

CLEAN GRID VISION:

A U.S. PERSPECTIVE

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CLEAN GRID VISION: A U.S. PERSPECTIVE



Chapter 3. Transmission Grid-Supporting Technologies

Vahan Gevorgian, Jun Hao, Rui Yang, Yingchen Zhang, Ella Zhou –
National Renewable Energy Laboratory

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Fatih Birol	International Energy Agency
Roland Brundlinger	Austrian Institute of Technology
Leon Clarke	Pacific Northwest National Laboratory
Laura Cozzi	International Energy Agency
Paolo Frankl	International Energy Agency
Dolf Gielen	International Renewable Energy Agency
Toni Glaser	German Federal Ministry for Economic Affairs and Energy
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Daniel Kammen	University of California, Berkeley
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Hans Jorgen Koch	Nordic Energy Research
Jiang Lin	Lawrence Berkeley National Laboratory
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Any error or omission in the report is the sole responsibility of the authors.

List of Acronyms

AGC	automatic generation control
BESS	battery energy storage system
DOE	U.S. Department of Energy
EES	electrical energy storage
EPS	electric power system
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
FACTS	flexible AC transmission systems
FERC	Federal Energy Regulatory Commission
FFR	fast frequency response
IBR	inverter-based resource
IEA	International Energy Agency
ISO	independent system operator
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
PV	photovoltaic
VAR	volt-amp reactive
VRE	variable renewable energy

Preface

The *Clean Grid Vision—A U.S. Perspective* is a part of the National Renewable Energy Laboratory’s (NREL)’s 2015–2021 Chinese Programme for a Low-Carbon Future and collaborative research with China’s State Grid Energy Research Institute (SGERI). This multiyear program seeks to build capacity and assist Chinese stakeholders to articulate low carbon pathways to achieve energy systems with a high share of renewable energy, energy efficiency, and low carbon emission.

The Clean Grid Vision comprises two major reports: *Clean Grid Vision—A U.S. Perspective*, written by NREL, and *Clean Grid Vision—A Chinese Perspective*, written by SGERI. The former summarizes NREL’s lessons learned on some of the main issues in power system transition:

- Power system planning and operational analysis are discussed in Chapter 1, “[Clean Grid Scenarios](#).”
- Renewable grid integration challenges and modeling tools at the distribution network level are discussed in Chapter 2, “[Distribution Issues and Tools](#).”
- Grid reliability and stability challenges and the technologies to address them at the transmission-network level are discussed in Chapter 3, “[Grid-Supporting Technologies](#).”
- Recent dynamics in electricity demand such as energy efficiency, demand response, and electrification are discussed in Chapter 4, “[Demand-Side Developments](#).”
- Emerging issues in power market design and market evolution related to the increasing penetration of renewable energy are discussed in Chapter 5, “[Power Market Trends](#).”

The scope of *Clean Grid Vision—A U.S. Perspective* is limited to summarizing the main lessons learned and best practices through NREL’s power system research in the past 6 years, with a focus on the U.S. power system. It can be compared to and contrasted with SGERI’s report that focuses on China’s power system.

As a summary report, most of the works cited here were conducted during 2015–2020. While some of the assumptions for these studies, especially the ones related to renewable energy and battery technology costs, are outdated, the main conclusions remain salient and offer valuable insights for planning and operating power systems and power markets with high levels of renewable energy.

More information on the Clean Grid Vision is available at www.nrel.gov/international/clean-grid-vision.html.

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Chapter 3: Transmission Grid-Supporting Technologies

Highlights

- New reliability and stability challenges may emerge as the power system evolves toward inverter-dominated systems.
- Renewable generators and storage have been demonstrated to provide reliability services and grid flexibility.
- Grid-forming inverters with carefully designed control functions can provide all reliability requirements based on current grid codes and potentially can meet future resilient requirement (e.g., black start).
- Modern grid technologies, such as flexible AC transmission systems, can further enhance grid reliability under high penetration of renewable energy.

