs have caused system strength issues to affect the entire power system rather than only some remote parts.
    - Present GFL IBPS are designed to operate in a stable manner down to a certain minimum system strength level. Loss of multiple network elements can result in a decline in system strength compared to normal conditions. Automatic disconnection of IBPSs or a significant power runback is sometimes used due to inherent inability of GFL IBPSs to maintain stability under reduced system strength. In areas with a significant concentration of IBPS, the occurrence of multiple outages could result in concurrent power reductions of several GWs of IBPS, significantly larger than the largest credible contingency.
    - Unlike synchronous machines, which act as a source of system strength, presently GFL IBPSs do not contribute to system strength, but rather have the overall effect of reducing it. In some cases, SCs are installed to mitigate this inherent limitation of GFL IBPSs. The

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expectation of SOs is that the connection of IBPSs should not result in the reduction of system strength below levels required for existing power plants, and for the overall power system. A GFM IBPS has the potential to achieve this goal.

2. Inertia and rate of change of frequency (RoCoF)
    - There is a strong interrelation between system strength and inertia since, with present technology, both are provided by synchronous machines. Presently, synchronous inertia must be maintained at all times for islanded or dc-connected power systems such as GB, Ireland, Texas, and Tasmania. A minimum level of overall synchronous inertia is needed for two purposes; 1) To reduce the initial RoCoF after a large generation or load disconnection, thereby avoiding a cascading disconnection of SGs, particularly gas turbines, 2) To arrest the frequency decay and raise the frequency nadir after a generation trip, or to arrest the frequency increase and lower the frequency zenith after a load trip.
    - This minimum level of synchronous inertia can be reduced, though cannot be fully substituted, with the fast frequency response (FFR) that can be provided by GFL IBPS. Additional inertia above the minimum level, required to form a viable island in case of system separation, and to maintain power system security, can be provided by additional synchronous machines or supplemented through FFR from IBPSs. A response time of several hundred milliseconds is generally sought. Research and several practical examples from small island system applications have demonstrated that a minimum inertia level requirement can be eliminated if a certain share of inverters is grid-forming with sufficient energy buffer.
3. Disturbance ride-through
    - High and low voltage ride-through

      In addition to remaining connected to the power system, IBPSs are expected to support system recovery by injecting active and reactive current of appropriate magnitude in a timely manner. The need for fast active power recovery is not a major issue in highly interconnected power systems, but is critical in islanded or weakly interconnected ones. Unless designed with significant overcurrent capability, IBPSs may have limited ability to provide high active and reactive current injections simultaneously. A further concern with GFL IBPSs is the potential need to intentionally slow down injection rates in low system strength conditions. State-of-the-art GFL converter control system designs assist in mitigating this concern. However, the response is inherently dependent on the various real-time system conditions. Stable response of a GFM IBPS does not depend on the available system strength. A higher or faster injection of active or reactive current will not therefore destabilize its performance, provided that it can be sustained by the power system to which the GFM IBPS is connected.
    - Step-changes in voltage phase angle

      Transient step changes in the source voltage phase angle could result in incorrect operation of control systems used in GFL IBPSs. Not only is the depth of voltage dip important, but also the instantaneous change in phase. This implies the need to study the impact of a range of disturbance types and locations rather than focusing only on severe close-in faults.

      GFM IBPSs have inherent ability to prevent fast angular change and improve system security for more severe system disturbances.
4. Adverse system interaction

Adverse interactions among multiple power plants has been experienced for several decades, including sub-synchronous resonance and sub-synchronous torsional interactions. These interactions are generally associated with certain operating conditions that can be studied and mitigated during project design. Control interactions involving control systems of several IBPSs are generally more complex to identify and analyze than those pertaining to SGs. This is because the frequency at which the interactions occur could vary substantially spanning the sub- and super-synchronous frequency ranges. There are no particular operating scenarios or outages that necessarily initiate these interactions, and they can occur without any disturbances. Stable operation of GFM IBPSs does not depend on the available system strength. As such a GFM IBPS with properly designed controls will be less susceptible to adverse interactions under reduced system strength conditions.

5. Protection system impact

A combination of declining number of online SGs and limited short circuit current capability of IBPSs lead to an overall reduction in the system fault current levels.

