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Achieving a 100% Renewable Grid

Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy

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WHAT DOES IT MEAN TO ACHIEVE A 100% renewable grid? Several countries already meet or come close to achieving this goal. Iceland, for example, supplies 100% of its electricity needs with either geothermal or hydropower. Other countries that have electric grids with high fractions of renewables based on hydropower include Norway (97%), Costa Rica (93%), Brazil (76%), and Canada (62%). Hydropower plants have been used for decades to create a relatively inexpensive, renewable form of energy, but these systems are limited by natural rainfall and geographic topology. Around the world, most good sites for large hydropower resources have already been developed. So how do other areas achieve 100% renewable grids? Variable renewable energy (VRE), such as wind and solar photovoltaic (PV) systems, will be a major

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> In future grids, the number of inverter-based devices may be more than 50% of the rated power at any time, thereby forming an inverter-dominated grid.

contributor, and with the reduction in costs for these technologies during the last five years, large-scale deployments are happening around the world.

Countries such as Denmark, Ireland, and Germany have aggressively installed VRE systems and are operating with annual VRE penetrations of more than 20% at the national level. The annual penetration level is used to describe how much VRE is produced on an annual basis, but instantaneous penetrations vary widely during the year to reach those levels (see "VRE Penetration Levels"). The instantaneous penetration may be an even more important factor when considering the actual stability of a power system at high VRE levels. For example, Ireland currently limits its instantaneous penetration to 55%. Currently, VRE provides approximately 13% of the annual energy in Europe and 5% in the United States, but VRE technologies have seen rapid deployment during the last five years. So what would a power system dominated by these technologies look like?

Dealing with Variability and Uncertainty

Several studies have examined increasingly higher levels of renewable penetrations in the United States. Figure 1(a) and (b) shows potential future deployments from the National Renewable Energy Laboratory's "Eastern Renewable Grid Integration Study," which examined up to 30% of the VRE deployed in the eastern United States; generators are color coded: blue represents wind locations, and yellow represents solar locations. The future scenario in Figure 1(b) shows the highly distributed nature of potential future deployments of VRE technologies across the Eastern Interconnection. Reaching 100% renewable energy would have even more VRE systems distributed and deployed across the grid.

Wind and solar power are different from most thermal generators because they have variable and uncertain power output determined by local weather conditions. Conventional generators, such as coal and gas plants, are considered dispatchable because they can more easily change their power output (both up and down) to meet changes in load. As the penetration of VRE increases within a system, many factors require greater grid flexibility to accommodate the changes in generation. PV power, in particular, has a natural challenge associated with its diurnal cycle because it does not produce any power during the night. This makes the power output between individual PV generators very well correlated, with large amounts of energy in relatively small windows of time. This can lead to larger net load ramps than might otherwise be seen in the evenings.

Wind energy also has a diurnal cycle, albeit one that is less pronounced than that for PV power. In many locations within the United States, there tends to be more wind energy produced during nighttime hours than during daytime hours. Wind power can also produce ramps in power output when there are large changes in weather conditions across large geographic areas. Generally, these ramps tend to occur during multiple hours when there is a sufficient amount of geographic diversity in the wind power resource. In addition, because of the time coincidence of VRE, there can be times when there is too much supply, and the curtailment of VRE makes sense for economic or reliability reasons. An example of this is shown in Figure 2, which depicts the generation dispatch stack from the "Renewable Electricity Futures Study" during a week of low load and 80% renewable energy penetration. During times when both wind and solar power have high output values, curtailing some of these generators is the most economic option; however, these curtailment decisions rely on a complex set of variables, including the flexibility of the remaining generation fleet.

Although there are a number of additional challenges associated with large penetrations of renewable energy, there are also many solutions that can provide the flexibility needed to handle these challenges. These include the smoothing of overall VRE power output through sufficient amounts of geographic diversity when siting the VRE generators. Another solution is an expansion of the transmission system to be able to move large amounts of power more efficiently from regions where VRE generators are currently producing to the areas where load is currently needed. The increased effective geographic diversity of VRE generators and utilization of transmission resources can both be accomplished through greater coordination among balancing authority areas and faster interchange intervals.

A technology that allows for the temporal shifting of VRE is energy storage. Energy storage has value in the power

VRE Penetration Levels

- Annual VRE penetration level = Fraction of annual energy (kWh) met by VRE
- Instantaneous VRE penetration level = Fraction of instantaneous power (kW) met by VRE at any point in time