3.1 Introduction: What Is Grid Reliability?

This section will discuss the reliability metrics and standards used in North America, how these standards define the reliability requirements for planning and operation. As the power system continues to evolve, Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation (NERC) continuously improve reliability metrics and standards to keep up with a growing need for a refined understanding of the services necessary to maintain a reliable and efficient system. NERC's responsibility includes development and enforcement of reliability standards, annual assessment of seasonal and long-term reliability, and monitoring the bulk power system through system awareness, and so on. Electricity, unlike water and gas, cannot be stored in large volumes at this time. Electricity must be generated and used at the same time, which means the supply and demand needs to be balanced. Another characteristic of electricity is that it cannot be routed over transmission lines. This means that the generation and transmission operations must be monitored and controlled in real time. Therefore, grid reliability is fundamental to secure the delivery of energy. Figure 3- 1 shows the basic components of a power system. Electricity is generated at power plants and delivered through high-voltage transmission lines and low-voltage distribution lines to customers. Transformers step up the voltage at power plants for energy saving and step down the voltage substation for safe and efficient delivery of energy.

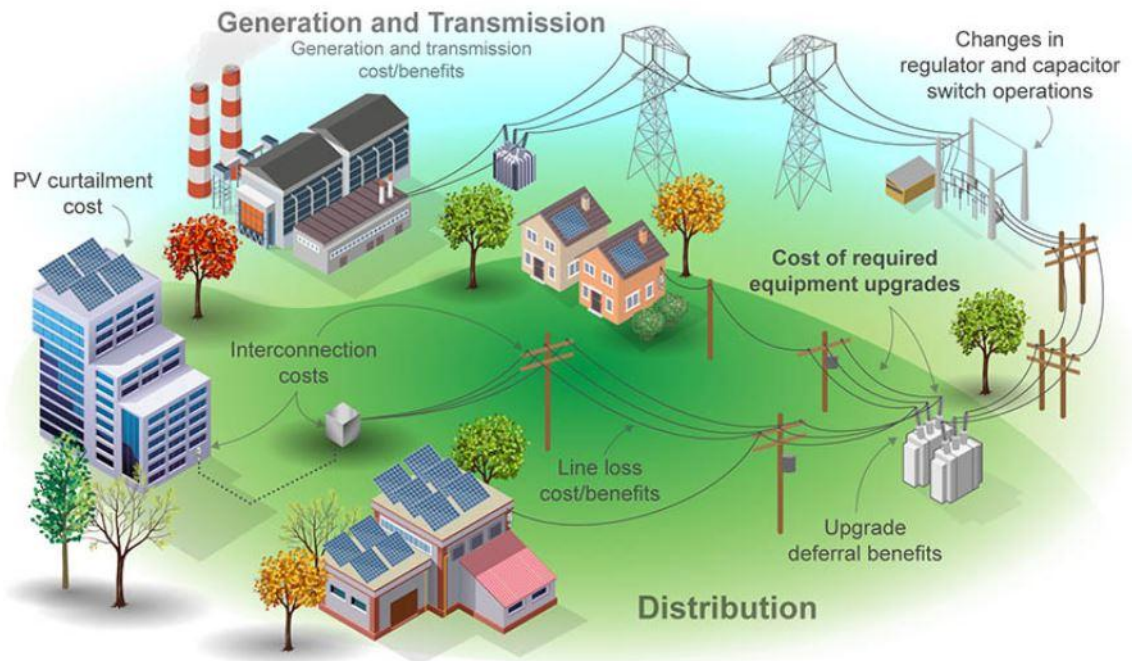


Figure 3- 1. Power systems

Source: [1]

The generation and transmission elements and their corresponding control system comprise the bulk power system. NERC defines the reliability of the interconnected bulk power system in terms of two basic and functional aspects [1]:

- **Adequacy:** The ability of the power system to provide the overall electricity and energy demand of the customers at all times, including scheduled usage and reasonably unscheduled demand.
- **Operating Reliability:** The ability of the bulk power system to undergo abrupt disturbances, such as electricity short circuits or unpredicted loss of system elements from contingencies, while preventing uncontrolled cascading blackouts or equipment damage.

