By Vahan Gevorgian, Shahil Shah, Weihang Yan, and Geoff Henderson

Grid-Forming Wind

Getting ready for prime time, with or without inverters.

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VARIABLE WIND POWER IS ONE OF THE fastest-growing energy-generation technologies, harnessing the energy of wind, both on land and at sea. During the past decade, the global share of wind power has grown tremendously, and wind power is evolving into a major contributor to electricity supplies in many countries. In this journey, wind is also becoming a source of reliability services to the grid, which has required grid-supporting functions originally provided by synchronous generators, enabling very high levels of instantaneous penetration (ranging from 60 to 70% in some power systems). To get beyond this, a fundamental shift is required to address challenges associated with the transition to a grid with only a few remaining (or even without any) conventional synchronous generators while achieving a minimum acceptable level of stability. These challenges in grids with very high shares of inverter-based resources (IBRs) can be grouped into the following few main categories:

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- The impact of degrading grid strength and short circuit current levels on stability, transient performance (fault ride-through), and the adequacy of protection
- Degrading system inertia impacts on power system frequency stability
- The increasing number of stability issues caused by control interactions, oscillations, and resonances in IBR-dominated grids
- The responsibility of forming the grid (or grid formation) in the absence of synchronous generators
- How to jump-start the grid after blackouts and how to operate it when it is divided into many smaller islands.

The increasing need for power grids to maintain system strength because of IBRs is a main concern for grids in transition. Degrading grid strength is considered a main stability "deteriorator" in the evolving grid, along with decreasing inertia and short circuit ratio. Droop-controlled grid-forming (GFM) converters, as first-order nonlinear systems, can improve stability better than phase-locked loop (PLL)-based grid-following (GFL) converters, which act as second-order nonlinear systems. However, like GFL converters, the limited overcurrent capability of GFM inverters establishes another constraint on the transient stability of IBR-based grids. Even though the latter problem can be addressed, either by oversizing the GFM converters or by large-scale deployments of synchronous condensers to maintain the system strength, both solutions are costly. Further, another challenge with GFM IBRs is how to determine the optimal control structure and how to control them for the best grid stability.

How can wind power help address these challenges? Does the wind turbine industry have a solution to offer? One such solution to address all these problems has been around since the 1990s. It is known as *synchronous wind power*, a variable-speed wind turbine generator coupled with a fixed-speed synchronous generator using either a hydrodynamic coupling between the generator and the gearbox (for example, a German DeWind D8.2 2-MW wind turbine), or a hydrostatic torque reaction embedded into the turbine gearbox with torque limiting (SyncWind powertrain concept used in Windflow wind turbines in New Zealand). The synchronous generator wind turbines, also known at Type-5 wind turbines, operate without power converters, and their principle of operation and consequent grid impacts is similar to any conventional power plant except for the following three main differences:

1) Unlike conventional plants, the turbine of Type-5 machines is decoupled from the grid.
2) The prime mover of Type-5 wind turbines, namely, the wind, has variable nature compared to conventional generation.
3) Type-5 wind turbines have reduced synchronous inertia—that of the generator rotor, driveshaft, and any attached flywheel alone—with the main wind rotor's inertial energy being decoupled but accessible through fast frequency response.

Unlike Type-5 wind turbines, modern variable-speed wind turbines use power electronics converters to provide variable-speed operation and satisfy the requirements of both the generator and the power grid. They are known as *Type-3* and *Type-4 wind turbine generators*, and they use doubly fed induction machines (DFIGs) with partially sized power converters or full-power conversion topologies, respectively. Types 3 and 4 are the two main wind turbine technologies being used globally, reaching up to 14 MW of single-turbine capacities for direct-drive (no gearbox) Type-4 offshore wind turbines. The older Type-1 and Type-2 topologies, which use fixed-speed or small-slip-range induction generators, are obsolete and are rarely used today.

In this article, we discuss how wind power can become an enabler to a carbon-free, renewable-based power grid as a provider of not only bulk variable energy but also of a new valuable set of additional services to the grid. GFM is one such important service because IBR-dominated grids are not capable of operating in a stable way without it. Is wind technology ready for it?

Three Wind Turbine Topologies

First, let's look at three wind turbine electrical topologies under consideration. The general diagram of the Type-3 topology is shown in Figure 1. This type of wind turbine uses a wound-rotor induction generator directly coupled

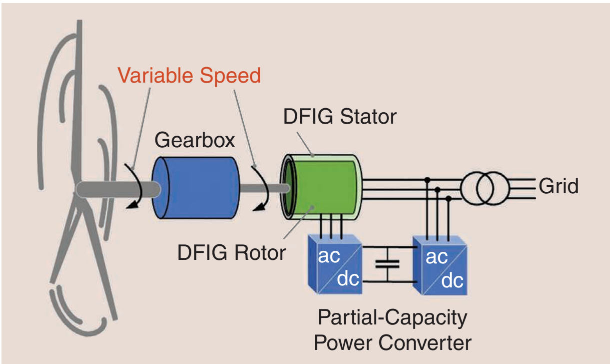

Figure 1. A Type-3 wind turbine topology.

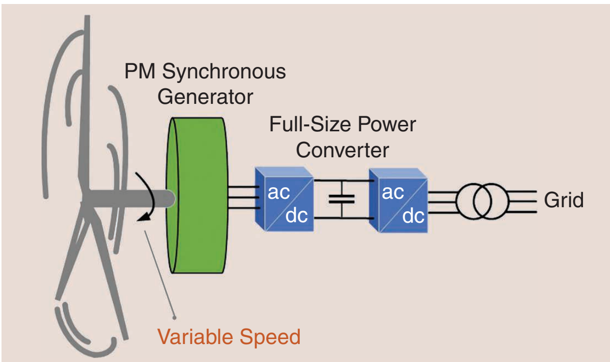

Figure 2. A Type-4 wind turbine topology. PM: permanent magnet.

with the grid, and a partially scaled power converter connected to the rotor circuit. The power rating of the converter is typically near 30% of the overall generator capacity and is defined by the variable-speed operation.

Type-4 wind turbines use a full-scale power converter, which acts as an interface between the generator stator windings and the grid. The Type-4 turbine can be geared or gearless, as presented in Figure 2, where a permanent-magnet, low-speed, synchronous generator is coupled directly with the wind rotor without a gearbox.

Variable-speed Type-5 wind turbines use a fixed-speed synchronous generator directly connected to the grid and can be divided into two categories, depending on the method used for torque conversion to achieve constant-speed operation. A Type-Va topology using a full-capacity-rated hydrodynamic transmission system located between the turbine gearbox and the generator is shown in Figure 3. This design has been used in recent decades, but it did not achieve successful commercialization. Any transmission failure in this design because of torsional stresses during grid faults could cause considerable expense. On the other hand, a powertrain solution that embodies a hydrostatic torque reaction system built into the turbine gearbox itself can provide considerably lower capital and maintenance costs (Type-Vb topology). Such a system can be rated at a small fraction of the overall turbine capacity (5%), and it inherently protects the main drivetrain from torsional stresses by diverting a small amount of power into a parallel mechanical path. This topology is depicted in Figure 4. If a mechanical failure occurs in that subsystem, it is an inexpensive item to replace.

