

Paving the Way

A Future Without Inertia Is Closer Than You Think

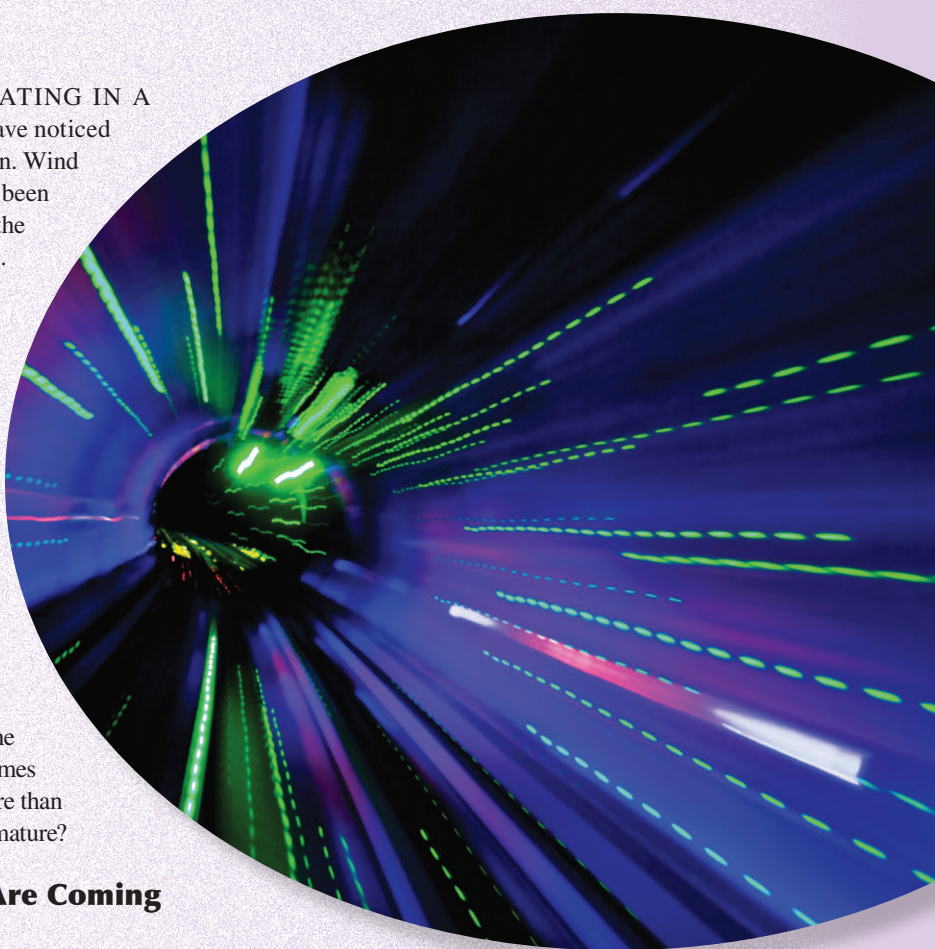
UNLESS YOU HAVE BEEN HIBERNATING IN A remote cave for the past decade, you will have noticed the explosion of variable renewable generation. Wind power and solar photovoltaics (PVs) have been the subject of dozens of articles, just within the pages of *IEEE Power & Energy Magazine*. Charts illustrating relentless growth, such as the example from the United States shown in Figure 1 with futures tending toward 100% renewable energy, are common. This figure, provided by the National Renewable Energy Laboratory (NREL), reflects a low-cost, high-renewable projection scenario.

But closer inspection of this type of annual energy data alone doesn't support concerns about a zero-inertia world. After all, in Figure 1, look at the most extreme reaches of 2050. Only wind turbines and PV systems are converter-based technologies, providing about 60% of the energy in the 2050 scenario. Only just over half the energy comes from nonsynchronous resources, and that's more than 30 years in the future. Isn't this article a bit premature?

Everyone Knows Renewables Are Coming

Remember: It's Power, Not Energy

The reality of wind and solar generation is well understood to be dominated by the availability of the resource; i.e., is it windy or sunny? Sometimes, a considerable amount of wind and PV power will be available when there is relatively little load. The concept of



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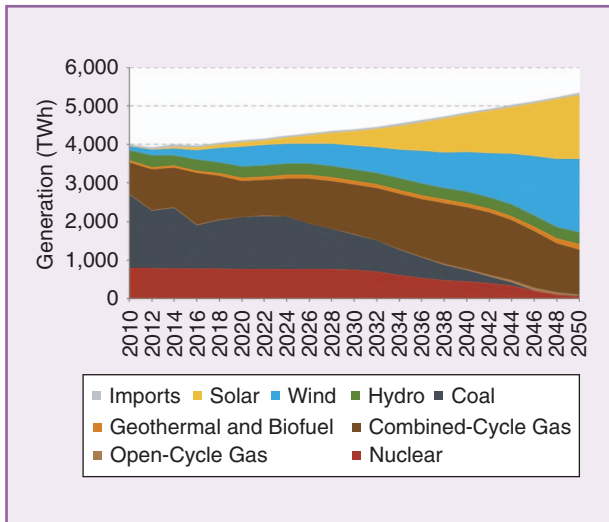


figure 1. Renewable energy projections for the United States. (Source: NREL, 2017).