All other system disturbances that cause the unpredicted or uncontrolled interruption of customer demand, regardless of cause, fall under operating reliability. When these interruptions are contained within a localized area, they are considered unplanned interruptions or disturbances. When they spread over a wide area of the grid, they are referred to as “cascading blackouts”—the uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread electric service interruption that cannot be restrained from sequentially spreading beyond an area predetermined by studies.

Adequate actions need to be taken to keep the balance between generation and demand within a control area. In North America, these actions include:

- **Public appeals**
- **Interruptible demand:** The demand that can be curtailed or interrupted by utility company or by end user at the request of the system operators.
- **Voltage reduction**

- Rotating blackouts: Each distribution feeder is disconnected for a certain time, typically 20–30 minutes, and then the feeder is connected back to power grid and another feeder is disconnected, and so on, transferring the outages among feeders.

Resiliency of the bulk power system is dependent on both adequacy and operating reliability and is the ability of power system to reduce the risk of outages and unserved loads due to high-impact low-probability events such as cold wave that impacted the operation of power system in Texas in February of 2021.

Penetration of very high shares of inverter-based resources (IBRs) brings new reliability challenges to the grid in the form control interactions between IBRs, subsynchronous oscillations, harmonics resonances, etc. To address these new reliability challenges, a new set of simulations tools is needed to understand the nature of such instabilities and develop solutions that can be used at the system planning stage and mitigation controls to address these issues if they occur during real-time operation of the system. This, in turn, will raise a need in new reliability metrics, standards, and requirements adopted to the evolving grid conditions, especially considering the fact that certain shares of grid-forming services will be provided by IBRs.