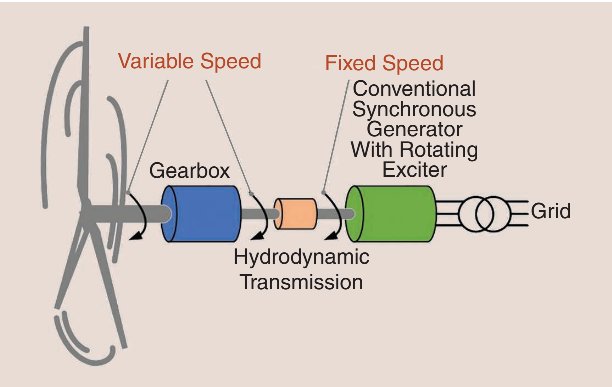

Figure 3. A Type-Va wind turbine with full-capacity hydrodynamic transmission.

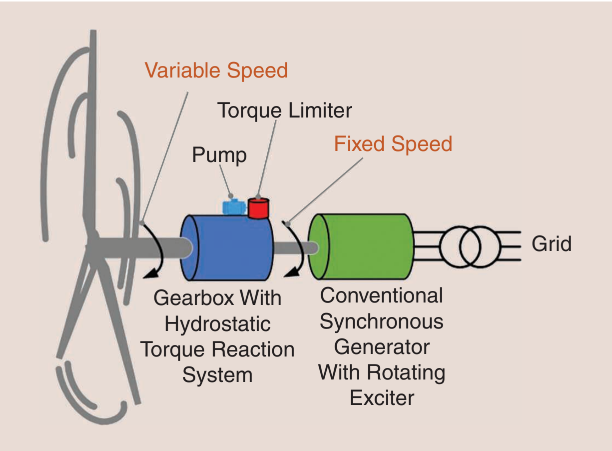

Figure 4. A Type-Vb wind turbine with a torque limiter and recently developed low-variable-speed system.

As mentioned previously, Types 3 and 4 are the two most used turbine topologies today, with many manufacturers in different countries mass producing these multimegawatt wind turbines for grid-scale operation. Grid impacts and the performance of such machines in GFL mode are well understood, and in many cases, the performance is standardized through national and international grid codes and standards. In contrast, for GFM operation for Types 3 and 4, there is a knowledge gap on how to control and operate GFM wind turbines, how to account for this new mode of operation in the turbine design stage, and understanding the stability, reliability, and resilience benefits. For the Type-5 wind turbine topology in particular, a holistic evaluation of this technology in the context of larger power systems that shows the overall benefits and revives industry interest is long awaited.

What Does It Take for a Wind Turbine to Become Grid Forming?

The general answer is not much, at least from an electrical design viewpoint. Conversion to GFM operation is essentially a control software upgrade with no need for new electrical hardware components of the drivetrain and the power converter in Type-3 and Type-5 wind turbines. In some cases, however, certain modifications are needed, depending on the design characteristics of a given turbine. The National Renewable Energy Laboratory (NREL) has been testing a multimegawatt Type-3 wind turbine generator in GFM mode during 2021 with controls developed by GE. This turbine uses the same components as those for GFL operation, with controls redesigned to operate on programmable f-P and V-Q droops. Since 2019, Siemens-Gamesa has been successfully demonstrating GFM operation of the 69-MW Type-4 Dersalloch wind power plant in Scotland. This power plant demonstrated stable performance in GFM mode during weeks of operation, with controls to emulate various levels of inertia constant H.

In a GFL operation, the wind turbine converter controls the level of injected current depending on the active and reactive power set points with a specific phase-angle difference from the voltage at the point of common coupling (PCC) interconnection; therefore, to inject the desired levels of power, the turbine controller needs to calculate the reference current, which, in turn, requires knowledge of the grid voltage's fundamental phasor. For this purpose, a PLL is used to measure the phase angle of the grid voltage at the point of interconnection. Using additional outer

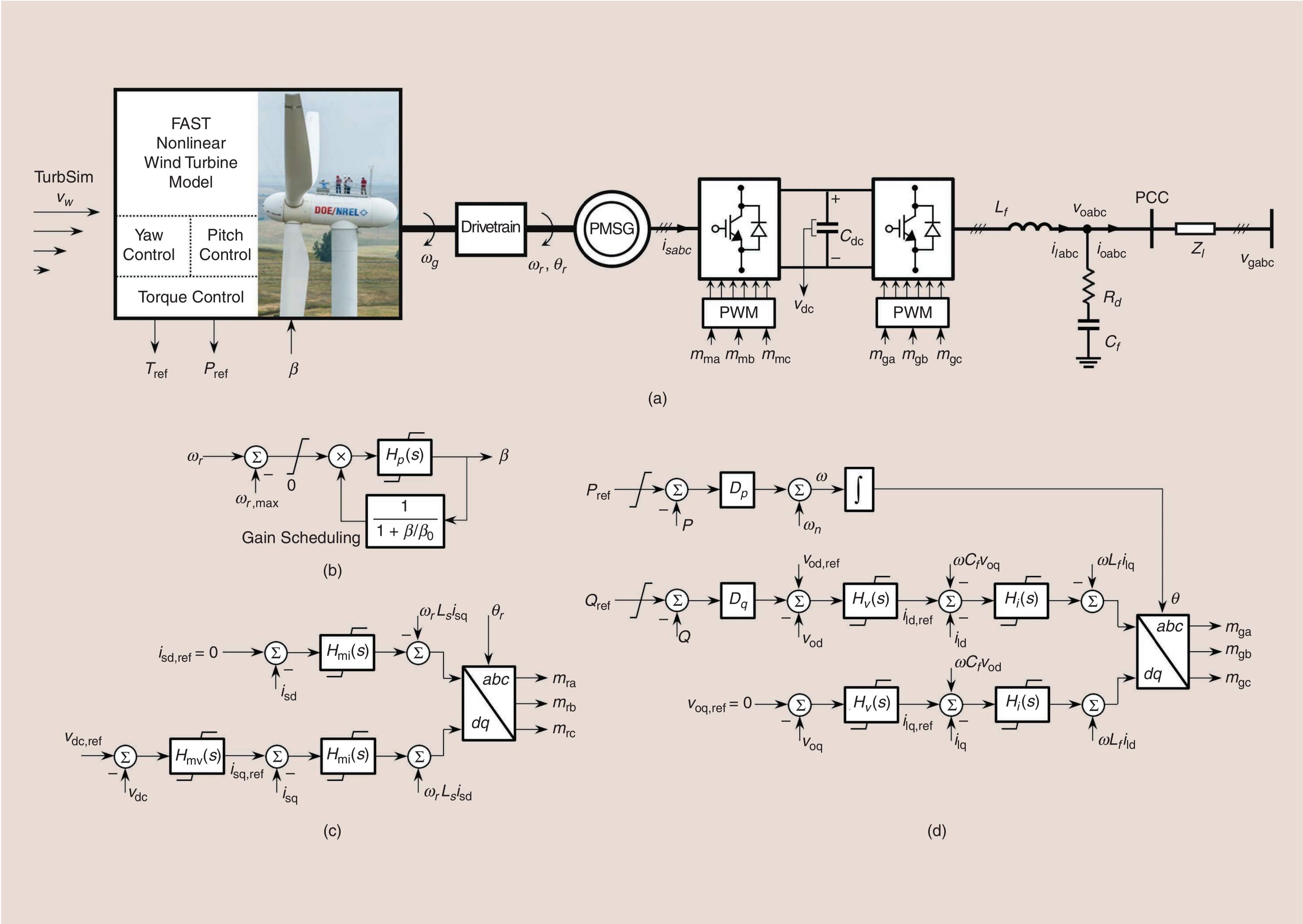

Figure 5. The GFM control for a Type-4 wind turbine generator. PWM: pulsewidth modulation. (a) The circuit diagram of the GFM-controlled Type-4 WTG. (b) The turbine patch control. (c) MSC control. (d) GFM GSC control (courtesy of NREL). GFM: grid forming; PMSG: permanent magnet synchronous generator; MSC: machine-side converter; WTG: wind turbine generator; GSC: grid-side converter.

control loops, it is possible to control the active and reactive power injections to provide additional frequency- and voltage-responsive services.