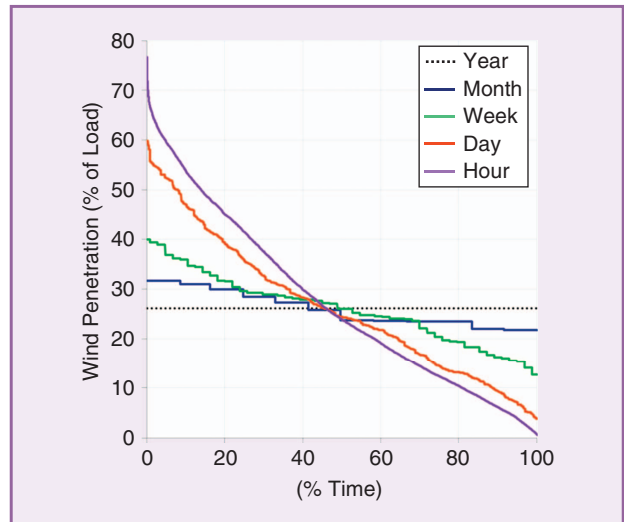


figure 2. Wind penetration duration curves for a nominally 30% annual energy system.

penetration is illustrated in Figure 2. This figure considers a near-future scenario with enough wind generation to meet 30% of a study system's annual energy needs. The first dotted line is at 27% and represents the actual annual energy from wind as a fraction of the load energy consumed—for the year. The available wind energy was 30%, but this system experienced curtailment of wind during some operating hours because of dynamic security limitations.

Moving to shorter time frames, the blue trace shows that some months are relatively windier than others, with the highest monthly penetration reaching approximately 32%

and the lowest reaching approximately 22%. Likewise, some weeks are windier than others (green trace), some days are windier (orange), and some hours are windier (purple). This relentless trend is common to all systems with wind and solar. We can see that this particular 27% annual wind energy system exceeds 70% hourly penetration at times—a level of wind, or wind plus solar, that is well within near-term reach. For this system, increasing the annual wind energy to about 40% would result in many hours during which the desired operation of the system is at 100% (or greater, if export is possible). Some power systems in the world already find

Current Shares of Nonsynchronous Sources

Many small power systems (up to 10-MW peak demand) already achieve very high instantaneous nonsynchronous generation (NSG) penetration levels of 60 to 80%. Instantaneous NSG is thereby defined as generation from power converters [plus high-voltage dc (HVdc) imports, if applicable], divided by demand plus exports.

The power system on the island of St. Eustatius, for instance, is using 1.9 MWp of photovoltaic (PV) and 1 MW of batteries together with three diesel generators, with a total capacity of 4 MW. PV and battery instantaneous penetration levels as high as 89% have been observed, and the instantaneous penetration level will increase further as the PV system is extended. Currently, even at high NSG penetration levels, a synchronous machine (diesel generator) operates at low output power, acting as a synchronous compensator to provide a solid voltage source, while the converters provide the power. Plans are under way to upgrade the St. Eustatius grid so that

it can be operated at certain times without any synchronous generator; i.e., a 100% instantaneous NSG penetration level could be achieved.

Also, larger power systems already reach significant penetration levels. Tasmania is an island electrically connected to mainland Australia by a monopolar HVdc interconnector (Basslink) rated at 500 MW but offering a dynamic rating of 630/480 MW (export/import). Tasmanian demand ranges from 900 to 1,700 MW, and the generation sources include hydro at 2,250 MW, gas at 380 MW, wind generation at 300 MW, PV at 96 MW, and 478 MW HVdc import. The record NSG penetration level reached 78%, considering wind, PV, and HVdc import.

In Ireland (5-GW peak demand and approximately 3-GW wind power installed), the maximum NSG penetration level is currently limited by the system operator to 60%, but it is expected that the limit will be increased incrementally in the near future.

themselves with very high shares of converter-based power supply (see “Current Shares of Nonsynchronous Sources”).

What About the Windy, Sunny Neighborhood of the Grid?

Another reality of wind and solar power generation is that some places are more productive than others. In the case of wind power, location is critical to achieving high capacity factors (and, therefore, good return on capital investment). Similar considerations drive utility-scale PV installations. If we consider the representative system shown in Figure 3, a challenge presents itself. In this system, one corner has a considerable amount of good wind and solar generation, extremely limited economic synchronous generation, and limited transmission to the rest of the grid. A grid-wide view of the renewable penetration might look like Figure 1, but the corner with a good deal of wind and solar can easily reach or exceed 100% penetration of converter-based generation. What happens if that corner of the system disconnects from the rest of the grid? Today, the answer is that the island can’t run with 100% converters.