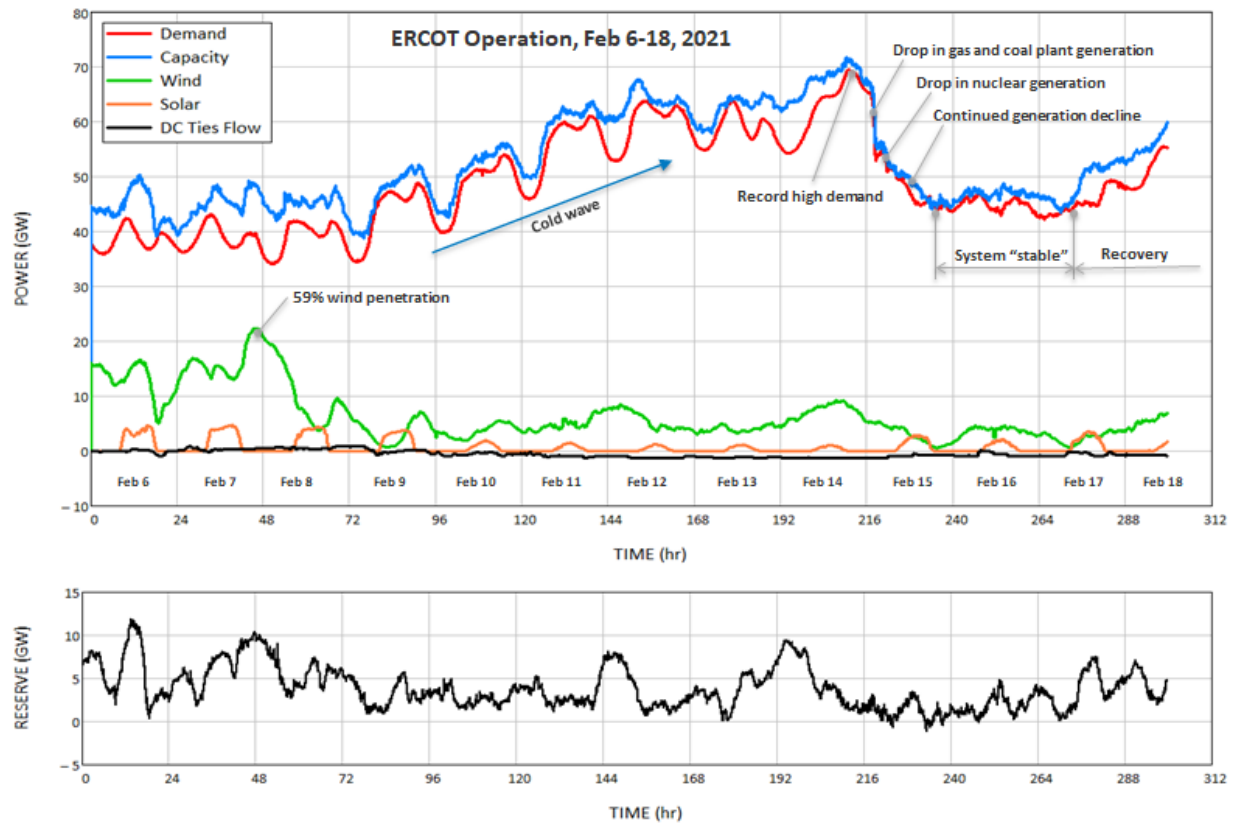


Figure 3- 2. Texas blackout, February 15, 2021

The blackout started at around 1:30 a.m. on February 15, 2021, after record winter load in Texas that was increasing steadily since February 10 due to an arctic cold blast that impacted the whole state. Due to extreme cold, several gas and coal power plants stopped operating, and generation decline continued through most of the day. The power system operator was able to stabilize the system by disconnecting around 20 GW of loads, causing rolling power outages. The system recovery started around midday on February 17. This event coincided with a period of low wind and solar generation, making the impact on

the system even more severe. This event demonstrated the importance of system resiliency that needs to be addressed in both planning and operation of power grid.

The recent Manhattan blackout of July 2019 [18], for example, was an uncontrolled cascading blackout. In contrast, what happened in the summer of 2000 in California [19] is a controlled rotating blackout to keep the balance between supply and demand; however, the four actions listed above are the last defense to prevent uncontrolled power outages/blackouts. The best strategy is to improve grid reliability and avoid taking actions like rotating blackouts. Reliability standards are enforceable in all interconnected jurisdictions in North America: the continental United States; the Canadian provinces of Alberta, British Columbia, Manitoba, New Brunswick, Nova Scotia, Ontario, Quebec, and Saskatchewan; and the Mexican state of Baja California Norte. Following adoption of a standard by the NERC Board of Trustees, NERC files the standard with the appropriate authority in each jurisdiction. In the United States, NERC petitions FERC for approval of standards.

3.2 Types of Reliability Services

This section will discuss the types of the existing essential reliability services as defined by NERC and new evolving reliability services for variable generation to provide their share of grid support [2] [3]. The services discussed will include:

- Active power control capabilities
- Fast frequency response (FFR)
- Primary frequency response
- Secondary frequency response or participation in automatic generation control (AGC)
- Ability to follow security-constrained economic dispatch set points that are sent every 5 minutes through its real-time economic dispatch market software.
- Voltage, reactive, and power factor control and regulation.