The general control diagram of a Type-4 wind turbine generator is shown in Figure 5, with specific control functions for both the grid-side converter (GSC) and the machine-side converter. In GFM operation, the wind turbine converter itself is controlling the PCC voltage magnitude and phase; therefore, in this particular control implementation, there is no need for the PLL to measure the voltage phasor (unless it is needed for the provision of certain frequency response services or grid resynchronization). In this case too, however, like GFL operation, it is possible to use outer loops to control the levels of the injected active and reactive power when operating in grid-connected mode. In islanded mode, the GFM wind turbine will operate as a "swing bus," adjusting its active and reactive power to follow the load. The benefit of PLL-free operation is better stability and avoidance of various interactions with the power controller. In certain cases, a PLL-free GFM controller offers a relatively simpler method that allows the converter to synchronize with the grid and operate on active power-frequency droop and reactive power–voltage droop. However, stable GFM operation can be achieved even using a PLL, depending how the PLL is used within the control.

Modeled current time series during a 150-ms zero-voltage ride-through by a Type-4 GFM wind turbine is shown in Figure 6(a). The current-limiting control kicks in immediately after the fault is initiated, at t=0.5 s, protecting the turbine converter from overcurrent. The same Type-4 turbine current in GFL mode is displayed in Figure 6(b). In this case, the injected fault current increases more slowly because of the specifics of the controls in the current-control mode, but it is still limited to the maximum-allowed level by the current-limiting control. Quite the opposite, the Type-5 wind turbine, when exposed to the same fault, injects a significantly higher level of fault current [Figure 6(c)] because of the natural response of the synchronous generator used in the Type-5 topology.

The electrical controls of Type-3 GFM wind turbines are more complex than those for Type-4 because the DFIG's stator is connected directly with the grid, so the induction generator of the turbine needs to operate like a synchronous generator. Figure 7 shows a DFIG with a rotor-side converter (RSC) and a GSC with NREL-developed vector current control implemented in the back-to-back converters. The same implementation is used for the GFM and GFL operation modes. Figure 8 depicts the outer control loops of the RSC for operating a Type-3 wind turbine in GFM mode. The active and reactive power control loops set the references for the frequency and the magnitude of the stator voltage. Testing of a 2-MW Type-3 wind turbine drivetrain was conducted at NREL using GFM controls designed for the specific hardware. The GFM controls used in testing are different from the one shown in Figure 7. The measured zero-voltage ride-through performance of a 2-MW Type-3 wind turbine generator in GFM mode is presented in Figure 9. This test was conducted at the NREL using a medium-voltage grid simulator that emulated a 150-ms three-phase voltage fault on the turbine terminals. The turbine can ride through the fault and recover its power production quickly after the fault is cleared. Because the stator winding of the Type-3 machine is connected directly to the grid, it is capable of injecting a large level of short circuit current. This is unlike the Type-4 topology, where the current injection is limited by the power converter rating.

Another important aspect of Type-3 GFM operation is the stability issues related to this topology, such as its performance under weak grid conditions and being prone to subsynchronous oscillations (SSOs) when interconnected with series-compensated transmission lines. The modeling studies conducted by the NREL demonstrated that the Type-3 turbine in GFM mode is less likely to experience SSO-related problems and can operate stably

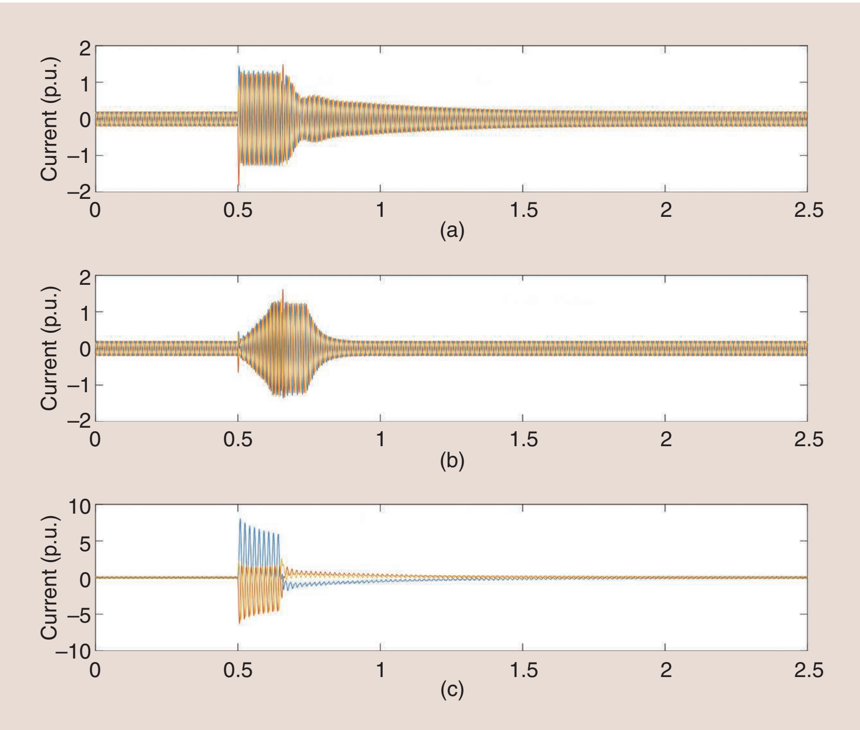

Figure 6. The ride-through performance of a GFM Type-4 wind turbine compared to a Type-5 one. p.u.: per unit. (a) A Type-4 grid-forming wind turbine, (b) Type-4 grid-following wind turbine, and (c) Type-5 wind turbine.

with weak grids compared to the same turbine operating in GFL mode.

Impedance-based methods are effective for evaluating the stability of IBRs and of Type-3 and Type-4 wind turbines under different grid conditions and their impact on the stability of bulk power systems. A comparison of the positive-sequence impedance response of the 2.5-MW Type-3 wind turbine when it is operated in GFM and GFL modes is shown in Figure 10. Without special tuning to mitigate subsynchronous oscillations, phase response of the impedance for the GFL mode is outside the ±90° range at subsynchronous frequencies. This results in negative damping at these frequencies, which can in turn result in SSOs, particularly when the GFL wind power plant is interconnected with series-compensated transmission lines. In GFM mode, however, the same Type-3 turbine does not exhibit negative damping resistance, making it less likely to experience SSO problems. This fact demonstrates another stabilizing property of GFM wind turbine technology.

Type-5 wind turbines do not need any GFM controls because GFM is their natural form of operation. To better understand turbine loading and mechanical stresses in various components of Type-5 wind turbines, more research and testing are needed; however, the track record of a 46-MW Type-5 wind power plant in New Zealand that uses torque-limiting gearboxes (TLGs) (which have been in operation since 2006, providing 10% of New Zealand's installed wind capacity) indicates successful operation under various wind and grid conditions. That 46-MW wind power plant used the TLG system invented in the 1980s. This is a narrow-band variable-speed system. A recent development has been to add broadband variable-speed capability by incorporating a low-variable-speed (LVS) system, comprising an electric motor-driven pump to drive the torque-limiting pump as a motor in low winds.