The point of these simple examples is that the possibility of achieving actual operating conditions with zero synchronous inertia exists now and will grow rapidly in the immediate future. As an industry, we cannot wait until some distant future, when total renewable energy penetrations on an annual basis reach toward 100%. In the very near future, economic and reliability imperatives will require much of the industry to run with zero inertia some of the time.

In this article, we explore the challenge and options associated with this radical transformation of the grid. We start by examining present design and practice for the power electronics that enable wind and PVs to deliver ac power to the grid.

100% Renewables Isn’t Exactly the Same as 100% Converters

The rapidly emerging worlds of renewable energy and converter-based generation are tightly intertwined. A recent article in the March/April 2017 issue of *IEEE Power & Energy Magazine*, “Achieving a 100% Renewable Grid,” looked at a spectrum of issues. But while most wind generation and all PVs rely on converters, many renewable resources deliver their power through synchronous machines. The most obvious is hydro power, but solar thermal, biomass, biogas, and geothermal also use synchronous generators.

Further, we are not concerned solely with generation: it is understood that energy storage will likely play a role. At present, the largest energy storage resource worldwide is conventional pumped storage hydro (PSH), which uses synchronous machines. But rapidly growing energy storage technologies, including batteries and variable-speed PSH, use converters. Converters providing high-voltage dc interconnection, converters serving loads, converter-based static reactive compensation, and even nonrenewable generation that interfaces through converters (such as microturbines) all contribute to the growing trend of converter-dominant systems.

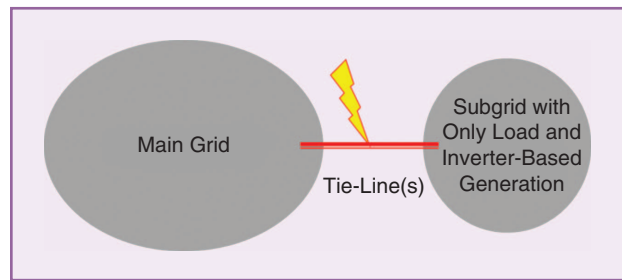


figure 3. A fictitious grid with high wind and solar extremity.

The Actual Behavior of Converters

The main limitation preventing converters from providing the sole source of energy on a grid is the converter controls that are implemented today. Presently, grid-connected converters (even so-called voltage-sourced converters, using forced-commutation devices) are controlled by software to operate as current sources that are grid following. Physically, this means that converters provide a current that is shifted according to the correct phase angle with respect to the grid voltage to provide the desired active and reactive power. Practically, it means that these converters require “appropriate support” to provide the grid with a stiff voltage, which is presently accomplished by synchronous machines. Eliminating all synchronous machines would mean that no frequency reference would be available to the grid; therefore, grid-following converters would not be viable.

Hence, it is essential for some converters to control the voltage. These converters, called *grid-forming converters*, have controls that ensure the grid’s voltage waveform is stable even at a very short time scale. This type of control enables the system to operate at a stable voltage even if loads connect/disconnect from the grid. Figure 4 illustrates the behavior of a converter operating as a current source when a load connects to it.

Changing the Electrical System Paradigm

Going from a system driven solely by synchronous machines to a system with only power electronics introduces tremendous changes in the system’s dynamic characteristics. Synchronous machines are controllable in the steady state and dynamically within certain constraints set by the device’s physical limitations. Additionally, in the case of synchronous machines, the fast-transient behavior is imposed by the physical (both electrical and mechanical) characteristics of the machine. Therefore, regardless of the behavior of controls (e.g., excitation and governors), the system’s performance is largely predictable.

With converters, the controls are much faster, and the behavior of such devices depends mainly on the characteristics of the control software. On one hand, this feature of converters makes the system more controllable. On the other hand, the system is more vulnerable and so more dependent on reliable design and functioning of the controls. Consequently, the specification for converters will need to be more precise and