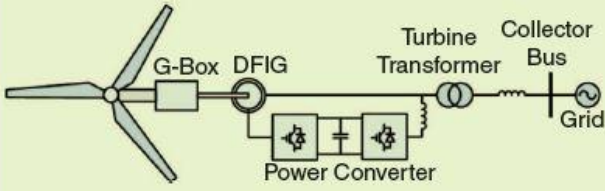
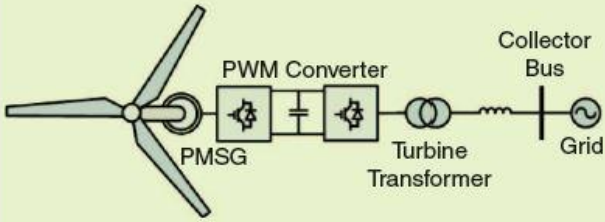
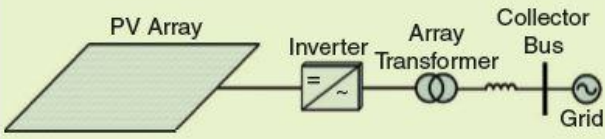
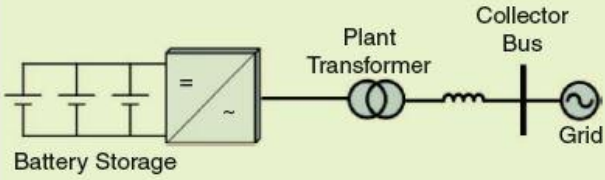
Generation Type	Inertia	Active Power Control	Reactive Power, Voltage Control	Fault Ride-Through
Conventional synchronous generation 	√	√	√	
DFIG wind turbine generator with partial power conversion 	√*	√	√	√
Wind turbine generator with full-size power conversion 	√*	√	√	√
	√**	√	√	√
	√*	√	√	√
<p>*Synthetic rotational inertia-like response possible at any operating conditions. **Synthetic rotational inertia-like response possible if curtailed with headroom.</p>				

Figure 3- 3. Generation types and capability for grid stability

Source: [4]

AGC is a centralized mechanism of operational plans and requires the participation of elements in a power grid for automatically adjusting generation within a balancing area. AGC plays a vital role in the power system. It can provide regulation service and bring the frequency back to a nominal level after a grid disturbance. Wind, photovoltaic (PV) systems, and battery storage systems can offer active and reactive power control in a similar way to traditional synchronous generators. The development of inverters enables the potential for the control of active and reactive power separately. Wind turbines are able to provide extra active power into the power system through utilizing the energy stored in the

rotating mass of blades and generators. PV inverters can also achieve the same support if curtailment is reserved. Energy storage can be managed to adjust its active power to imitate the inertial response of rotating machines like synchronous machines. As the penetration of variable renewable energy (VRE) increases in the power systems, the grid requires greater flexibility to deal with the changes in generation aspect. VRE can only generate power when its resources are available. PV systems, in particular, are limited by the diurnal cycle. It means there is no power output from PV systems during night and will lead to larger load ramps than other kinds of power sources because PV generators are correlated well in the same geographical area. Wind power can also cause ramps, but these ramps usually happen during a couple of hours. Active power control can help to limit or mitigate the ramping rate by limiting the injections from PV systems, or managing shiftable load to match the generation cycle of VRE. During the time window when both wind and solar have high output, active power control will curtail part of the generation, which is proven to be the most economic strategy. The decision is based on multiple variables.

The inertial response is the instant response to a power system contingency, and it overcomes the immediate imbalance between power supply and power demand. It is an important factor to determine the transient stability and small signal stability. Synchronous machines can provide the inertial response by nature. Active power controllers for VRE can realize a synthetic inertia response through a specific designed strategy.



Figure 3- 4. VRE with and without synthetic inertia controls

Source: [3]

A wind turbine can realize inertial control by utilization of its kinetic energy stored in the rotating mass of wind blades. Thus, the wind turbines can mimic inertial response from traditional synchronous generators. The response is achieved by improving the power output of wind turbines in a short period. The short power injection can help the grid to reduce the rate of change of frequency during a contingency/imbalance event. Figure 3- 4 shows the results of our research [3]. The presence of inverters enables PV systems to provide FFR when the PV systems have headroom to provide active power during an underfrequency event. Another way for PV to provide inertia response is combining with energy storage systems.

Wind turbine and solar systems can provide droop-like response. Wind turbines can achieve this by utilizing synthetic inertia, and solar systems need to be curtailed to achieve the primary frequency response. Note that the plant droop is calculated in the same way as traditional generators. Our research results also support that VRE can provide primary frequency response [5] [6].

VRE has the capability of offering secondary frequency response if the controller is designed carefully and controlled accurately. The barrier is that precise generation forecasting is required at various time windows to ensure the availability of reserves from wind turbines and PV panels. The VRE can also participate in AGC. Figure 3- 5 shows the results. It should be noted that 10% of the output was curtailed and the PV plant followed the operator's AGC commands.