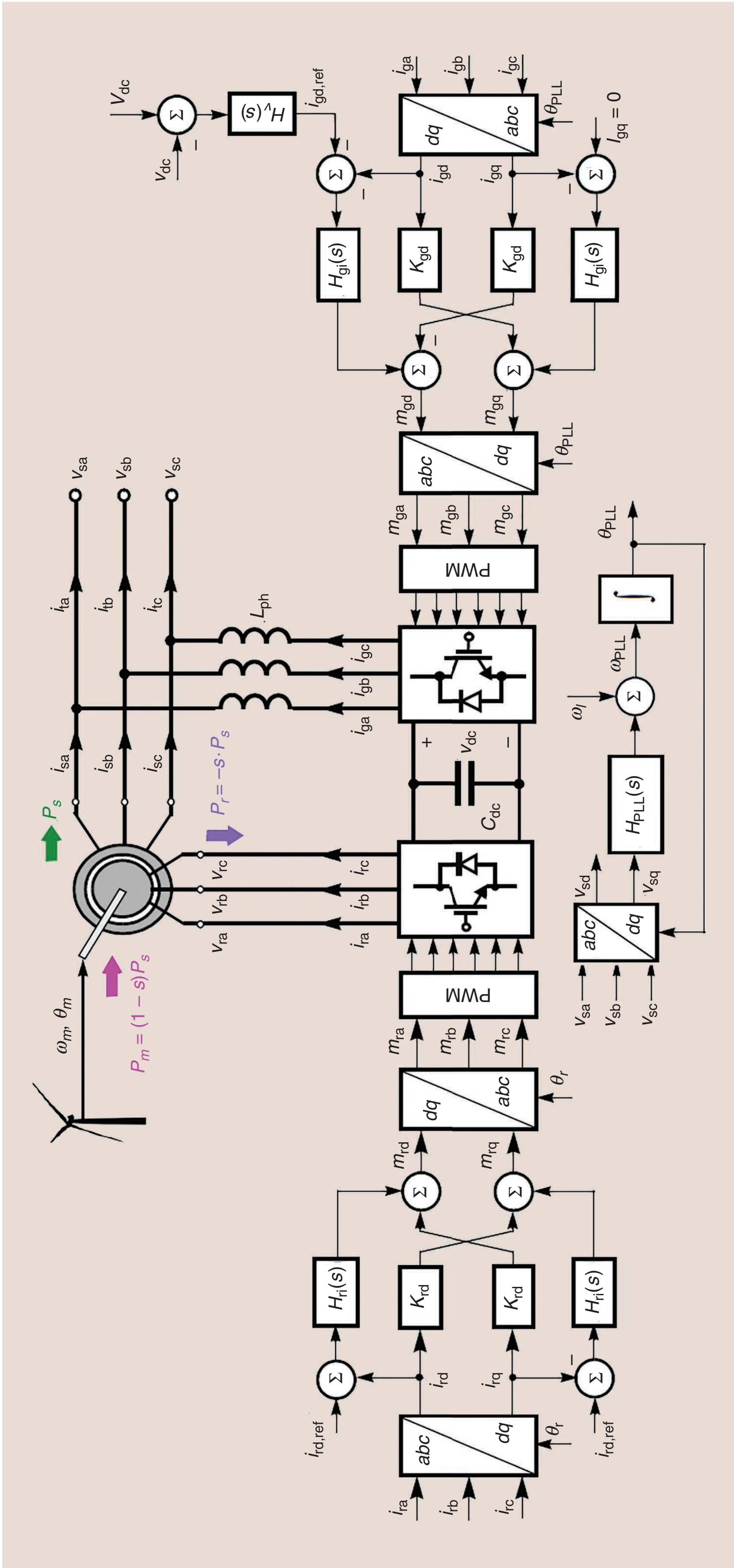

Figure 7. A Type-3 wind turbine with vector control. PWM: pulsewidth modulation.

Because the torque requirement in these winds is low, it is possible—with the same hydraulic power rating as in TLG mode (5% of the wind turbine rating)—to achieve the broad variable-speed range, which has become mainstream in inverter-based wind turbines.

The synchronous generator control and behavior are the same in both the TLG and LVS implementations of the Type-Vb turbine. In terms of its ride-through performance, Figure 11 depicts how the Type-5 system provides inherent, self-exciting response of the classical synchronous machine/voltage regulator combination. This is fundamentally different from the response of IBRs, which introduce active control lags and have severe current limits.

The voltage fault response of a Windflow 500 synchronous wind turbine generator measured on 8 September 2012 at the 46-MW Te Rere Hau wind power plant in New Zealand is displayed in Figure 11. The event demonstrates an example of the short circuit current contribution and ride-through of a Type-5 synchronous turbine during a system voltage disturbance that lasted approximately 100 ms. It is the same basic response as any other "conventional" generating plant on the grid. Figure 11(a) shows the voltage dip on the grid. Figure 11(b) depicts the short circuit current response. Figure 11(c) displays the real and reactive power response, and in particular, the red line shows the reactive power immediately being exported to oppose the

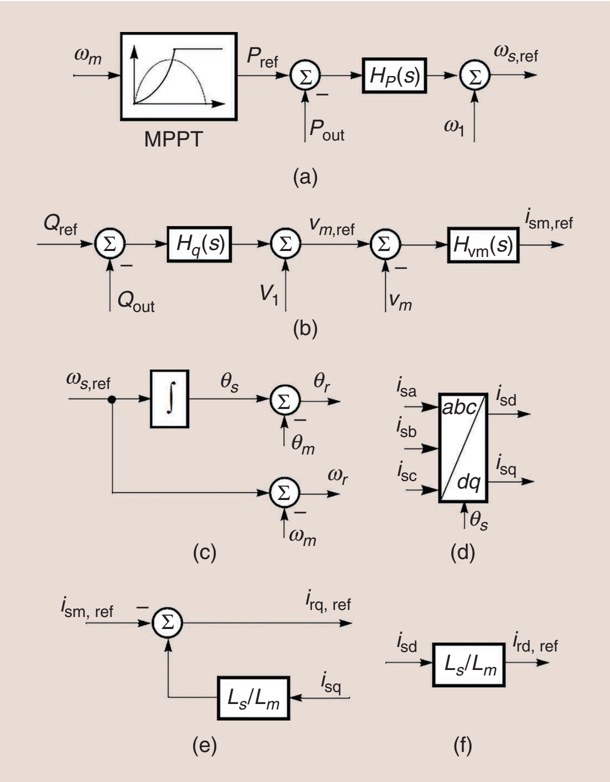

Figure 8. Outer control loops of the RSC for the GFM operation of a Type-3 wind turbine. MPPT: maximum power point tracking. (a) A turbine power controller. (b) A reactive power and voltage controller. (c) A phase angle reference signal. (d) A park transform for machine side converter. (e), (f) A rotor current control reference.