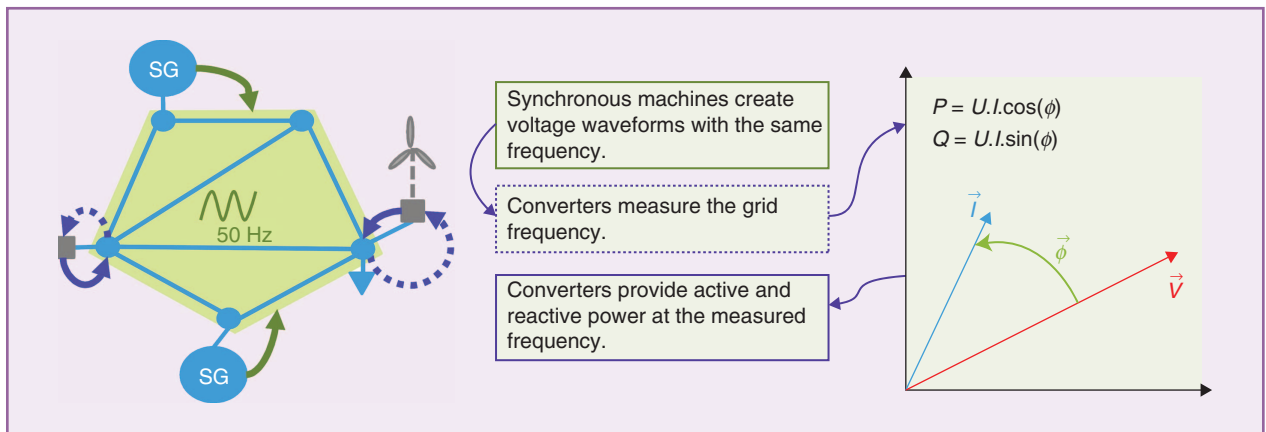


figure 4. The actual grid operation with grid-following converters. SG: synchronous generation.

cover aspects that have never been examined for synchronous machines (the shape of voltage during transients, fault current values, and other similar characteristics).

Frequency, from Analog to Digital

System electrical frequency today is related to the rotor speed of synchronous machines. With converters, however, the change is radical, as frequency is a function of converter control. Frequency can vary rapidly and even in a discrete fashion. Present equipment on the grid usually assumes that frequency is continuous and slowly varying and will not function appropriately in a fast-frequency-varying environment.

A Weak Grid?

A weak grid is characterized by the short-circuit current being “low.” This definition can be seamlessly applied to synchronous machines because their behavior during a short circuit and in normal operation is guided by the same electrical characteristics of the machine. Different aspects need to be taken into account when considering weak grids with converters. For example, synchronous machines can provide extremely high current for a short period (1–100 ms), whereas converters can normally provide little more than their nominal current. This would imply that the short-circuit power will decrease. However, the issue is more complex:

- ✓ Often converters have a low loading factor. Therefore, the ratio between the maximum current that can be provided by converters and the actual active power produced before a fault may not always be as low relative to the active power being produced. As an example, at an initial loading of 20% (which is a typical average load factor), the short-circuit power that can be fed is approximately five times the active power delivered to the grid.
- ✓ With synchronous machines, the active power delivered to the grid is often close to the machines’ nominal power, based on the assumption that synchronous machines are operated at maximum power and the

short-circuit power delivered to the grid is three to five times the active power fed before the fault.

With regard to the stiffness of the network, the short-circuit power is a good indicator; but, for converters, voltage regulation is the main behavior driver, and control in steady state and in fault mode can be radically different. As an example, the voltage regulation of a grid-forming converter can create a very stiff grid voltage; in the meantime, controls can block the converter during fault mode, thereby providing no fault current.

A new definition will probably be needed to address the grid stiffness with converters. The behavior of grid-forming converters during a fault is one of the issues that will need to be carefully addressed, with one of the key aspects being how to control of the voltage while maintaining current below the maximum converter capacity.

Technology Options

Grid-forming converters, with appropriate controls both in the active power loop and in the reactive power loop, together with correctly designed droop characteristics provide the ability to develop and operate inertia-less systems. The proof of concept can be demonstrated by means of large-scale system simulation with effective models in positive sequence time-domain simulations of large systems.

In a recent project completed by the Power Systems Engineering Research Center (PSERC), the viability of a zero-inertia power system has been systematically examined and analyzed. This viability analysis was conducted on a large-scale system using the conventional industry practice of positive-sequence time-domain simulation. A key initial step in this study was to develop an appropriate model for converter-interfaced generation that would capture the essential characteristics of the actual device.

The study focused primarily on the possibility of controlling and operating a zero-inertia system; therefore, the reserve margin was not studied. It was found that the principles of power-frequency droop, coupled with the

availability of fast response from the converter devices, can serve ably in both arresting frequency change and the recovery of frequency.

This analysis has shown that the control and operation of a zero-inertia power system is viable. The primary assumption here is that adequate active power margin is available to balance the system. For this to be the case with *only* converter-based renewable generation, some of the renewable sources of energy would need to be dispatchable, or widespread use of energy storage would be needed. A second assumption is that every converter-interfaced generation source is capable of providing voltage support, which requires sizing the converter to ensure that sufficient current is available to provide the needed active and reactive current.

Verification by Simulation on a Large-Scale System

Large-scale simulations were performed by the Western Electricity Coordination Council, which includes all parts of the United States west of the Rockies, the northern part of Baja California in Mexico, and the Canadian provinces of British Columbia and Alberta. Among others, the following contingency case was examined using the inertia-less system model.