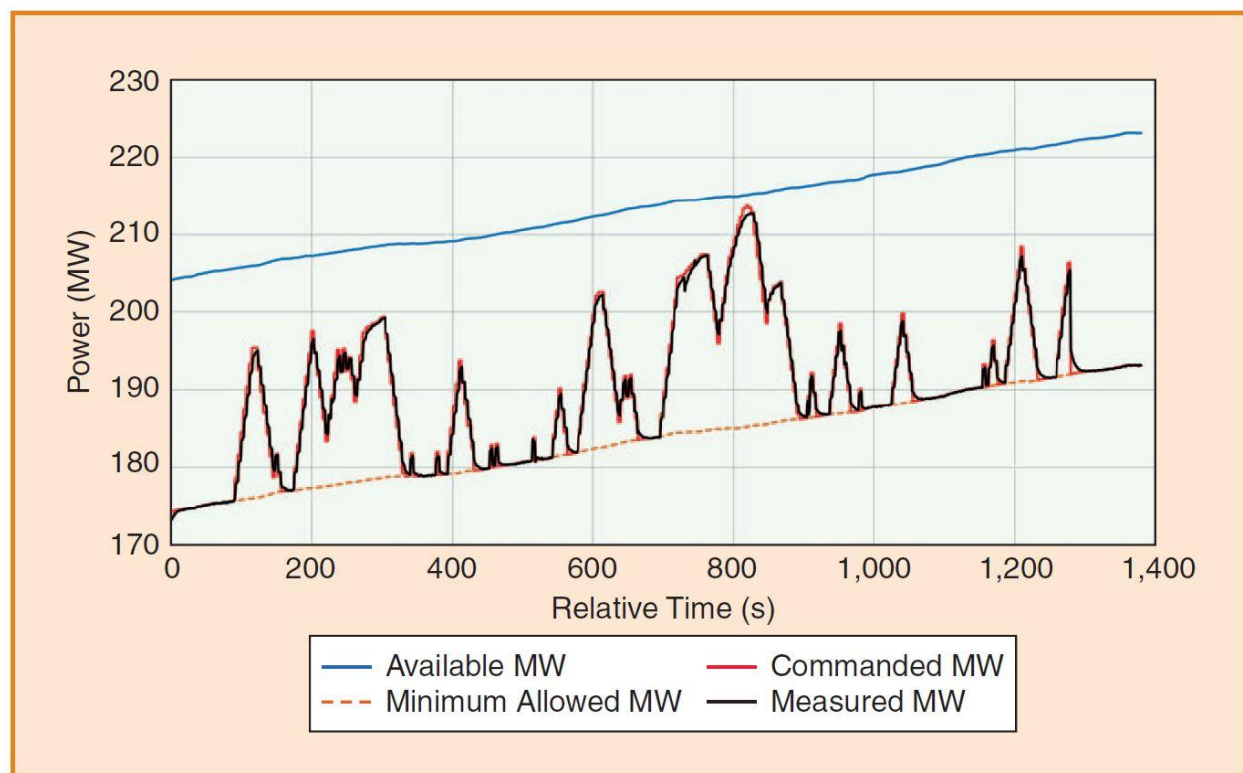


Figure 3- 5. PV plant participation in AGC










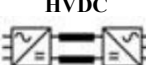
Source: [3]

Maintaining high-quality voltages at all feeders in a power grid is fundamental to ensuring the power is delivered safely across the transmission network. In terms of voltage regulation and reactive power regulation, the excitation system in conventional generators ensure output voltage is stable. VRE can provide voltage regulation through voltage controllers. The trade-off is impairing their capability to provide real power because it can be realized at the same time. Volt/volt-amp reactive (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.

Inverter-based generators have good fault ride-through capability. With the appropriate converter design, wind energy, PV systems, and energy storage can ride through different types of balanced and imbalanced and overvoltage and undervoltage faults and frequency fluctuation; therefore, the power system reliability is improved. If needed, VRE can provide certain amount of reactive power to help voltage recovery.