In addition, most IBPSs have been historically designed to provide positive-sequence current injections only. Transmission-level protection systems rely on negative- or zero-sequence quantities in addition to the positive-sequence component. This includes an appropriate magnitude of these components, as well as the expected phase relationship. In scenarios with high penetration of IBPSs, unbalanced faults have led to incorrect operation of distance protection. As the penetration of IBPSs increases, these issues may continue. German grid codes already require deliberate injection of a negative-sequence current component, addressing this concern to some extent. Some of the commercially available GFM IBPSs provide a fault current contribution of 200% of rated value at the inverter terminals. This higher current injection capability, compared to the existing GFL IBPSs, would allow simultaneous injection of both the positive- and negative-sequence current components, alleviating the concern discussed above. Commercially available GFL IBPS are not currently made with comparable overcurrent capability, even though this is technologically possible.

6. Contingency frequency control during islanding conditions

In islanded scenarios with high share of IBPS, additional energy storage or deliberate headroom on IBPSs might be required to provide sufficient contingency frequency control. GFL IBPSs however need sufficient system strength to provide a stable frequency response. To maintain required system strength, additional SCs may be needed.

A related question is whether the combined capability of SCs and GFL IBPSs in controlling voltage and frequency can emulate the capabilities traditionally provided by a SG, or if the use of GFM inverters is essential. While these are concerns shared by many operators, there are limited studies that indicate that GFM IBRs can help mitigate these issues. More studies are required to confirm this.

7. Initiate/support system restoration

GFL IBPS have limited ability to support system restoration since they require a minimum system strength for stable operation. Conversely, GFM IBPSs could be used in the early stages of system restoration, including acting as black start units, provided that it is equipped with sufficient energy buffer.

8. Accurate and fast simulation models

Electromagnetic transient (EMT) models may be required in an inverter dominated power system to overcome issues associated with accuracy and appropriateness of phasor-domain models. AEMO has developed full EMT network models for three of its five regions. ERCOT and National Grid in GB are also using EMT models for part of their networks with high penetration of IBPSs. As a result of providing an in-depth level of detail and accuracy, EMT simulations are computationally-intensive, and, therefore, impractical for control-room applications, such as dynamic security assessment tools. Significantly faster simulations with the accuracy of the EMT models are required. This is the subject of ongoing research.

Manufacturer's Perspective

The majority of IBPSs connected to bulk power systems are based on GFL technology. During the last two decades manufacturers have focused on pushing the limits of this technology, successfully developing grid support capabilities (fault ride-through, voltage control, frequency control, weak grid operation, and other similar features) for the vast majority of applications. However, the limits of GFL technology are being approached in areas such as Ireland, Texas and South Australia.

Akin to the development of any manufactured product, IBPSs manufacturers depend on a robust market for their products. In the eventuality that a power system could not accept the connection of additional IBPSs due to reliability constraints, IBPS manufacturers would be severely impacted. Hence, there is interest and openness among manufacturers to incorporate new features, if these are necessary for secure power system operation.

Due to intense competition, IBPSs manufacturers generally only consider the development of new products and capabilities if sufficient incentives and market value exist, for example, based on grid code requirements or market incentives.

To identify system needs and ensure the availability of solutions, some fundamental rules should be respected:

- Technical requirements need to be transparently discussed and proven.
- Technical features that are critical for overall operational security, and cannot be delivered as ancillary services, should be defined as minimum interconnection requirements for all generators (e.g., fault ride-through capability and active power-frequency control).
- Ancillary services should be acquired on a least-cost basis. This applies to conventional services such as load/generation balancing, voltage support and black start as well as potential new services such as FFR and damping.

IBPSs, presently, operate in maximum power point (MPP) tracking mode to harvest the maximum amount of energy from a variable energy resource and maximize commercial value of a project. An energy buffer is not required for such operation and is typically not included with today's technology. GFM capability, however, relies on the existence of an energy buffer (battery storage, headroom on wind or PV IBPSs, supercapacitors, or a combination of these, depending on the application). Depending on size and capabilities, the economics associated with an energy buffer could be prohibitive. GFM capability could also result in extended times of operation outside of the MPP mode for PV and wind IBPSs.

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GFM IBPSs based on MW-size battery systems are already available on the market and are being used in several actual projects. Some of these projects allow for parallel operation of several inverters performing GFM functions. The battery-based IBPS launched by the Imperial Irrigation District in California uses 30 inverters of 1.25MVA and can black start motor loads and energize high voltage transformers. This control concept can be scaled by simply adding more inverters. High current rating requirements can be overcome by increasing the number of inverters or by accepting degraded performance, such as deeper voltage sags during motor start-ups.