The closing of a transmission line was studied to ensure that it does not cause excessive transients of current and voltage. To observe this scenario, the power flow of the system was solved with an outaged line between two major buses in Arizona, resulting in a high angle difference between the buses. At $t = 15$ s, the line was closed, leading to a severe transient. With the maximum converter current set as 1.7 pu, Figures 5 and 6 show the converter currents for nearby generating units. Based on the figures, we can see that, although there is a large increase in the instantaneous current, the predisturbance current value is achieved within 1 s. In addition, as expected, the unit located close to the line is affected to a much greater extent, but the system is stable and secure. However, if the nearby generating units had a maximum current value of 1.4 pu, the unit located close to the line would trip, while the other units would pick up the slack.

This large-scale simulation-based exercise has demonstrated that the use of only grid-forming converters with well-designed control and adequate headroom in the generation resources could work effectively, even in large systems, and tolerate large disturbances, including significant loss of generation and closing of large transmission lines.

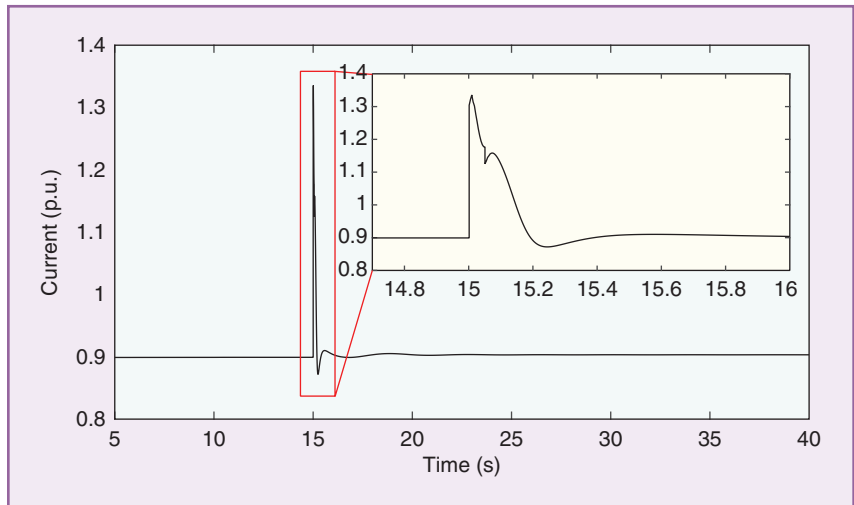


figure 5. The converter current of one Plant A unit for the opening of a tie line between Arizona and Southern California following a line fault.

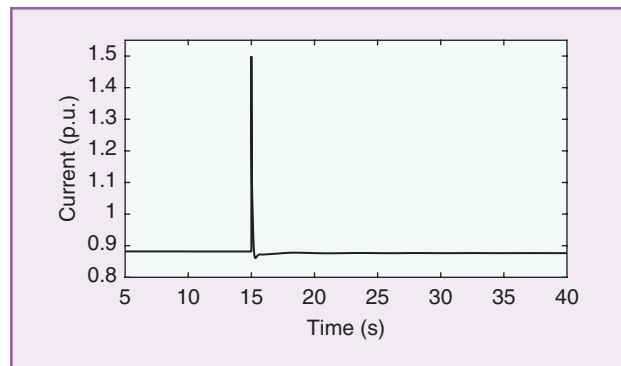


figure 6. The current of a generating unit located close to the line with $I_{\max} = 1.7$.

Near-Term Solution: Power Electronics Must Be Able to Provide Ancillary Services

In most countries, generation sources are required to provide some ancillary services. Usually, the type of service depends on the size of the installation or the voltage level where it is connected. For transmission-connected installations, it is now common to provide ancillary services such as reactive power control and frequency response, but more services will be needed from converters when they are maintained in a grid-forming configuration.

- ✓ **Volt/volt ampere reactive (or VAR) regulation:** the adjustment of reactive power following a set point or using a droop control that links the terminal voltage and the reactive power. This is required today for most converters while they are producing active power. As active power of such installations is usually fluctuating, it will become increasingly necessary that the reactive power capability does not depend on the active power output. Such a requirement is sometimes called

Measuring Frequency: Not As Easy As You Might Think

For more than a hundred years of utility practice, the speed of synchronous generators has been the proxy for grid frequency. Turbine-generator governors have used deviations in rotor speed as the measure of departure of the grid from 50 or 60 Hz. Today, nonsynchronous resources must measure frequency directly from the grid. This is conceptually simple, but there are challenges. For example, when is a disturbance a change in frequency, and when is it something else? Figure S1 shows a single phase of a 50-Hz voltage sine wave. In the middle of the signal, a 20° phase jump occurs, as might be associated with a transmission-line switching event. The elongation of the half-wave means that the “frequency” (in this case, defined by time between zero crossing) has dropped dramatically to 45 Hz for the next half-cycle. Of course, a synchronous machine would filter this out to a negligible deviation. Suitable filtration of the signal here would do likewise. But be careful what you ask for: rapidly measuring frequency can have some strange outcomes.