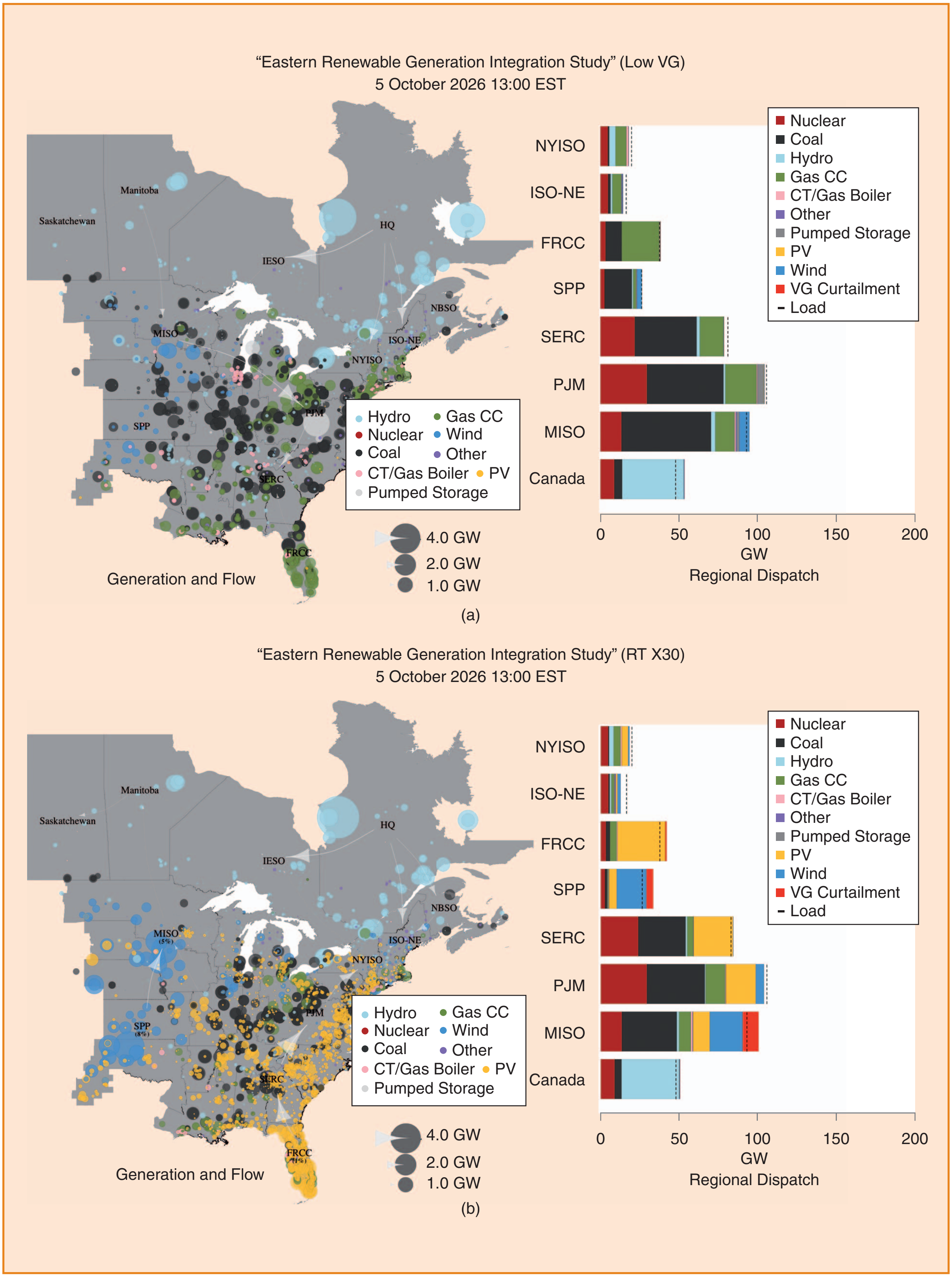

figure 1. (a) A future grid with 10% VRE in the eastern United States. (b) A highly distributed future grid with 30% VRE in the eastern United States.

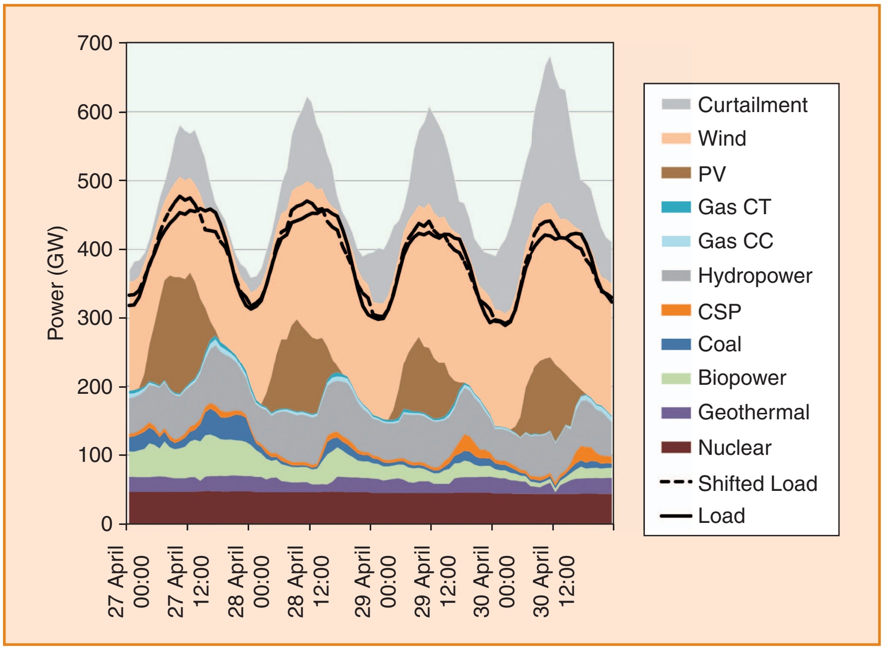

figure 2. The off-peak national production charts for an 80% VRE transmission-constrained scenario show massive curtailment at high renewable energy penetrations.

charging, can play a similar role. Another technology that can aid in the efficient utilization of flexible resources is advanced renewable energy and load forecasting. Characterizing or reducing the uncertainty associated with VRE output or load enables a more efficient utilization of the entire power system, including conventional generators, storage devices, and transmission infrastructure.

As we add more VRE into power systems, the grid of the future will have many more inverter-based generators and be much more distributed than the current power system, which is dominated by central-station synchronous generators. In general, VRE resources often use inverters to connect to the grid instead of synchronous generators, and if the instantaneous penetration

system at many timescales, the most important of which is in shifting wind and solar power from times when it might otherwise be curtailed to times when the power output of VRE is lower than current demand. This intra- and interdaily shifting of power can be performed by several different storage technologies, such as the existing pumped hydropower fleet, compressed air energy storage systems, or various battery technologies. Demand-response technologies can play a similar role by shifting load demand so that it coincides with VRE generation or lowers the ramping requirements of the remaining generation fleet. Similarly, new loads that have flexibility in their use patterns, such as electric vehicle

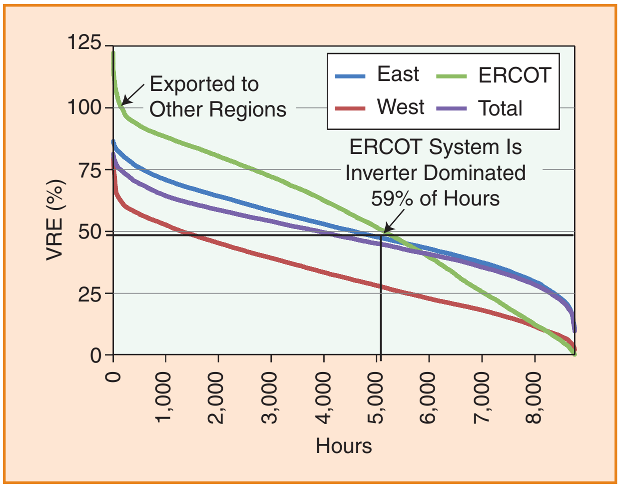

figure 3. The cumulative hours in a year compared to the instantaneous VRE penetration for three interconnections and the total in the United States for the scenario when total annual VRE penetration is 80%.

of VRE were more than 50%, the system would be operating as an inverter-dominated grid. The challenges with high levels of inverter-based generation in power systems are discussed in detail later in this article, but studies such as the "Renewable Electricity Futures Study" show that, at higher levels of VRE penetration, there is an increasing number of hours during the year with more inverter-based generation than synchronous generation. Figure 3 shows the VRE penetration curves for each interconnect and the total in the United States for an 80% renewable scenario that is transmission constrained. This figure also illustrates that the Electric Reliability Council of Texas (ERCOT) would be an inverter-dominated system more than 59% of the time. Figure 4 is a scatter plot of VRE compared to load in ERCOT for the same scenario. The solid lines show a large number of hours when the system operates with more than 50% VRE, and in some cases with more than 100% VRE, due to exporting energy to the other interconnections. At these high renewable energy scenarios, the power system not only has a large number of inverter-dominated operational hours, but it also fluctuates between being synchronous generator dominated and inverter dominated on a daily basis.