In general, most existing MW-size GFM applications have technology of interest for bulk power systems. However, depending on the exact requirements the costs can be high compared to same size GFL IBPS. The primary cost drivers are energy buffer, oversizing of equipment, and the need for different control strategies based on user specifications. As an example, Table 1 shows some functional requirements for GFM IBPSs and IBPS aspects affected by these requirements, compared to GFL technology.

Examples of functional requirements for GFM IBPS	Affected product aspect of GFM BPS compared to GFL IBPS		
	Is higher current capability required? (Hardware)	Is energy buffer needed? (Hardware)	Are control algorithm changes needed? (Software)
Fast active power variations	Potentially	Yes	Yes
Response to grid voltage vector shift	Yes	Yes	Yes
Inrush current	Yes	No	Yes
Fault current contribution	Yes	No	Yes

Table 1. Examples of functional requirements for GFM IBPS and affected product aspects, compared to GFL IBPS.

Functional requirement examples listed in the table are further clarified below:

- The behavior as a voltage source can demand fast power output variations from a GFM IBPS during system transients, caused by generation tripping, grid voltage vector shift (see Figure 2) or system split. These variations in ac power output will likely demand an additional source of energy in PV and wind IBPSs. The magnitude and duration of these power surges are an important design consideration and will lead to additional costs.
  Battery-based IBPSs do not require an additional source of energy, as long as the battery's response speed allows the GFM to maintain its designed characteristics.
  To withstand all transients and, in particular, grid voltage vector shifts, supercapacitors may be needed, resulting in additional cost implications.
- Inrush currents, needed during energization of transformers, can impose a significant increase in current capability requirements. Rating and characteristics of equipment to be energized solely by the GFM IBPSs are an important design consideration.
- Current contributions during faults in excess of the IBPS rated current are commonly not required in present GFL IBPS. Increased fault current contribution requirement from GFM IBPSs is an important design consideration and will lead to additional costs.

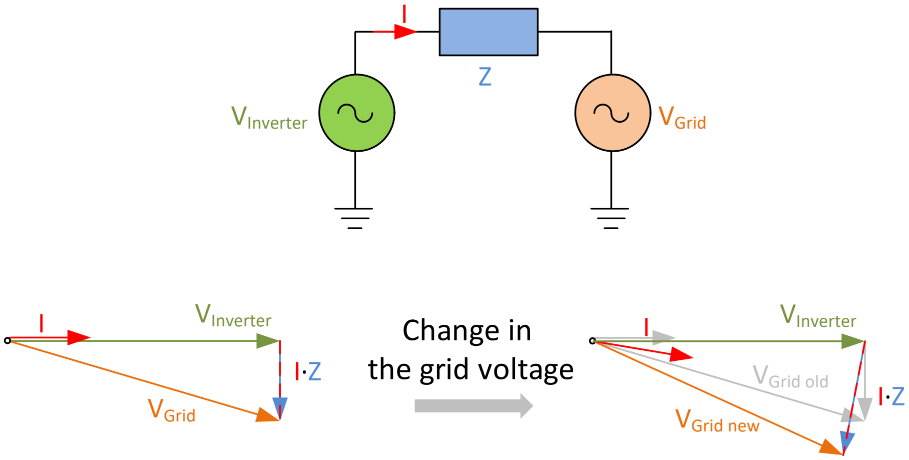

Figure 2. Vector shift and response expected from a GFM IBPS. Grid forming inverters shall keep the voltage and frequency reference constant or stable as long as their current limit is not exceeded. In case of a vector shift of the grid side, the inverter voltage ($V_{Inverter}$) is identical before and after the change of grid voltage. Thus, the voltage drop (I·Z) and inverter current (I) have to change.

Design considerations for GFM IBPS are affected by the grid characteristics associated with active and reactive power changes caused by voltage angle and magnitude changes, respectively, at the point of interconnection of the IBPS. Understanding the expected range of these variations will reduce the likelihood of undesired interactions.

In today's setting, where expectations for the functionality and performance of GFM IBPSs are non-uniform across different interconnections, manufacturers lack incentives and guidance to develop GFM capability. Non-uniform requirements will drive up the development cost for manufacturers, and, consequently, for the IBPS project developers. Commonly agreed upon requirements for active and reactive power performance, response to small and large disturbances, and control modes are necessary to allow manufacturers to develop and maintain one set of products and reduce complexity for product applications.