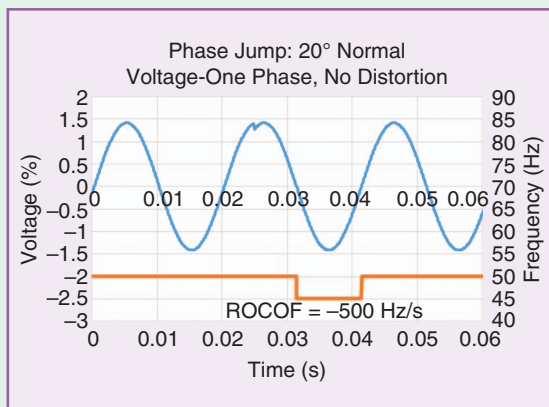


figure S1. A single phase of a 50-Hz voltage sine wave. ROCOF: rate of change of frequency.

STATCOM capability. It is a very important ability because it ensures a stable voltage at any time of the day (with or without sun/wind).

✓ *Active power control:*

- *Frequency regulation:* very similar to what is done presently for synchronous machines. There is a droop control between grid frequency and the active power delivered by the converter. The converter measures the electrical frequency and adjusts its active power accordingly. (This requires some reserve of active power to be able to deliver more power when frequency decreases.)
- *Limited frequency control:* similar to frequency control but with a large deadband that makes it act

only when the frequency deviation exceeds a “normal” deviation (200–500 mHz). This usually has to be provided without keeping any reserve. (For units operated at maximum power, they will not provide any control in cases of decreasing frequency.)

- ✓ *Fast frequency control:* so-called synthetic or emulated inertial response. To limit frequency deviation, converters can provide short-term frequency regulation. The energy provided to the grid can come from different sources: the kinetic energy of a wind turbine, a dedicated battery, and other such reserves. The main difference between emulated inertia and actual inertia is that the emulation requires the frequency to be measured (see “Measuring Frequency: Not As Easy As You Might Think”); therefore, its effect on the grid is delayed, and, for very-fast-frequency transients, it may not be enough.
- ✓ *Ancillary services for active power/frequency control:* defined based on specific system needs and procured through market mechanisms. This would allow suitable technologies to provide the services in the most efficient way. For example, large industrial loads with under-frequency relays are capable of providing fast, effective, and sustained response during under-frequency events.
- ✓ *Specific fault ride-through behavior:* converters formerly used to disconnect when the voltage was too low now providing current even during faults. Importantly, the current is fully controllable, and it can be tuned to provide active only, reactive only, or any configuration of the two. This can be tuned to limit the voltage drop on the grid during a fault transient. Today, converters are even able to provide unbalanced current during faults for specific needs such as protection.

Other mitigation measures, such as power-production limits due to weak grid concerns (e.g., in the Electric Reliability Council of Texas), nonsynchronous generation penetration limits and/or inertia limits (e.g., in Ireland), use of synchronous condensers throughout the network, and other methods can be applied in the interim to maintain system reliability.

Long-Term Solution: To Push the Limit of Converter Penetration Up to 100%, New Controls Will Be Necessary

The first capability is for converters to be grid forming. One of the consequences of being grid forming is that the converter’s output power is now driven by the ac grid and not directly by the primary source. From a consumer’s point of view, a basic requirement is to be certain that when a new load is connected, it will be fed by the grid. From a producer’s point of view, this is more challenging.

The converter is basically a link between an uncontrollable load and varying but predictable primary energy. Controls can change the operating point of the converters to adjust the output to the input, but, during transients, some additional energy will be needed, leading to the requirement for some type of storage or headroom. (The amount of

In a recent project completed by the Power Systems Engineering Research Center, the viability of a zero-inertia power system has been systematically examined and analyzed.

storage or headroom will depend on the speed of the controls; small-sized devices could be sufficient.)

Protecting the Converter Against High Current

Voltage-controlled converters are prone to over-current during grid transients. In case of a grid transient, if the voltage angle shifts, it leads to a shift between active and reactive power, but the total current remains constant and limited to the maximum value. When converters are operated in the voltage-source mode, the active and reactive power that flows out is guided by the network voltage amplitude and phase before the action of the controls. The apparent power of the converter has very limited impact on the over-current, and network modification, due to topology changes can lead to high over-current, as illustrated in the “Near-Term Solution: Power Electronics Must Be Able to Provide Ancillary Services” section. Constraining transients for a grid-forming converter can be tie-line opening and closing or “large” load connection/disconnection close to “small” converters.