Inverter-Dominated Grids

So what is an inverter-dominated grid? If we examine existing large-scale ac power systems, we note that they are predominately powered by conventional synchronous generators [Figure 5(a)]. Nuclear, coal, gas, and hydropower systems all utilize synchronous generators to connect to the rest of the electric grid. These generators are interconnected through an extensive transmission and distribution system providing reliable and affordable electricity to customers; however, one of the main distinguishing aspects of VRE integration is that, aside from concentrating solar power, VRE technologies interface to the grid through power electronics devices called inverters that convert native dc electricity into grid-compatible ac power. Although it is common for a VRE resource, such as wind, to utilize multiple ac-dc and dc-ac conversion stages before interfacing to the grid, we focus our attention on the final output stage that converts dc to grid-compatible ac because that is the circuit that directly interacts with the ac power system. In future grids [Figure 5(b)], the number of inverter-based devices may be more than 50% of the rated power at any time, thereby forming an inverter-dominated grid.

The synchronous generators used in conventional power plants are machines that have a stationary part (stator) and rotating part (rotor) that produce a rotating magnetic field inducing a voltage within the stator windings. This process creates ac electricity at a specified frequency (typically 50 or 60 Hz). These machines have unique characteristics that have dictated how power systems have been planned and operated since the inception of electric machinery more than a century ago. Once synchronized to the rest of the grid, the real power of the machine can be controlled through the shaft torque, and the reactive power is controlled through the field current. To ensure the reliable operation of the interconnected power system, the system frequency and voltages are tightly regulated through a combination of fast-acting closed-loop controllers at each machine (primary frequency response through governor controls) and slow, centralized controllers (automatic generator control, or AGC) that system operators use to restore the system frequency to its nominal value. Ultimately, frequency and voltages are the key variables that must be regulated in the system and form the main objectives of system control.

From a physics standpoint, the turbine system and rotating components inside each machine exhibit mechanical inertia, and as such they are capable of storing kinetic energy in this rotating mass. Because that energy can be extracted from or absorbed into these rotating masses during system disturbances, an interconnected system of machines is able to withstand fluctuations in net load and generation. Specifically, a net excess (or deficiency) in generation delivers energy into (or extracts energy from) the rotating masses and subsequently leads to an increased (or decreased) system frequency; hence, the direction of the frequency deviation is an indicator of net energy excess or deficiency on the system. Further, the total amount of system inertia (i.e., the net rotating mass across all interconnected machines) is proportional to the ability of a system to absorb variations across

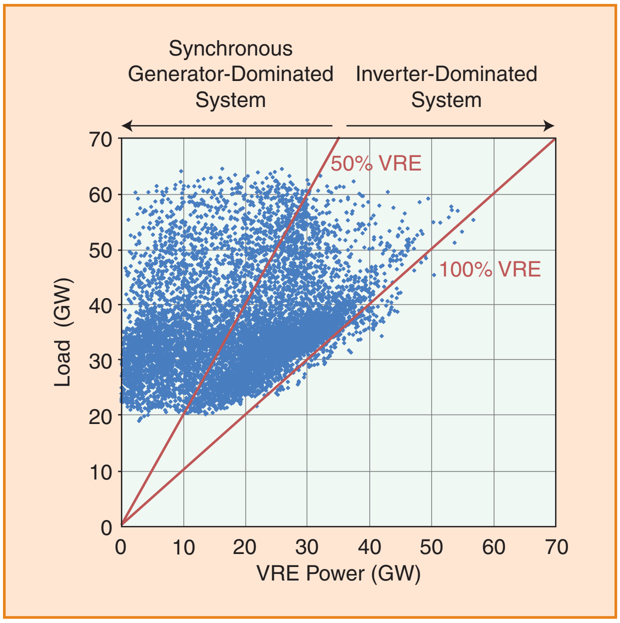

figure 4. VRE compared to load for only the ERCOT system at the 80% VRE transmission-constrained scenario.

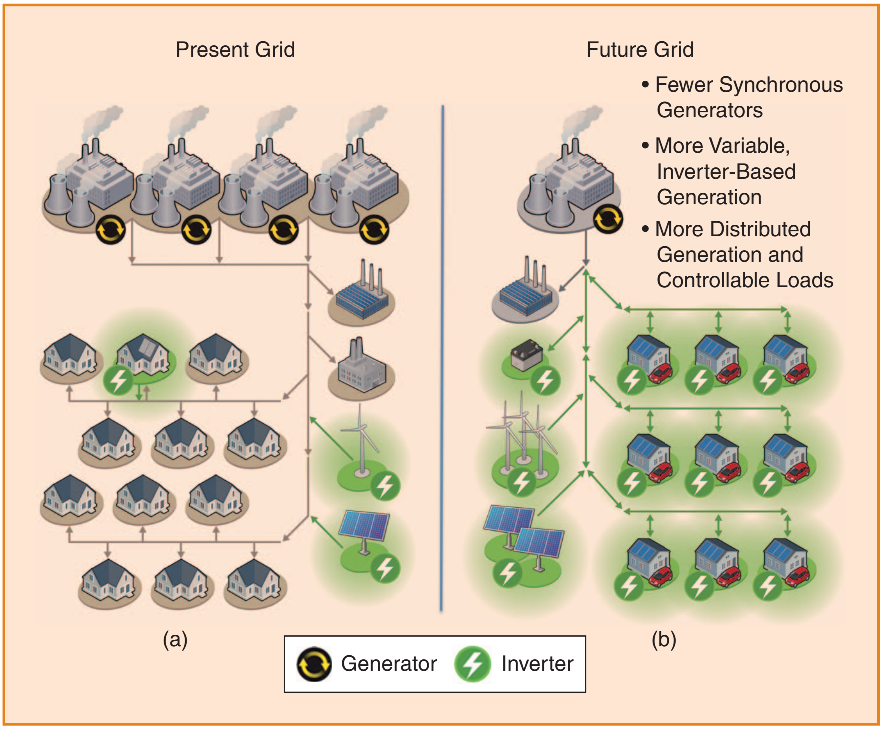

figure 5. The present grid is dominated by synchronous generators having large, rotational inertia with a relatively small amount of inverter-interfaced VRE sources. The future grid will be realized as VRE penetration increases and conventional synchronous machines are gradually replaced with power electronics-based generation, storage, and loads.