Ancillary services or other market-based approaches should be developed to value the system benefits from GFM technology, just as is the case for frequency support and black start. In this case, the market most effectively decides how to manage cost of development and deployment. Another incentive is to allow the developers gain access to the network locations with lowest SCR that cannot be securely served by GFL technology.

The key is for manufacturers, grid operators and policy makers to maintain a dialog on conditions under which GFM technology is needed and expected performance. Manufacturers then can develop new capabilities, balancing performance objectives and costs most efficiently. Manufacturers also need to closely work with grid operators and developers to understand how to best leverage the new capability in different situations, whether it be through simulation or operational practice. This iterative dialogue is crucial for optimizing the effectiveness of any additional technical capabilities and, especially, for managing the cost of GFM technology deployment.

There is no one-size-fits-all solution to achieve the desired grid support capabilities. There are many ways to provide it with a wide variation in costs. Once the physical needs of a power system with very high penetration of IBPS are clear, and a technology-agnostic description of the desired performance exists, then the industry has the capability to provide solutions that fit the need, one of them may be GFM IBPS.

Research Perspective

With very high penetration of GFL IBPSs, which rely on fast rigid controls to inject current into the grid, stability of the power system cannot be assured. As the number of online SGs reduces, the impact of electromechanical dynamics becomes less pronounced and the faster electrical dynamics dominate. Chief among the fast control loops that result in instability is the phase lock loop (PLL) losing synchronization with the network. Among other studies, this phenomenon has been demonstrated in studies on a 36-node model of the GB network for 2030 (see Figure 3), and a futuristic 100-node model of a portion of a North American utility's system (see Figure 4). The latter study also shows that one GFM IBPS can ensure small signal stability of the isolated system upon its islanding from the main grid.

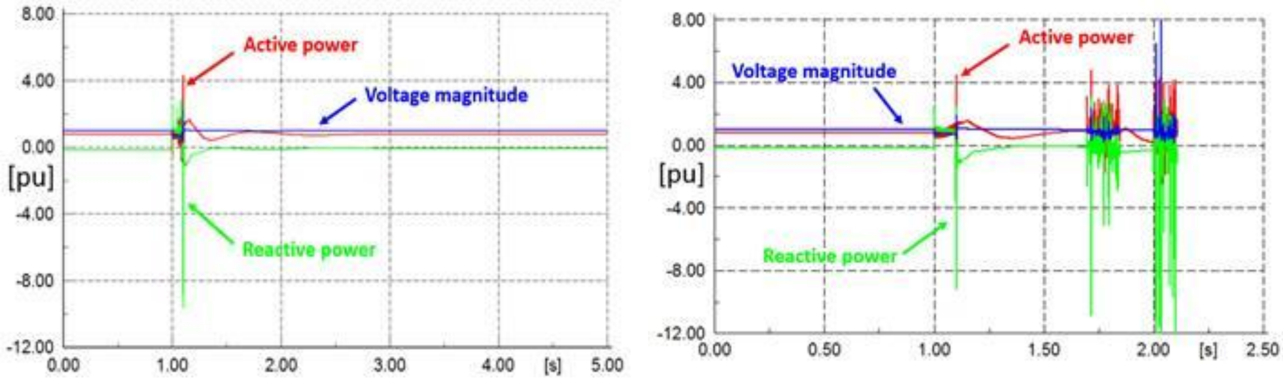

Figure 3: Simulation results for GB network in 2030; response of SG in Southeast Scotland for a marginally stable case with 70% IBPSs penetration (left) vs marginally unstable case with 71% IBPSs penetration(right).