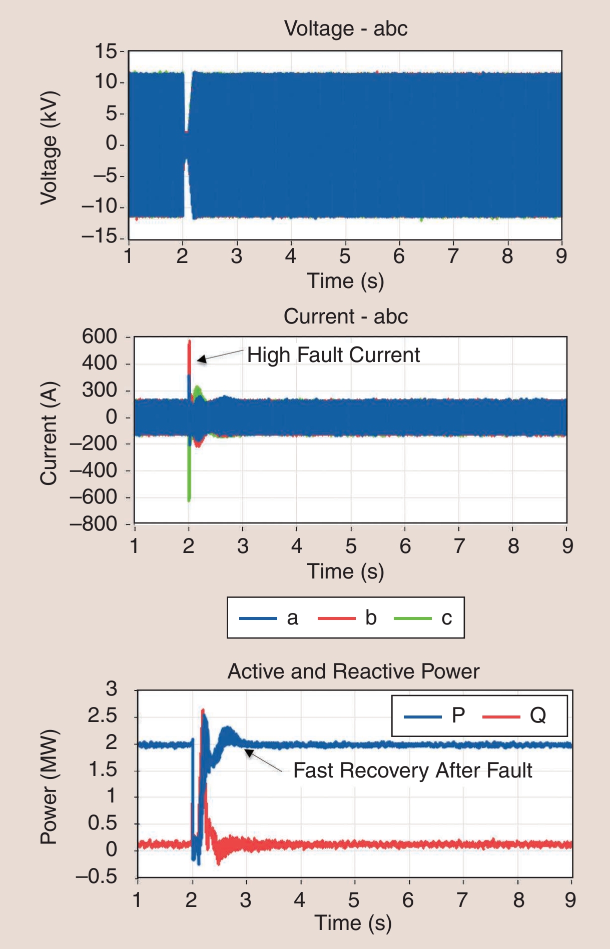

Figure 9. The measured fault ride-through of a 2-MW Type-3 GFM wind turbine.

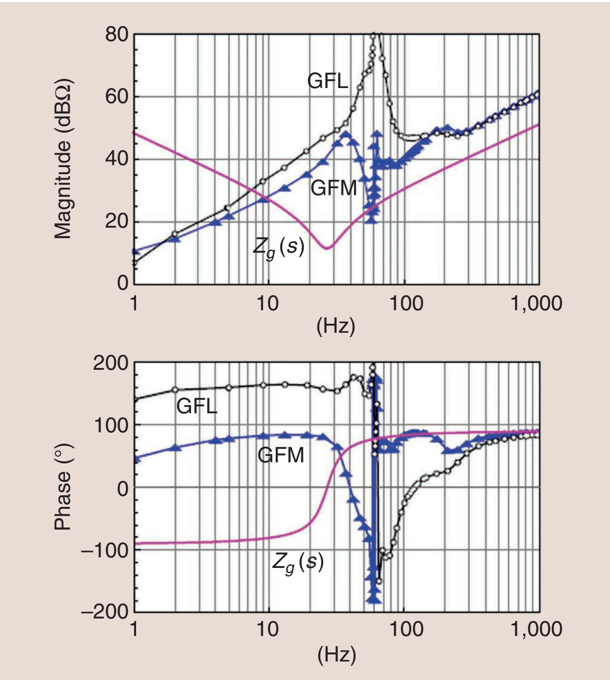

Figure 10. A comparison of the positive-sequence impedance response of a 2.5-MW Type-3 wind turbine in GFL and GFM modes.

dip in voltage. Initially, this occurs at approximately 0 kvar but shoots up to three-times rated before settling as the voltage recovers. By effectively responding to the voltage dip instantaneously, the 46-MW synchronous wind power plant played its part alongside the larger generators online at the time (typically totaling 4,000 MW) to ensure that New Zealand's national grid could achieve a rapid and stable return to normal operation. Figure 11(d) and (e) presents the instantaneous voltage and current from the generator and shows the turbine remaining online and returning to the approximate prefault levels shortly afterward. Note that the peak current on one phase is nearly five times the rated current (it was at rated before the disturbance) and that this peak precedes the maximum voltage dip.

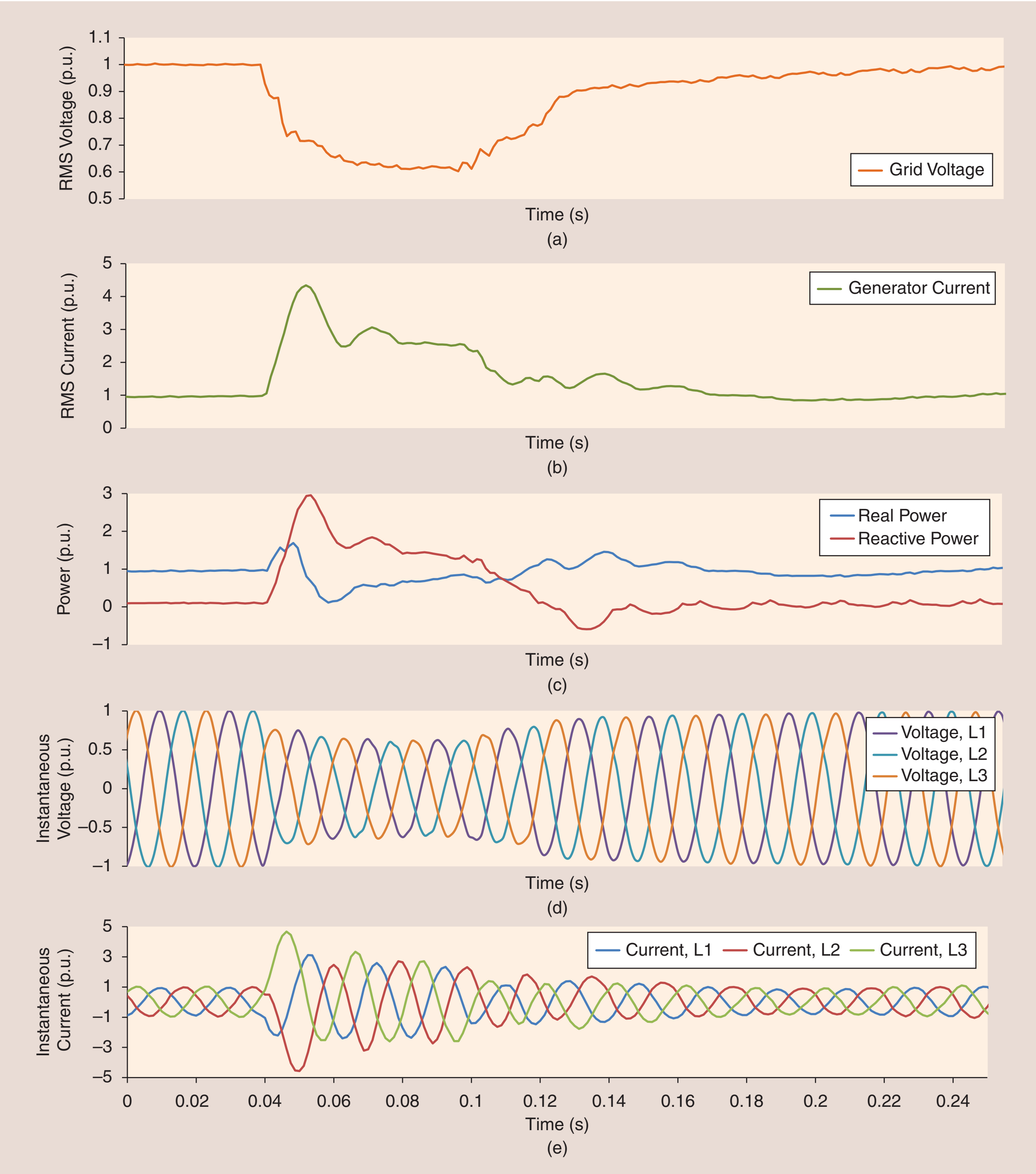

Figure 11. The measured voltage fault response of a Windflow 500 Type-5 wind turbine. p.u.: per unit; RMS: root mean square. (a) RMS voltage, (b) RMS current, (c) active and reactive power, (d) instantaneous voltage, and (e) instantaneous current.

Is There a Better Wind Turbine Topology for Grid Stability?

So what are the specific distinctions among all three considered turbine types in terms of their impact on the grid and their ability to address these integration challenges in the evolving grid? In Table 1, we consolidate some comparative knowledge points about specific grid integration challenges.