> Grid-following controllers represent the most prevalent type of control strategy for grid-connected PV and wind inverters.

loads and VRE when the magnitude of the frequency deviation is inversely proportional to the net inertia on the system. Consequently, a system with low inertia is vulnerable to larger and undesirable frequency deviations.

Another important factor determining the dynamic behavior of existing power systems is the synchronizing torque produced by synchronous generators. The synchronizing torque along with inertia has a crucial role in determining the initial rotor speed behavior of conventional generators following a contingency event in the grid. The active power injected by synchronous machines maintains synchronism and damps mechanical oscillations through their synchronizing and the damping torque components of the total electric torque. The abundance of inertia and synchronous torque from synchronous machines along with their controls allows for the mitigation of the large active and reactive power imbalances in the grid. This fundamentally important characteristic of power systems would change dramatically with growing penetrations of inverter-based generation.

In contrast, VRE technologies utilize a fundamentally different set of technologies for energy conversion and interfacing to the grid. VRE sources typically connect to the grid through a power electronics interface called an *inverter.* The inverter converts dc electricity to ac power and manages the flow of energy by controlling switching semiconductor devices at a fast timescale. In contrast to a generator, an inverter is strictly electronic and does not contain any mechanical components or rotating masses. Accordingly, it does not exhibit the physical properties of the machines described previously. Inverter technologies are especially important because they are used across a wide variety of applications.

Wind turbines that use power electronics interfaces include what are called Type III or doubly fed induction generators (DFIGs), in which the rotor windings are connected to the grid via slip rings and an inverter. Type IV wind turbines convert all power delivered by the wind turbine generator to dc and then back to grid-compatible ac power through an inverter. PV systems always require an inverter because PVs natively generate dc electricity and the inverter must deliver this power to the ac grid. Although battery storage is not a VRE source in itself, it will play a key role in managing energy balance in systems with high penetrations of VRE, and it is also interfaced to the grid through inverters.

Regardless of the VRE type that interfaces to an inverter, a closed-loop controller is required to regulate the energy flow from the dc input, through the power electronics, and ultimately to the ac grid. These controllers are typically executed on digital controllers where real-time measurements are processed and user-defined controls are programmed and executed. Of particular importance, the characteristics of the chosen control strategy, not the inverter's physical properties, dictate the electrical dynamics of the inverter during disturbances and how it interacts with the grid on its ac side. In other words, its physical response is dictated by how its digital control is programmed. This is in contrast to synchronous machines, where the physical properties of the machine itself, such as the amount of mechanical inertia and electrical parameters, play the largest role in determining its transient behavior. To highlight this difference between inverters and electrical machinery, inverters are often described as having zero inertia because their response depends almost entirely on the particular control strategy they utilize and they have no moving parts.

Broadly speaking, there are two classes of inverter controllers: grid following and grid forming. Grid-following controllers represent the most prevalent type of control strategy for grid-connected PV and wind inverters. At the core of its operation, a grid-following controller utilizes a phase-locked loop to estimate the instantaneous angle of the sinusoidal voltage at the inverter terminals. Subsequently, the power electronics are manipulated to inject a controlled current into the grid that tracks the sinusoidal terminal voltage. In essence, a grid-following inverter acts like a sinusoidal current source that "follows" the voltage at its terminals; hence, it is called a grid-following unit.

As one limitation, grid-following inverters work under the presumption that a "stiff" ac voltage with minimal amplitude and frequency deviations is maintained at its terminals such that it can simply follow its local voltage and inject a controlled current. In practice, this translates to the assumption that the collective behavior of the synchronous machines, the generator and system controllers, and voltage regulating equipment on the system provides a sufficiently stiff frequency and voltage at any point on the grid. Historically, this assumption has held up relatively well because the cumulative amount of VRE with grid-following inverters has been relatively small compared to conventional synchronous generators that regulate the system frequency and voltages (see the left side of Figure 4). However, what will happen as we transition to a system that may be dominated by or built entirely on inverter-interfaced VRE sources? If one tried to build a zero-inertia system entirely with grid-following inverters, it is unclear which grid assets would regulate the voltage because grid-following inverters merely act as voltage-following current sources. It would be challenging, if not infeasible, to obtain an inverter-based system with grid-following control.

To overcome this shortcoming of grid-following inverters, it is necessary to develop next-generation grid-forming inverters that enable the transition to an inverter-based infrastructure and are capable of regulating system voltages and frequency through local decentralized control. Before considering the necessary characteristics that these grid-forming inverter controllers must have, it is worth looking at a few key aspects of the challenges that lie ahead. First, it must be recognized that next-generation inverter-based systems will be realized gradually over several years or decades as synchronous machines are gradually replaced with renewable sources. Further, given that power electronics inverters are typically several orders of magnitude smaller in power rating compared to synchronous machines, this implies that the system load in an inverter-based infrastructure must be satisfied with a much larger population of inverters. For large-scale electric grids, this will likely translate to the installation of millions of inverter-interfaced VRE units across large geographical regions. Considering these points, these new controllers must have the following features:

- ✔ Grid-forming inverter controllers must be compatible with existing systems and provide a seamless path between the architectures shown in Figure 4 as the system evolves over time.
- ✔ Very large collections of geographically dispersed units imply the need for decentralized approaches that do not require communications for fast-timescale control.
- ✔ To pave the path toward a resilient and reliable infrastructure that lasts into the foreseeable future, the grid-forming units must be able to operate in the complete absence of synchronous machines, if needed.
- ✔ In addition to active and reactive power controls, controllers of grid-forming inverters must employ advanced control methods to maintain adequate power quality characteristics of the energy supply to loads

To achieve these objectives, a variety of grid-forming control strategies have been proposed. The most established approach, droop control, is motivated from traditional control methods for synchronous machines and is implemented by programming a linear relationship between real and reactive power compared to frequency and voltage; however, because the computations of real and reactive power are carried out on a relatively slow timescale, droop-controlled inverters are susceptible to a sluggish response during transients. Alternatively, researchers have explored methods of emulating various physical phenomena with inverters to create so-called *virtual synchronous machines* or *virtual inertia*. In this type of application, the governing equations of a machine or its inertial responses are programmed on the inverter controller. Last, a class of grid-forming methods based on the dynamics of nonlinear oscillators has received recent attention. Drawing inspiration from the emergence of synchronization in networks of coupled oscillators and leveraging the algorithmic flexibility of digital control, these new virtual oscillator controllers yield rapid response times and have been shown to be capable of creating zero-inertia, inverter-based systems.