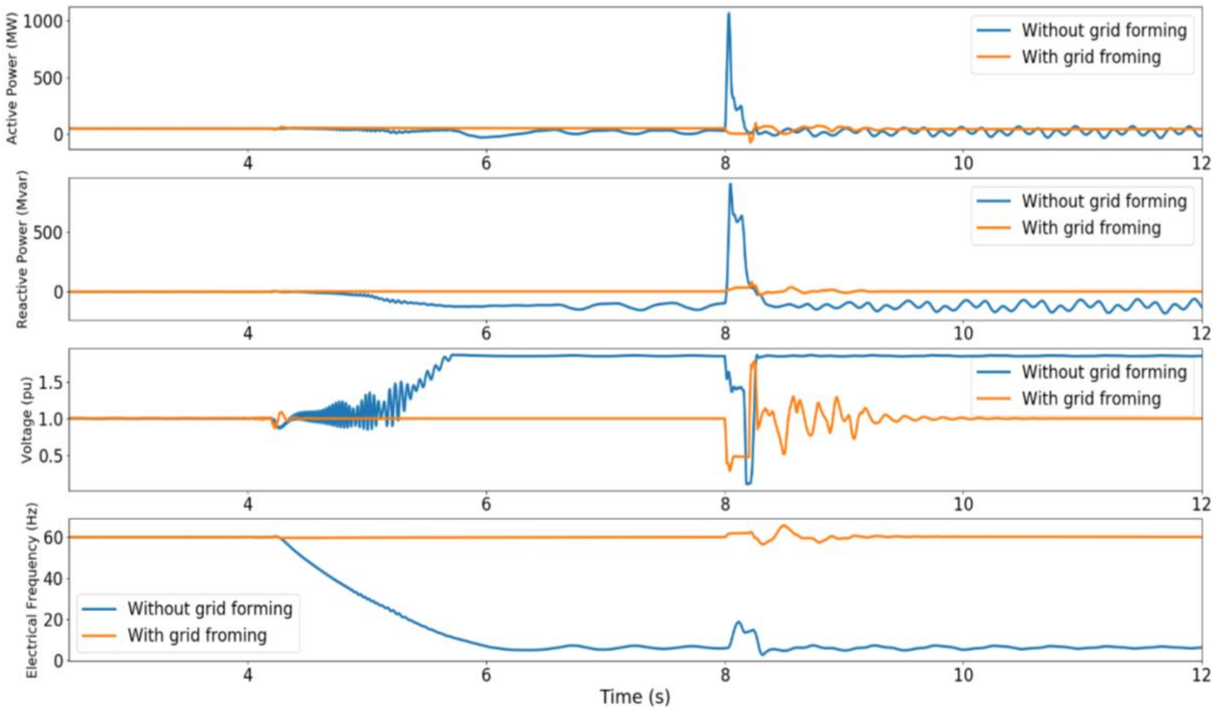

Figure 4: Simulation results showing that one GFM IBPS in a portion of a North American utility can ensure small signal stability of the system upon islanding of that portion from the main grid. At 4 seconds, the entire system becomes an all inverter system and without grid forming inverters, the controllers are not able to ensure a stable operation. At 8 seconds, a three phase bolted fault is applied on this all inverter system.

Due to their voltage-source behavior, GFM IBPSs, provide an immediate step response and inherently adapt to grid changes compared to the slower response of GFL IBPS (see Figure 5).

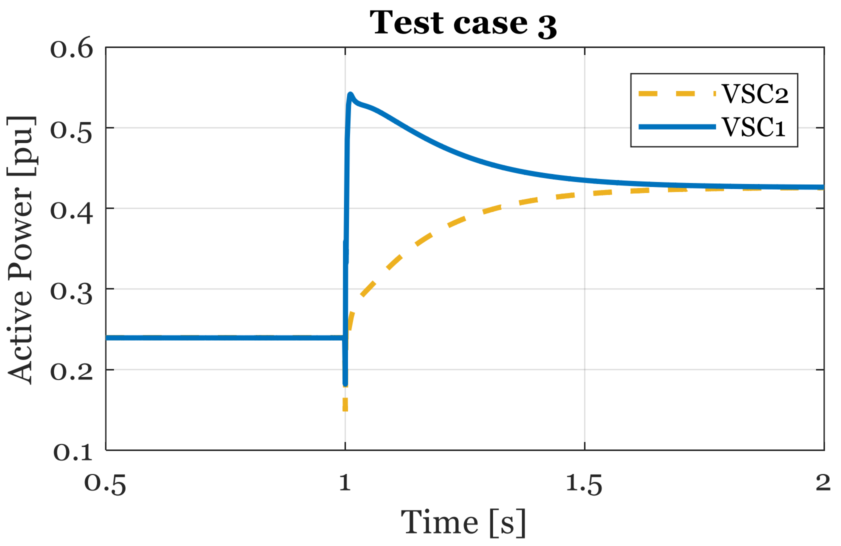

Figure 5: Comparison of GFM (VSC1) and GFL (VSC2) response to a step increase in load.