Synchronization of Converters and Virtual Synchronous Machines

The synchronous torque inherently synchronizes rotating machines, but this is not obvious for converter-based generation. The control must achieve synchronization of every unit with changing conditions and, most importantly, without measuring frequency—for at least some of them (as previously stated, some converters need to form the grid).

This synchronization can be achieved with two main varieties of grid-forming converter-control algorithms. The first variety emulates a synchronous machine and is commonly referred to as a *virtual synchronous machine (VSM)*. The conventional grid-following converter current-control loop architecture has a control bandwidth significantly in excess of 50/60 Hz and aims to source sinusoidal balanced currents synchronized with the existing grid voltages using a phase-locked loop. It is possible to completely replace this control architecture with one that, instead, mimics a physical synchronous machine rotor. Only a generic representation is required, so parasitic effects such as saliency and non-linearity are not crucial. (See “Grid-Forming Converters: A 20-Year View from an Island.”)

The critical model parameters are rotor inertia, rotor electrical damping, and the transient impedance X' . In practice, X' is equivalent to (and can be defined) by the converter filter inductance, which behaves almost exactly as a real machine X' . The simulated rotor dynamics form

a second-order transfer function with a resonant frequency (normally) around 2 Hz for reasonable values of inertia H (in seconds), damping, and X' , just as in a real machine. It can be shown that, to provide a response closely approaching true inertia from a converter, it is necessary to accept that there will be a damped resonance. It may be possible to configure higher levels of damping than a real machine provides, even up to critical damping, because in the converter, damping is implemented mathematically and is not constrained by physical damper-winding design or efficiency losses. However, more research is needed to fully understand the ramifications of high damping levels.

The VSM needs to have a suitable automatic voltage regulator (AVR) control loop applied, which provides voltage and reactive power control just as in a real machine. A governor is also required and can take many forms, either following active-power set points, controlling frequency, providing droop response, or any combination of these. Optionally, “slow” prime-mover responses can be simulated, i.e., steam turbine responses. Determining exactly which governor and prime-mover models to use for a particular scenario requires more research, especially in the context of renewables. The energy and power flow against time, as well as the requirement for short-term or long-term energy stores to ride through dynamic events, needs to be examined.

Grid-Forming Converters: A 20-Year View from an Island

In the latter years of the 20th century, the Native Alaskan community of Metlakatla faced a difficult technical and economic power system riddle: how to manage the extreme active power swings associated with the biggest load on their island grid. To replace an expensive, dirty diesel generator needed for frequency regulation, a 1 MW-class utility-scale battery-converter system was built. That system uses 1990s vintage self-commutating converters, with an early version of grid-forming virtual synchronous machine controls. The system has been used to set frequency and voltage, black-start the grid, and manage a variety of difficult grid dynamics. After 20 years, the system has saved the community millions in diesel fuel costs, while maintaining a cleaner and more reliable grid.

It can be shown that, to provide a response closely approaching true inertia from a converter, it is necessary to accept that there will be a damped resonance.

The VSM behaves as a voltage source, because both its rotor dynamics (~ 2 -Hz bandwidth) and AVR dynamics have bandwidths $< 50/60$ Hz, and the adjustments to the pulsewidth modulation patterns are slow relative to the 50/60-Hz fundamental. It therefore does a very good job of “mopping up” unbalance, and it can provide power to heavily unbalanced loads. It is also quite good at “mopping up” harmonic voltages, although linear load is also (or more) effective at high harmonic orders. Because the VSM is a voltage source, during the closest faults, some intervention is needed to protect the solid-state devices from overcurrent. Viable methods have been demonstrated in the laboratory, able to sustain >140 -ms full-depth balanced and unbalanced faults, but without compromising the normal “voltage source” capability. Additional interventions can be made during faults. For example, setting $H = 999$ during a fault helps to stop the virtual rotors accelerating while fault ride-through is active and so can potentially make VSMs more robust than real machines against faults. Parameters such as damping, inertia, and governor response can, if needed, be adjusted in real time, remotely via software.

Because the VSM is a voltage source, with frequency and voltage stabilized by its virtual inertia and AVR, it provides “synchronizing torque.” It also provides inertia. But, crucially, it is not necessary that inertia be established to provide synchronizing torque; they are not the same thing. Thus, it is possible to provide synchronizing torque without providing inertia.

This can be achieved by using a second variety of grid-forming (voltage source) converter-control algorithm. This second variety implements frequency and voltage control loops that operate on a strict pair of droop slopes: active power to frequency and reactive power to voltage. There is effectively an “instant” (~ 10 -ms) governor/prime-mover response time. The converter simply measures its output power over a short window such as one exact cycle (which provides good harmonic mitigation) or measures the instantaneous power output and applies low-pass filtering of the order of <1 cycle period so that the control-loop bandwidth is $<50/60$ Hz (normally, perhaps in the ~ 20 -Hz region).