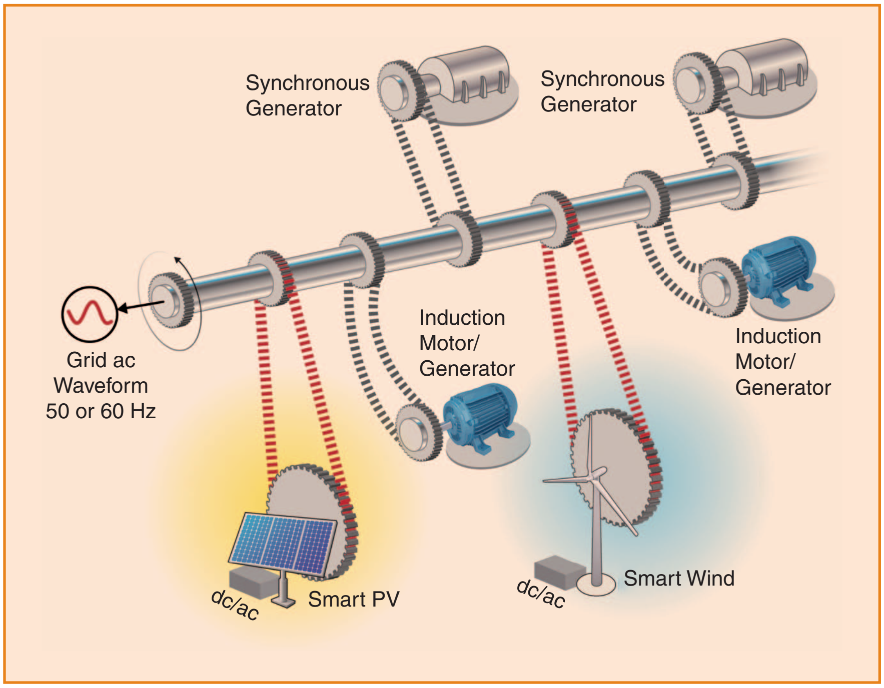

figure 6. The representation of an electric power system showing tight coupling of synchronous generators and smart VRE systems and loose coupling of induction motors/generators.

Power System Stability

AC power systems rely on the basic physics of synchronous generators to provide grid stability. For all synchronous generator rotors, the rotating mass electromechanically couples to each and every one of them through the electric grid so that they rotate in synchrony during stable operating conditions. In synchronized conditions, this is equivalently represented as one large generator shaft running at the nominal ac frequency (typically 50 or 60 Hz). Figure 6 shows a representation of the tight coupling among synchronous generators. This equivalent rotating mass is

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known as the system inertia and consists of summed generator masses. Induction motors/generators do not have coupling as tight, and therefore they are not usually considered in the system inertia. The inertia of a power system is also a measure of how well the system can "ride through" disturbances and still maintain stable frequency and voltage. Future PV and wind systems will need to help maintain the grid stability at high penetration levels.

Power system stability can be divided into three major categories: rotor angle stability, frequency stability, and voltage stability. Each of these categories can be further divided into two subcategories: small-signal stability and transient stability.

- ✔ Rotor angle stability is the ability of synchronous generators in an interconnected power system to remain in synchronism after disturbances.
- ✔ Frequency stability is the ability of a power system to maintain steady frequency during normal operation and restore frequency to its scheduled level during system contingencies when large imbalances between load and generation may be present.
- ✔ Voltage stability is the ability of a power system to maintain voltages within safe limits at all buses after disturbances to prevent outages and blackouts.

Generators and loads are providing various types of ancillary services to ensure the stable operation of a power system during steady-state and transient conditions. Ancillary services can be either cost or market based. Independent system operators set the required amount of ancillary services based on the least-cost option. In the current power system, ancillary services are mainly provided by conventional generators and loads. If controlled properly, VRE is capable of providing the full set of ancillary services, and it can successfully contribute to maintaining stable and reliable operation of the power system.

Many conditions of the power system, including generation and load levels as well as transmission availability, are both variable and hard to predict; therefore, additional capacity called operating reserves is made available during the dispatch process to ensure the system's frequency stability during sudden imbalances. The variable nature of VRE increases the importance of the reserves due to the uncertain nature of these renewable resources. The classification of the operating reserve categories is shown in Figure 7. Both the normal and event-responsive reserve categories can be subdivided by their required response speeds. For instance, instantaneous events need a generator-level response to arrest the rate of change of frequency (inertial response) and stabilize the frequency at some steady-state