Note that Table 1 is for the potential benefit of comparison among three wind turbine topologies. While Type V wind turbines represent about 10% of New Zealand's wind power and the generator-AVR combination is well-proven in diesel generators and elsewhere, there is much less experience of their deployment in wind power plants worldwide, relative to Types 3 and 4.

Based on the Table 1 comparison among different grid integration challenges for three different GFM turbine topologies, all of them can provide a multitude of grid services for stabilizing the grid and for facilitating very high shares of IBRs. The main difference between the power electronics converter-based topologies (Types 3 and 4) and the synchronous topology (Type 5) is whether most of the services can be provided via controls or by natural

TABLE 1. A comparison of advantages for specific turbine types.

Grid Integration Challenge	Type 3	Type 4	Type 5
Weak grid operation	Yes, with controls		Yes, no controls needed, tends to make grid stronger Operation at sites with low short-circuit ratio (SCR) yet to be demonstrated
Short circuit current contribution	Limited	No, unless significantly oversized	High, no controls needed
Contribution to system inertia	Inertia-like response using controls, no curtailment	Inertia-like response using controls, with curtailment	Yes, no controls or curtailment needed (for example, a two-pole generator would give four-times real inertia compared to a four-pole generator)
Fast frequency response	Yes, fast response with special controls, curtailment, and/or transient uprating		
Primary frequency response	Yes, fast response with special controls and curtailment		
Participation in frequency regulation	Yes, curtailment needed		Yes, curtailment needed
Independent control of active and reactive power	Yes, with controls		Yes, with controllable automatic voltage regulator (AVR)
Transient performance and ride-through	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
Voltage control	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
GFM operation	Yes, with controls		Yes, no controls (default operation mode)
Black start and islanded operation	Yes, with controls and energy storage		Yes, no controls
Medium-voltage operation	Yes, with step-up transformer; transformerless might be possible in the future		Yes, up to 20 kV with no transformer
Protection impacts	May require adjustment to protection to accommodate lower short-circuit current than synchronous generation (Type 3 has more SCC capability than Type 4)		No change in the existing protection framework
Wind-free voltage support	Yes, with special controls (voltage control only, no inertia)		Yes, with clutch to disconnect generator from gearbox (synchronous condenser mode, provides voltage control and inertia, enhances grid strength)
Brushless operation	Brushes needed	Yes	Yes
Generator	Special design	Special design, dependence on rare-earth minerals for permanent magnet generators	Mass produced, global maintenance network and workforce exists, no dependence on rare-earth minerals
Cybersecurity	Yes	Yes	Fewer controls means fewer targets for external attacks

response based on the physics of the system, with no special controls. Some of the most critical services, such as maintaining grid strength, short circuit current level, and natural rotating inertia, come for "free" with Type-5 machines, whereas same services from Type-3 and Type-4 turbines can be achieved, either by oversizing or from special controls.

Frequency-Stabilizing Impacts of GFM Wind

We demonstrate some of the stabilizing effects of GFM wind on a larger power system by simulations conducted in PSCAD for a large power system test case. The model of the system with multigigawatt loads, 230-kV transmission lines, and a mix of many conventional generation plants has been tested at different penetration levels and various combinations of GFL and GFM Type-4 wind power plants (a simplified diagram of the system is illustrated in Figure 12). GFL Type-4 wind power plant models have turbine- and plant-level controls enabled (inertial response, frequency droop response, and voltage control). GFL and GFM Type-4 wind power plants have been placed in the model to compare the response of the system to a largest N-1 contingency at high levels of wind penetration. The conventional generators were modeled as a mix of hydro, steam, and combined-cycle plants with a total peak load of the system at ~6,000 MW.

The test system depicted in Figure 12 is modeled with automatic generation control applied to all conventional generation and wind power plants. Type-4 wind power plants operate with a 10% curtailment to have active power reserve for the provision of frequency-response services. Large-frequency events are emulated by tripping one large synchronous generator (approximately 10% of the load). In the base case, with no wind, the system frequency response is depicted in Figure 13 (blue line), and it is characterized by a deep-frequency nadir and a lower settling frequency. This is based on the turbine and governor characteristics of the modeled synchronous generation. The response of the system to the same generator trip at different levels of GFM and GFL

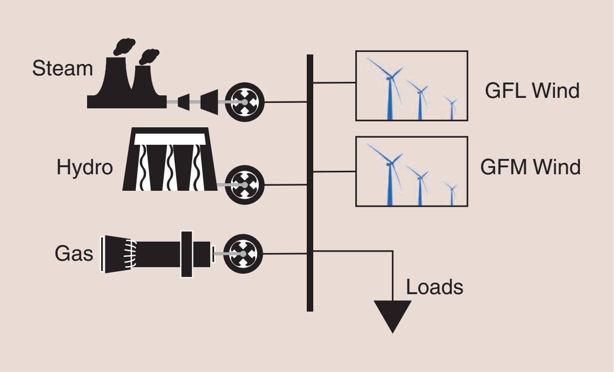

Figure 12. A simplified diagram of the test system with a combination of Type-4 GFL and GFM wind generation.

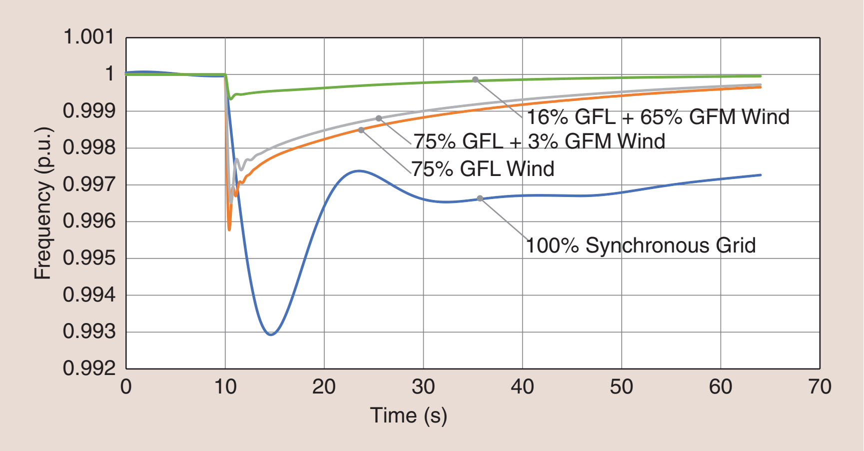

Figure 13. The frequency response of a test system for different combinations of Type-4 GFL and GFM wind generation. p.u.: per unit.