Then, using a simple linear droop slope with configurable frequency and power set points, a target frequency is determined. This target frequency is within a few percent of nominal for normal set point and droop slope configurations. The converter simply advances its virtual rotor at this frequency, and power synchronization is effectively achieved. A parallel loop operates on reactive power and voltage. Such a control scheme has acquired various names in the literature, such as *power synchronization* or *VSM0H*. This latter term

refers to the fact that the response of this architecture can be shown to be mathematically identical to a VSM but with $H = 0$, no direct rotor electrical damping, and an “instantly” responding (within one cycle) governor/prime mover delivering “instant” droop response.

While rotor electrical damping is proportional to rotor speed minus electrical stator frequency, droop response is proportional to electrical frequency minus set point electrical frequency. While they are different, the “instant” droop response actually provides a useful damping of grid frequency disturbance and is extremely effective at limiting frequency nadir during events. It also provides what would be called “synchronizing torque,” even though it has zero inertia, because it acts as a stiff, balanced voltage source, with a well-defined frequency close to nominal, behind a reactance (formed by its filter impedance). A network powered only by VSM0H converters is entirely viable. In this scenario, a discrete resistive load step results in a network frequency that transitions from one frequency to another (defined by the droop slopes and set points) over a period of approximately one cycle.

So, while this VSM0H-type controller offers no inertia, it is entirely viable as a grid-forming solution, as confirmed by the PSERC analysis, and can also be used in parallel with real machines and with VSM converters that do offer inertia. No special time-sensitive communications are required between the converters as long as sensible configurations of set points and conventional droop slopes are used to suit the network and connected energy sources. Sufficient energy must also be available on the dc buses to drive the converters and serve the loads.

In both previously described modes (VSM and VSM0H), the converters are grid forming, provide synchronizing torque, serve unbalanced loads and mitigate unbalanced voltages, and serve nonlinear loads and mitigate harmonic voltages. The converter contribution to these services is, by default, inversely proportional to the magnitude of the effective filter impedance—in exactly the same way that a synchronous machine’s contribution to these phenomena is inversely proportional to its transient reactance X' . For a real machine, X' is inversely proportional to machine rating, and this is normally true for a converter filter impedance as well. So the device’s contribution to power quality and synchronization torque is roughly proportional to its rating because X' is normally in the region of 0.1–0.15 pu for both machines and conventional converters. This presents some further challenges (and perhaps opportunities) for multilevel converters, which may in the future have much lower inductive filter impedances than conventional converters.

Because the VSM is a voltage source, during the closest faults, some intervention is needed to protect the solid-state devices from overcurrent.

Summary and Predictions

Compared to traditional generation, converter-connected devices are limited in maximum current due to the use of solid-state power electronics. They are also limited in terms of active power response because of application-specific limits of power and energy availability at the dc bus, particularly for renewable energy sources. However, if these constraints are managed, it is possible to provide stable converter-dominated—or even converter-only—power systems serving dynamic real-world customer loads that have unbalanced and nonlinear components. To accomplish this, at least a certain proportion of the converters needs to be grid forming, acting as voltage sources (not current sources), mitigating power quality, and providing active power as the loads demand.

To enable seamless, dynamic power sharing between converters, conventional frequency-power set points and droop slopes can be configured with low update rates commensurate with conventional network practice. Depending on the grid-forming converter-controller variety, it may offer VSM functionality with inertial support or VSM0H functionality that provides fast-acting droop response but no inertia. It is entirely feasible to operate a converter-only network with zero inertia and bounded frequency-nadir excursions, this having been demonstrated in simulation and practical experiments. However, there is insufficient industry experience to establish the exact proportion of inverters that need to be grid forming to create viable systems. Converting existing commercial installations to become grid forming will be impractical or impossible for much of the installed base.

Because so many existing grid-connected devices and machines expect frequency to change relatively slowly, sudden removal of all inertia from an existing network would be impracticable, with, for example, unpredictable consequences for protection relays as well as large power transients for directly connected pumps and ac machine loads. As noted in the opening, the evolution of the system will likely occupy a continuum toward lower levels of synchronous resources. Whatever strategies are adapted must be capable of working with some synchronous machines.

More likely, in the near to medium term, we will require a managed balance of inertia-providing and noninertia-providing devices, the choice for each device made considering the properties of the connected energy source. However, in the long term, a more holistic system-planning approach is needed. Band-aid solutions applied in the interim by system operators worldwide to maintain reliability may inadvertently limit further integration of converter-connected devices. Defining the

grid-forming function as an essential reliability service may attract new grid-forming inverters to the market but may also provide additional incentives for existing synchronous generation. Requiring grid-forming converter control from new converter-connected devices could be another route.

Still, it will take time until a sufficient number of these is installed. More research is needed to bridge that implementation gap between available grid-forming converter technology and integration of this technology into a power system with its existing energy resources, protection systems, interconnection requirements, energy and ancillary services, market structures, and other attributes.

For Further Reading

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