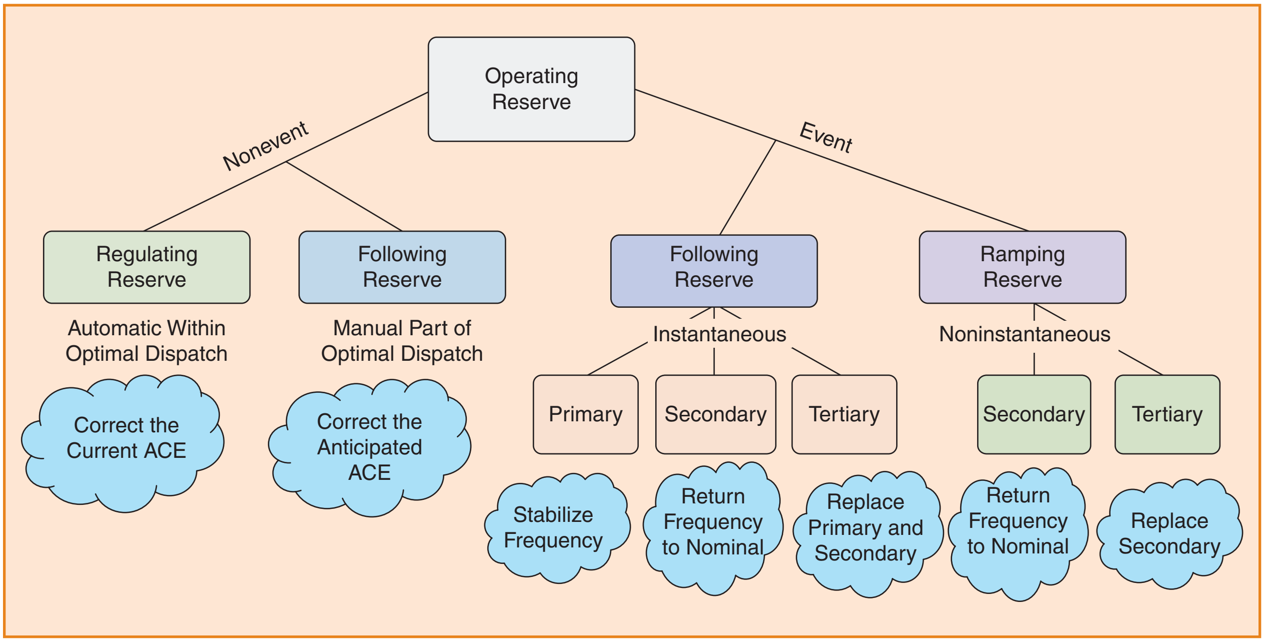
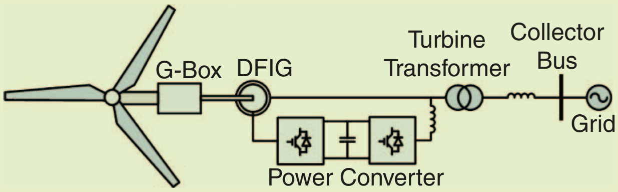
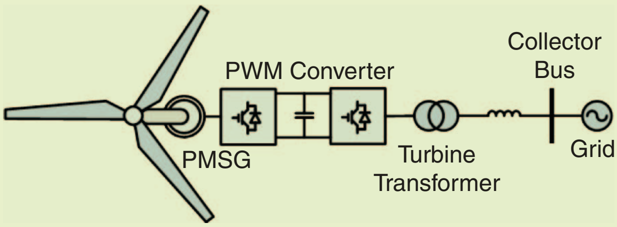
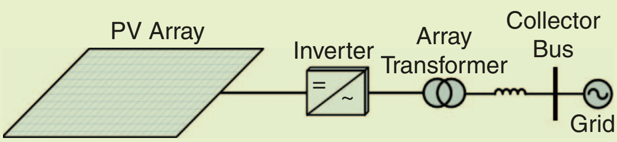
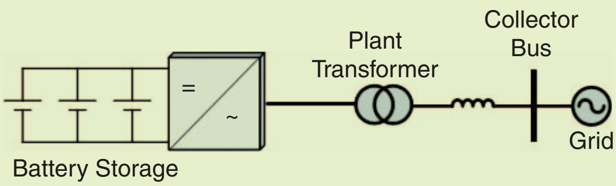


figure 7. Operating reserve categorization.

level (primary frequency response). The grid frequency is then corrected to its prefault level so the balancing authority area's control error is reduced to zero with slower responsive reserves (secondary frequency response). Tertiary reserves would be needed to protect the system against a possible subsequent event when both primary and secondary reserves have already been depleted. VRE is capable of providing any type of operating reserves; however, the challenge here is that accurate resource forecasts are needed at different time horizons to ensure the availability of such reserves from wind and solar generation. Energy storage can also be used to provide additional reserves and help correct possible imbalances due to forecast errors.

Table 1 describes the characteristics of several types of generators and their ability to provide various aspects of grid stability. Normally, power electronic converters provide full decoupling of the wind and solar generator from the grid

table 1. Generation types and capability for grid stability.

Generation Type	Inertia	Active Power Control	Reactive Power, Voltage Control	Fault Ride-Through
Conventional synchronous generation 	√	√	√	
DFIG wind turbine generator with partial power conversion 	√*	√	√	√
Wind turbine generator with full-size power conversion 	√*	√	√	√
	√**	√	√	√
	√*	√	√	√

*Synthetic rotational inertia-like response possible at any operating conditions.
**Synthetic rotational inertia-like response possible if curtailed with headroom.

Power system stability can be divided into three major categories: rotor angle stability, frequency stability, and voltage stability.

voltage and frequency; however, some wind turbines use the DFIG configuration with only a partial conversion of power (up to 30%). But even for the DFIG topology, the grid frequency is fully decoupled form turbine rotational speed. Wind, solar PV, and battery storage systems can provide active and reactive power control in a similar fashion to conventional synchronous generators. The presence of inverters allows for the control of active and reactive power independent from each other. With proper controller design, they can also provide synthetic inertia-like response. Wind turbines are capable of injecting additional active power into the grid by extracting the energy stored in the rotating mass of blades and generators. PV inverters can also provide inertia-like response if curtailment is utilized. Energy storage can also be programmed to modulate its active power to mimic the inertial response of rotating machines.

In addition, inverter-based generators have superior fault ride-through performance. With the proper converter design, wind, PV, and storage inverters can ride through various types of balanced and unbalanced under- and overvoltage faults and frequency excursions, thus improving the overall reliability of a power system. If desired, they can also inject desired levels of reactive current during the fault to assist in faster postfault voltage recovery.

Removing a significant number of synchronous generators from the system has several effects on power system stability. The loss of synchronous generators will reduce system inertia and effect transient and small-signal stability.

- ✔ **Transient and small-signal stability:** The loss of system inertia could reduce the ability to respond to disturbances. To enhance the responsiveness to faults, VRE interfaces need ride-though capabilities. In a 100% VRE system, the angle stability of the remaining machinery, such as synchronous motors and synchronous condensers, can be frequent and severe because of the lack of inertia in the system.
- ✔ **Frequency regulation:** The electrical frequency of an interconnection must be maintained very close to its nominal level at all times. Significant frequency deviations can lead to load shedding, instability, machine damage, and even blackouts. There is rising concern in the power industry in recent years about the declining amount of inertia and primary frequency response in many interconnections. This decline may continue due to increasing penetrations of inverter-coupled generation and the planned retirements of conventional thermal plants. VRE controllers, if carefully designed, can provide primary, secondary, and tertiary response that is superior to the response from conventional generators because of the fast-response speed from the power electronics interfaces.
- ✔ **Volt/volt ampere reactive (VAR) regulation:** Maintaining acceptable voltages at all buses in a power system is essential to ensure that power is reliably delivered across the transmission network. Voltage regulation from conventional generators' excitation systems keeps their terminal voltage stable. VRE can provide voltage regulation using voltage controllers; however, it is likely to reduce their ability to provide real power while providing voltage services. Volt/VAR control and the optimization of VRE will provide necessary voltage support and minimize the impact on the ability of renewable generators to produce real power.