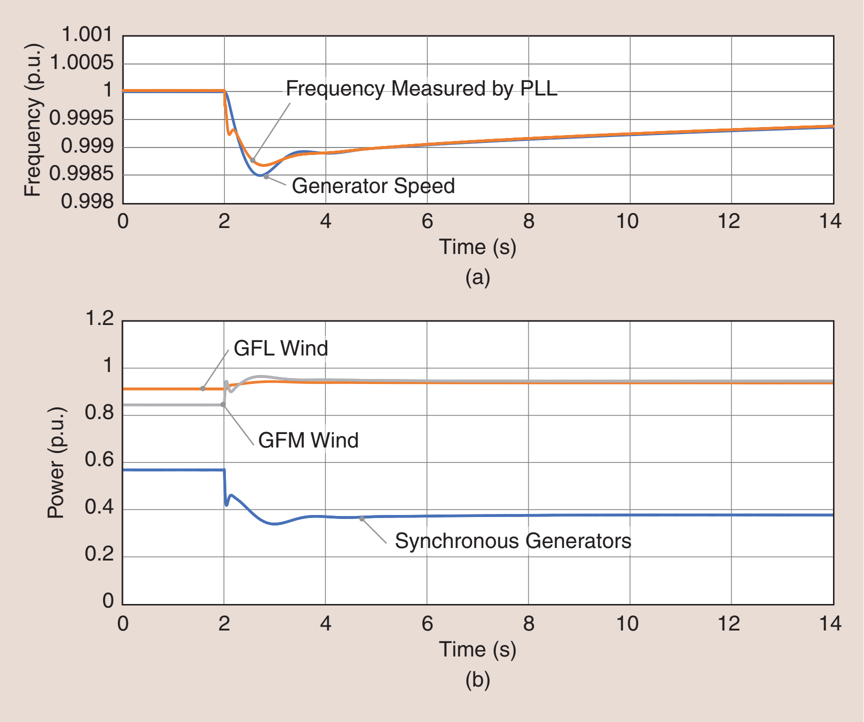

Figure 14. The system response to a loss of generation (66% GFL and 16% GFM wind). p.u.: per unit. (a) Frequency. (b) Power.

Type-4 wind power plants is also presented in Figure 13 for different ratios between the GFM and GFL wind power plants up to an 81% level of penetration. Inertial, frequency droop, and voltage droop controls were enabled in the Type-4 GFL wind power plant models. Frequency-megawatt and voltage-Mvar droops were enabled in the Type-4 GFM wind power plants. The highest share of the GFM wind provides a superior improvement on the frequency response, as shown in Figure 13. This is because GFM wind turbines can automatically and rapidly increase their power in response to frequency deviations. The same is true for other inverter-based GFM resources, such as solar photovoltaics (PVs) and battery energy storage systems.

Type-4 wind power plants operate with a 10% curtailment to have active power reserve for the provision of frequency-response services.

More detailed visualizations of the response of the system at different penetration scenarios are shown in Figures 14 and 15 for GFL- and GFM-dominated systems, respectively. The outputs of the selected individual GFL and GFM wind power plants and one of the remaining synchronous generators are illustrated in per units normalized to the MVA rating of each individual plant [Figures 14(b) and 15(b)]. Figures 14(b) and 15(b) show the frequency of the system during the event measured using a PLL (orange lines) and the speed of the synchronous generator in per units (blue lines). The frequency measured by a PLL depends on its components characteristics, and under dynamic conditions differs from generator speed. The presence of 16% GFM wind (Figure 14) provides significant frequency-response improvements compared to the synchronous generator and GFL-only cases, shown previously in Figure 13 (blue and orange lines). In the case of 66% GFM wind (Figure 15), there is a small "dent" in the system frequency after the loss of 10% of synchronous generation. This demonstrated excellent frequency-stabilizing characteristics of GFM wind, although the same is true for GFM solar PV generation (if operating with sufficient headroom) and battery energy storage systems with GFM inverters.

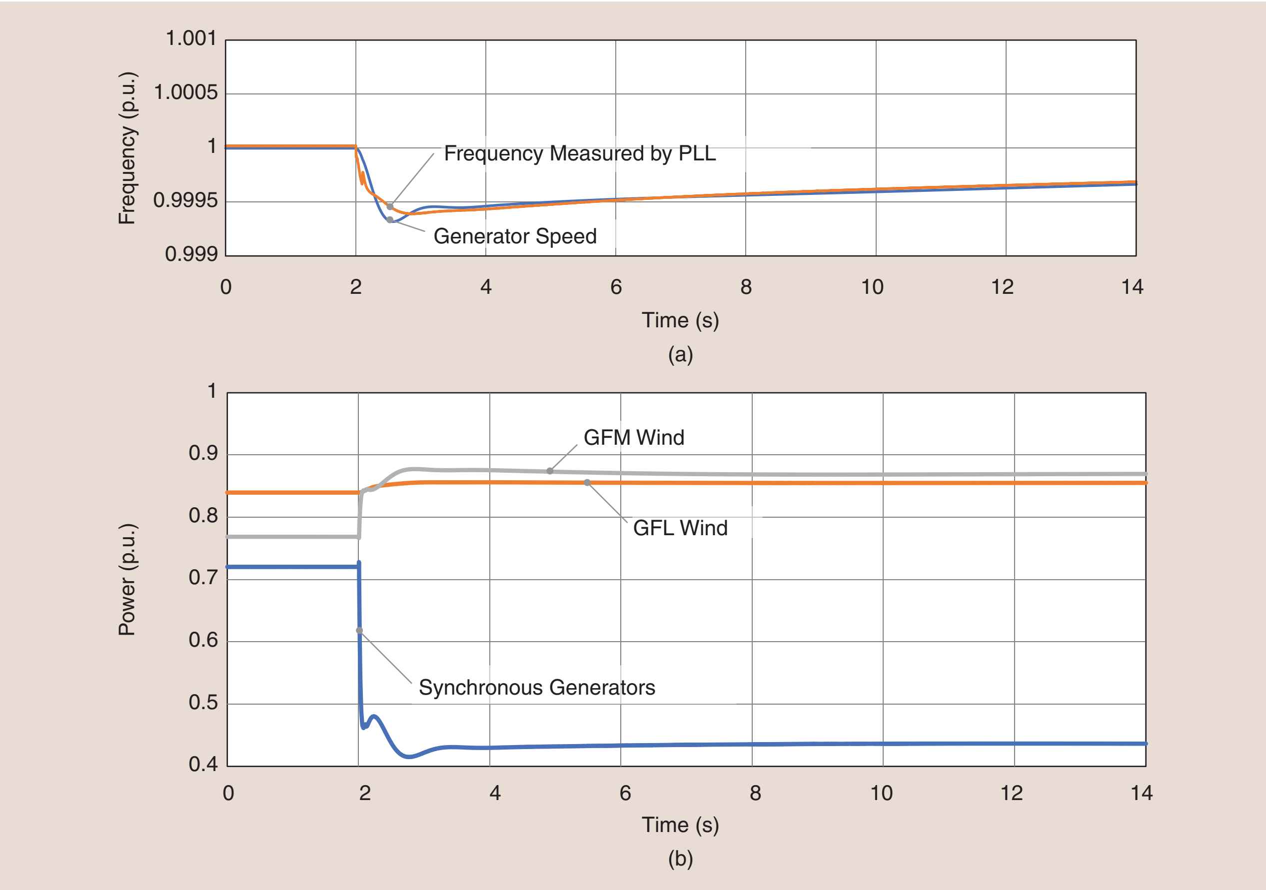

Figure 15. The system response to a loss of generation (16% GFL and 66% GFM wind). p.u.: per unit. (a) Frequency. (b) Power.

Type-5 Promise and Challenges

At first glance (see Figure 16), Type-5 wind power can meet all the stability challenges in a conceptually new (but old, from a physics standpoint) way by keeping the grid largely synchronous while being able to integrate high shares of variable generation. If this sounds too good to be true, it probably is. There are challenges, of course.

The pulsating torques produced during pole slipping can expose the shaft to excessive oscillatory shocks.

One main challenge of Type-5 turbines is pole slipping, which can happen between the synchronous generator and the grid, resulting in the flow of synchronizing power, which reverses twice every slip cycle. Pole slipping can occur after faults that cause a prolonged loss-of-load or loss-of-generation excitation. The pulsating torques produced during pole slipping can expose the shaft to excessive oscillatory shocks. If it is not addressed properly, a pole slip can result in serious damage to both the generator and the gearbox. If pole slipping is detected, the generator must be disconnected from the grid as soon as possible.