This behavior cannot be achieved with additional loops on GFL IBPS, as it needs to measure system variables (voltage, current, frequency) to react accurately, which inherently slows down the response. For example, the FFR from GFL IBPSs can help improve the system stability if there is a sufficient number of SGs connected to the grid maintaining minimum inertia level and ensuring an acceptable RoCoF in the first 100 milliseconds after a generator trip. Studies at University of Strathclyde (UoS) have shown that without this condition being met, FFR from GFL IBPS can be detrimental to stability.

Several research projects have investigated GFM controls proposing various technical solutions, meeting the requirements stated in the introduction. National Grid and UoS have demonstrated that upon replacing a portion of the GFL IBPS (10%-30%) with GFM controls, all studied scenarios could be stabilized, even in an extreme case representing a system split with 93% IBPSs penetration and very high power transfers. The European Commission-funded MIGRATE project also demonstrated the stability benefits of GFM controls on the Irish transmission system. While the exact required percentage of GFM IBPSs depends on the characteristics of the system being evaluated, research has shown that in general 10–30% of the total IBPSs is adequate.

The project teams of the Electric Power Research Institute (EPRI) and Arizona State University (ASU); EPRI and Washington State University; UoS and National Grid; and MIGRATE have investigated the following GFM controls:

- The virtual synchronous machine (VSM) that emulates the beneficial behavior of a SG
- The VSM with zero inertia (VSM0H), which is similar to a SG without inertia
- Frequency droop, which recreates the link between load/generation imbalance and frequency deviation
- The angle droop which directly links the load/generation imbalance to a deviation of the terminal voltage angle
- The dispatchable virtual oscillator control (dVOC) that mimics the behavior of a perfect inductance/capacitance oscillator and self-synchronizes on a grid.

Although these controls have somewhat different implementation, their behavior close to nominal conditions (in small signal) is similar. The MIGRATE project investigated interoperability of GFMs and demonstrated that VSM, frequency droop and dVOC can be operated on the same network in a stable manner (the other controls have not been similarly investigated, which does not mean that they are incompatible). Moreover, these controls do not change the fundamental system operation, as they recreate the linear link between frequency and load imbalance. However, the boundary between primary/secondary frequency control and inertia might change with the change of the system dynamics.

GFM control creates a direct link between the ac network and the dc side of the converter. This is one of the necessary conditions to ensure stable ac system operation, but it means that the dc side of the converter must be correctly modeled. For example, a GFM IBPS will immediately react to an ac load step change by drawing power from its dc side. An accurate representation of this is necessary, since energy depletion on the dc side will have direct impact on the ac-side voltage. Thus, a non-stiff dc bus could result in the coupling between active power and voltage; this effect has so far been largely ignored in power system analysis. Energy buffer is also required at the dc side of the converter. The size of this buffer will depend on the speed of response of other devices on the grid.

The line between the need for traditional phasor-domain and detailed EMT power system simulations becomes less distinct with the increase in IBPS. At its core, every converter that is used to interface a

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generation source to the power system is a voltage-source converter. However, by nature of the present IBPS control, the power system perceives these converters as virtual current sources, and the converters themselves follow the grid voltage angle and frequency. As the system strength decreases, the fast controllers of the IBPSs can experience stability issues, which are presently not observable with the converter models in a phasor-domain power system simulations. Conducting a detailed EMT simulation is the only avenue to have visibility of the phenomena, see Figure 7 (blue curve). However, through recent research conducted at ASU and EPRI, a new generic phasor-domain IBPS model has been developed for low system strength conditions to capture the oscillatory behavior observed in detailed EMT simulations as shown in Figure 7 (green curve). With this model the impacts of low system strength conditions on the behavior of IBPSs and possible mitigation measures can now be efficiently studied.