The inertial response is the immediate response to a power disturbance based on a frequency change. This is a key determining factor of both transient stability and small-signal stability by slowing down the rate of change of frequency immediately following a disturbance. Synchronous machines inherently provide the inertial response to power systems. If correctly designed, active power controllers for VRE can provide a synthetic inertia response to stabilize frequency excursions.

Inertial control utilizes the kinetic energy of the rotating mass of wind turbine generators to provide an inertial response capability for wind turbines, thus emulating the inertial response from conventional synchronous generators. The response is provided by temporarily increasing the power output of the wind turbines in the range from 5 to 10% of the rated turbine power by extracting the kinetic energy stored in the rotating masses. This short, quick power injection can benefit the grid by essentially limiting the rate of change of frequency at the inception of the load/generation imbalance event.

The impact on system frequency with wind-based synthetic inertia control is shown in Figure 8. Here, the controls act quickly to minimize the drop in system frequency. Although the severity of the frequency nadir is mitigated with the utilization of synthetic inertia, the frequency takes longer to stabilize.

Primary frequency response control from wind turbine generators can be tuned to provide droop-like response and significantly improve the frequency nadir as well as the steady-state frequency. Figure 9 gives an example of the

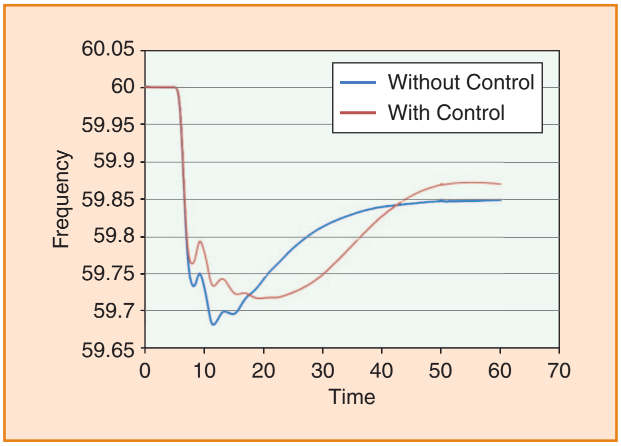


figure 8. VRE with and without synthetic inertia controls.

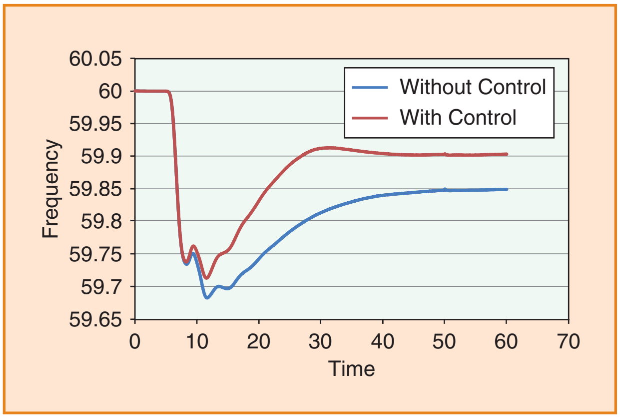


figure 9. VRE with and without both synthetic inertia and primary frequency response.

system frequency response using wind synthetic inertia control and/or primary frequency response control. This shows that using these controls can contribute to a faster-acting, more stable system.

Solar PV systems need to be leveraged in conjunction with storage or be derated from their maximum available power to provide synthetic inertia response for underfrequency events. An example of solar power providing primary frequency response (droop response) is shown in Figure 10. This response was measured on a real 20-MW PV plant when the plant was operating with 3 and 5% droop setting with a 12-mHz deadband. The scatter around ideal expected response (solid plots) is due to the irradiance variability. The plant droop is determined in the same way as that for conventional generators:

$$\text{Droop} = \frac{\Delta P / P_{\text{rated}}}{\Delta f / 60\text{ Hz}}.$$

The upper limit of the droop curve was the available plant power, and the lower limit was at a level that was 20% below the then-available peak power.

Another example of a PV plant participating in AGC is shown in Figure 11. These data were measured on a 300-MW PV plant that was curtailed to 30 MW lower than its available maximum power. The plant adjusted its active power output following the AGC commands sent by the system operator. This figure shows that the PV plant could easily follow the AGC signals as commanded.

Many utility-scale PV power plants are already capable of receiving curtailment signals from grid operators; although each plant is different, it is expected that the transition to operation with ancillary service provision will be relatively simple with modifications made only to a plant's controller and interface software.

Power System Protection

Additional challenges with the removal of a significant number of synchronous generators from the grid are protection systems and coordination. Synchronous generators produce approximately six times rated current during a fault (Figure 12).

This large amount of fault current is often used as a signature for certain types of faults and is the basis for time-overcurrent relay protection. A protective relay can sense the large amount of fault current and trip a circuit breaker to protect grid components. Inverter-based power sources do not have the same fault characteristics as synchronous generators. They can typically provide only a small amount above rated output current. In inverter-dominated systems, this may cause the protective relays to lose the ability to sense the fault conditions because the available fault current is drastically reduced. On the other hand, inverters can react extremely quickly to grid disturbances and may be able to disconnect from the grid, thereby not causing thermal overload on grid components. One unique characteristic of inverters is that their fault current can actually be programmed. They can sense a fault extremely quickly and stop producing current within one-fourth of a cycle, or they can

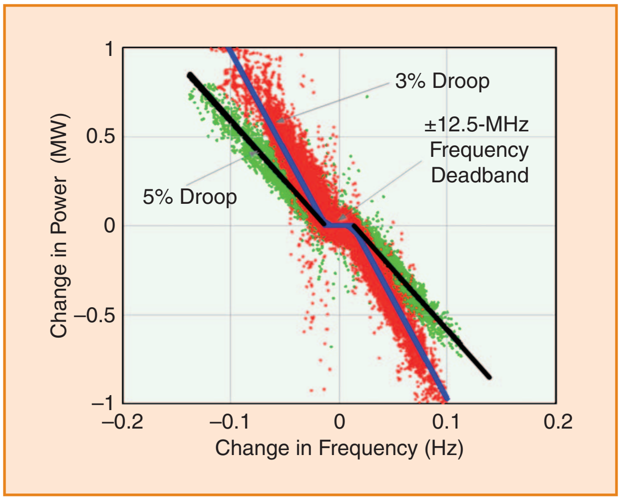


figure 10. A PV plant providing primary frequency response (3% and 5% droop).