In large conventional power plants interconnected with the power transmission system, the probability of a pole slip is low because there are many levels of protection against it. In particular, transmission-level protection systems ensure fault durations of less than approximately 0.1 s, which prevents generator rotor-angle excursions of a pole-slip magnitude. With larger numbers of smaller distributed synchronous generators, a potentially damaging situation with pole slipping can be avoided if proper countermeasures are implemented. In a Type-5 wind turbine, a prolonged voltage fault could cause significant rotor-angle excursions due to imbalance between the mechanical and electromagnetic torques driving the machine out of synchronism. One example of such an event was recorded on the Orkney Islands in Scotland because of a 0.3-s voltage fault on a 33-kV network. A Type-5 Windflow 500-kW wind turbine operating along with total of 10 MW of power-converter-based wind turbines was exposed to high-frequency voltage transients, causing a pole slip in the generator. The following protective measures can be employed in Type-5 turbines to prevent this from occurring:

- The use of TLG technology to protect the gearbox and the generator from the aforementioned torque transients (noting that in the aforesaid instance, the torque limiter behaved as a sacrificial element, which was appropriate given that it is significantly less expensive than the gearbox or generator)
- Improved gearbox designs
- The use of blade pitch control and/or generator frequency sensing to reduce the mechanical torque during low-voltage events
- If a pole slip happens, the use of pole-slip protection in the form of admittance relays to disconnect the

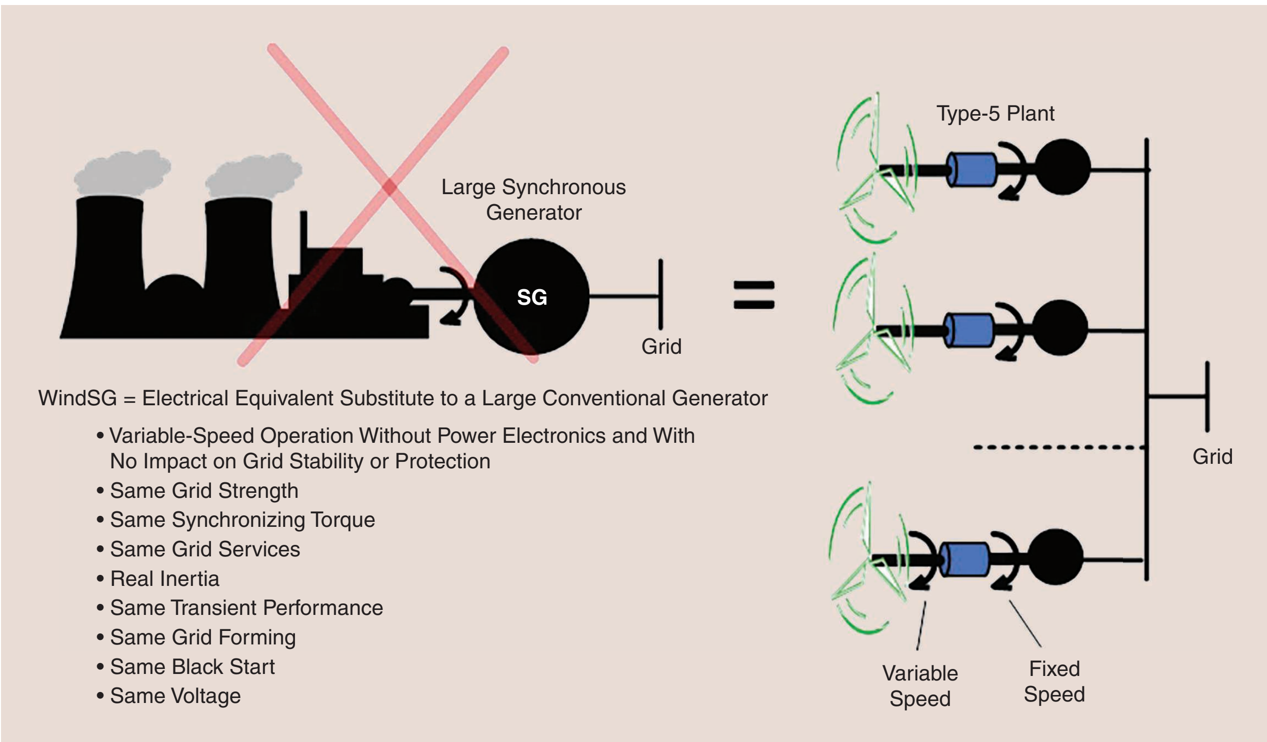

Figure 16. A Type-5 promise.

synchronous generator from the grid during the first half cycle of the pole slipping can avoid damage.

All of these measures are practical and low-cost solutions to keep the grid strong and stable compared to other measures that can be used in IBR-dominated grids, such as oversizing inverters or deploying synchronous condensers. In fact, Type-5 technology already provides all of these as natural behaviors with no controls and no additional cost.

Conclusions

GFM technology for IBRs is gaining traction in the energy industry as the grid continues to evolve with increasing shares of IBRs and retiring conventional generators. GFM control by IBRs can replace some of the services that synchronous generators have been providing. Mainstream wind power based on Type-3 and Type-4 electric topologies, as an IBR technology, is fully capable of providing GFM services. Testing and demonstrations have been conducted for both topologies. Although it is not yet commercially available (like GFM battery storage), GFM wind can make a quick market entry when required. There are still several aspects related to controls and design improvements of GFM wind is actively being developed by wind turbine manufacturers that the industry can address when there is a market in place to incentivize the provision of such services. The stabilizing impacts of GFM controls for IBRs have been demonstrated in many studies. This study demonstrated the stabilizing impacts of GFM wind, in particular. Despite many stabilizing characteristics of GFM IBRs as an enabler for the future carbon-free renewable grid, GFM alone is not a sufficient measurement to resolve all the integration challenges described in this article, with the issue of degrading grid strength and the consequent reduction in the fault current levels being the primary challenge. The substantial deployment of other enabling technologies, such as synchronous condensers, might be necessary to keep the grid strength within acceptable limits. From this perspective, wind power offers a unique solution in the form of Type-5 wind turbine topologies to address essentially all grid integration problems by keeping the grid largely synchronous at very high penetration levels (potentially up to 100%) of renewable generation.

The advantages of the Type-5 technology were described in this article, and certain design aspects (largely mechanical) might need further study and improvement for Type-5 wind power. It might be up to the mechanical and structural engineering community "to save" the grid because the electric and power systems engineering aspects of synchronous generation-based operation are well understood and conventional. Does this mean that we recommend that every wind power plant on the grid must become Type 5? Probably not, unless it proves to be significantly more cost-effective. In any event, the Type-5 technology, if commercially available, can be deployed at adequate capacities on the grid to maintain and enhance grid stability, especially in weaker parts of the grid. The additional option of being able to operate as a synchronous condenser during low wind means that this technology can be an enabler for the secure integration of all IBR resources, including PV and battery energy storage.

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For Further Reading

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Biographies

Vahan Gevorgian (vahan.gevorgian@nrel.gov) is with the National Renewable Energy Laboratory, Golden, Colorado, 80401, USA.

Shahil Shah (shahil.shah@Nrel.gov) is with the National Renewable Energy Laboratory, Golden, Colorado, 80401, USA.

Weihang Yan (weihang.yan@nrel.gov) is with the National Renewable Energy Laboratory, Golden, Colorado, 80401, USA.

Geoff Henderson (geoff.henderson@windflow.co.nz) is with SyncWind Power Ltd, Christchurch, New Zealand.