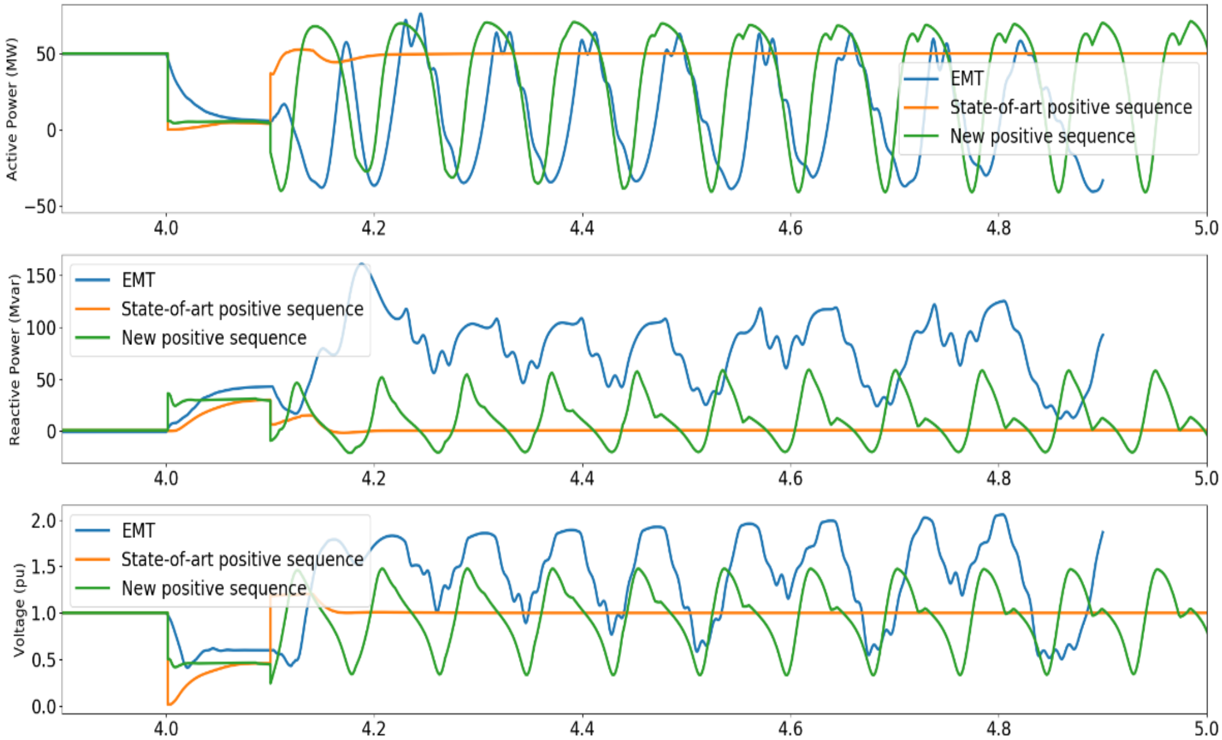

Figure 7. Comparison of EMT, present state of the art phasor domain model, and improved phasor domain model when a three phase bolted fault is applied at an IBR point of interconnection in a low short circuit area.

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It is important to point out that the GFM controls, even though capable of high amplitude fast response, must lower their bandwidth for the following reasons:

- To ensure system stability, inverters should not react faster than the network dynamics as the network is used to convey the synchronization information through voltage angle.
- To ensure that frequency does not vary too quickly, allowing for accurate frequency measurement by devices, providing frequency support.
- To enable system studies, specifically, to ensure that phasor-domain simulations are valid in most cases.

However, these slower time-scale dynamics do not need to be as slow as in present systems with SGs! Depending on system characteristics, a dynamics time-scale of 3 to 10 times faster than present could be achieved in a secure way.

Summary

Several interconnected systems already have reached or soon are expected to reach very high penetration levels of IBPS. This leads to operating challenges, mainly associated with reduced system strength, synchronous inertia and black start capability. Some System Opertors in these areas have determined required levels of system strength and synchronous inertia below which action is needed.

GFM technology is being intensively discussed as a possible solution to these issues in recent years. Researchers are developing alternative GFM control strategies and studies show that only a portion of IBPS need to be GFM to ensure secure system operation. The studies also demonstrate compatibility of various GFM control strategies used within one power system.

Several actual projects, mainly in small isolated systems, successfully demonstrate the feasibility of GFM technology. However, lack of clear functional requirements and very few use cases, do not provide sufficient incentive for manufacturers to develop commercial GFM IBPS for bulk power system application. Market signals are desirable, where possible. No one-size-fits-all solution is suitable, and combinations of GFM, GFL, and synchronous machines need to be considered with a detailed cost-benefit analysis in each case.

Grid operators, manufactures, researchers, and policy makers need to continually discuss conditions under which GFM technology is needed, and the performance requirements should be clearly defined in grid codes or standards. Manufacturers then can develop equipment with new capabilities that balance performance and costs. This dialogue is crucial for maintaining secure and efficient system operation with high penetration of IBPS.

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