As we add more VRE into power systems, the grid of the future will have many more inverter-based generators and be much more distributed than the current power system.

be designed to continue to provide current for several cycles through a fault condition.

One possible solution for the lack of high fault currents is again the use of synchronous condensers to provide fault current. Synchronous condensers are machines that provide only reactive power but can also provide the inertia and fault characteristics of synchronous generators. Denmark has recently installed several of these systems to provide both fault current and inertia to the grid, with good results. Other options may be to eliminate the use of overcurrent protection schemes and develop and implement more advanced protection schemes that use current differential or other methods to detect and clear faults. Besides fault current provision, synchronous condensers bring two other important benefits to the system: mechanical inertia and voltage control. Many integration studies have looked into the possibility of converting large, retiring thermal plants into synchronous condensers for the above purposes.

Another protection scheme also used in the grid is based on special relays that measure the rate of change of frequency (ROCOF). The controllers in ROCOF relays examine the derivative of the frequency to determine if a fault is occurring on the grid. With less system inertia, the rapid decline or rise in frequency during an abnormal event may require changes to the ROCOF settings or even the elimination of their use.

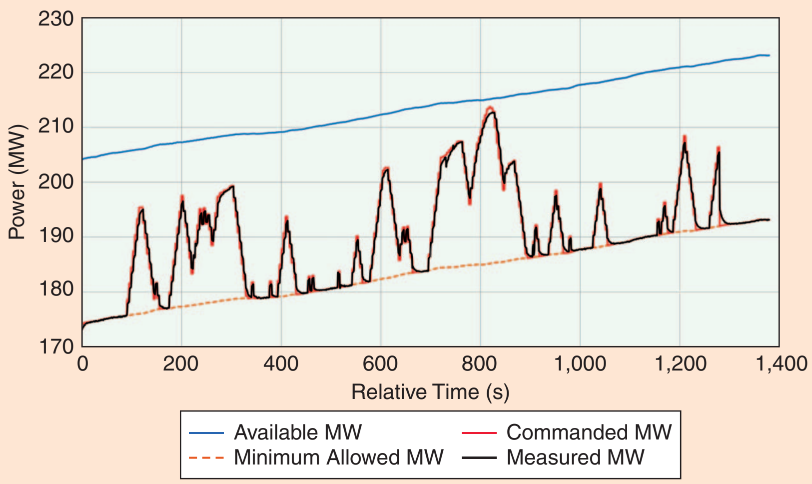


figure 11. PV plant participation in AGC.

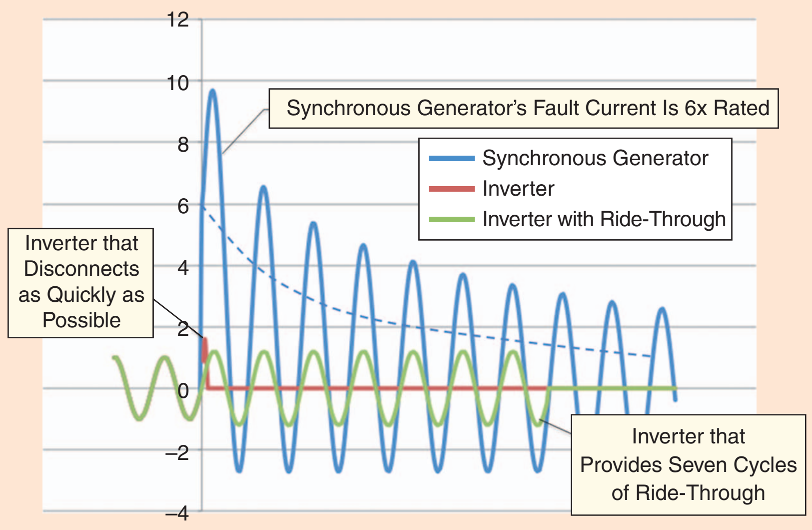


figure 12. Fault currents compared to time for a synchronous generator, an inverter with rapid disconnect, and an inverter with ride-through capability.

Unintentional Islanding

The risk of unintentional islanding is an important consideration when examining power systems with imbedded distributed generation. As power systems become much more distributed in nature, there are potentially many more parts of the grid that could create electrical islands during faults. The solution at low penetrations has been to require active anti-islanding techniques such as those used in inverter-based distributed generation. These techniques monitor grid conditions and actively try to push grid voltage and frequency out of the normal operating parameter so the units trip quickly. This works well when the grid is stiff, but the basic principle of this anti-islanding technique actually tries to destabilize the grid. In a future grid with much more distributed generation and potentially weaker grids, new anti-islanding techniques will need to be used that ensure overall grid stability. These may be communications based, wherein a permissive signal is sent to generators or phasor measurements are compared across the grid.

Black Start

One consideration for operating inverter-dominated ac power systems is the need to start grids once they have gone down, known as "black start." This ability to restart a grid is critical to overall system reliability. To accomplish this, the generation on the system needs to be able to both act as a voltage source and provide adequate power to start electrical equipment with high in-rush currents, such as transformers and motors. Synchronous generators are able to do both of these tasks when the load is properly sized to their capabilities. Inverter-dominated systems will need to be able to provide sufficient starting current, or the loads must be segregated in such a manner as to enable controlled repowering of the grid. These special characteristics of inverter-based sources must be considered by reliability organizations in their plans to restore power supply after blackouts or natural disasters.

Conclusions

Achieving 100% VRE grids will require

- ✔ better ways of matching supply and demand over multiple timescales
- ✔ significant curtailment
- ✔ proper operations with very high instantaneous penetrations of VRE.

As ac power systems evolve from synchronous generator-dominated systems to inverter-dominated ones, we must ensure that these technologies operate in a compatible manner. This incudes designing inverter-based systems to provide system stability and additional grid services necessary for proper ac power system operations. These requirements for grid stability should be incorporated at all sizes of inverters because a future grid might have extremely large numbers of small, highly distributed VRE systems. Initial studies have shown that with proper control considerations, inverter-based systems can not only maintain or improve grid stability under a variety of contingencies but also dramatically improve the response characteristics of power systems and increase operational stability.

Acknowledgments

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For Further Reading

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