Table 3- 1. Service Comparison

	Services							
Generation Type	Inertia	FFR	Primary Frequency Response	AGC	Voltage Support	Oscillations Damping	Fault Ride-Through	Short Circuit Current
Synchronous Generators 	<i>Real</i>	<i>No</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>
Synchronous Condensers 	<i>Real</i>	<i>No</i>	<i>No</i>	<i>No</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>
Wind 	<i>Real combined with controls</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Depends on electric topology</i>
Solar PV 	<i>Synthetic</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>
Solar CSP 	<i>Real</i>	<i>No</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>
Batteries 	<i>Synthetic</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>
Flywheels 	<i>Real combined with controls</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>
Supercapacitors 	<i>Synthetic</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>
H ₂ Fuel Cells 	<i>Synthetic</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>
HVDC 	<i>No</i>	<i>No</i>	<i>No</i>	<i>No</i>	<i>Yes</i>	<i>Yes</i>	<i>Yes</i>	<i>No</i>

In short, Table 3- 1 shows comparative characteristics of conventional synchronous generator-based resources and IBRs, including wind and solar generation and some representative inverter-coupled storage technologies. Essential reliability services such as inertial response, primary frequency response, ability to participate in AGC, voltage regulation, fault ride-through performance, and other services, such as FFR and wide area stability services, for damping of various types of power system oscillations. The ability of the resource to provide short circuit current contribution is compared as well. It can be observed in Table 3- 1 that IBRs can provide all types of reliability services similar to conventional generation; moreover, in some cases they can do it with faster response speeds and better precision, compared to conventional technologies. This also includes ability to provide inertial response because controllability of IBRs allows emulating different types of inertia-like response that can be optimized for system needs. The only characteristic that differs is the inability of IBRs to contribute enough levels of current during faults for protection activation. This issue will be discussed later in this section. High-voltage DC transmission is considered as an important component of future IBF-based grid. High-voltage DC transmission brings many benefits of economic long-distance overhead, underground and submarine power transmission. Being a transmission technology, it is not able to provide many active power-based services by itself (unless coupled with energy storage) but can be used for voltage support and stability services. In addition, multiterminal high-voltage DC systems can be used for controlling active power flows between terminals.

3.3 Overview of Reliability Metrics and Standards: U.S. Perspectives

This section will compare the reliability issues and concerns, metrics, and standards from the United States and China perspectives. Despite major difference in economic aspects of power systems operation in both countries, the main reliability concerns remain the same and can be addressed by similar risk-mitigating technical solutions; however, the underlying market mechanisms will define the optimum reliability improvement solutions applicable to specifics of each country.

Section 215 of the Federal Power Act requires the Electric Reliability Organization [20] to develop mandatory and enforceable reliability standards, which are subject to Commission review and approval. Commission-approved reliability standards become mandatory and enforceable in the United States on a date established in the Orders approving the standards. Under the resource and demand balancing category, BAL-001-2 [7] regulates the real power balancing control performance, which controls interconnection frequency within defined limits. BAL-002-WECC-2a [8] regulates the quantity and types of contingency reserve needed to guarantee reliability under various conditions. Other standards also set requirements about common criteria, data acquisition, and frequency responses about time error corrections and primary inadvertent. Each standard also defines the related entities and prerequisites.

For voltage and reactive standards, two aspects are regulated: (1) to protect equipment and ensure reliable operation of the interconnection, guarantee generators provide reactive support and voltage control within capabilities; and (2) establish performance criteria for the Western Interconnection to ensure a coordinated manner under various normal and abnormal conditions.

FERC has been developing regulatory mechanisms for power systems, enabling VRE in capacity, energy, and power system support markets. Back in 2011, Order No. 755 [21] aimed to improve the rewards for fast-responding energy like flywheels. Later in 2013, FERC enacted Order No. 784 [22], which guides the independent system operators (ISOs) to services by fast-responding energy. FERC proposed reactive power requirements for Non-Synchronous Generation in Order 827 [23]. In Order No. 819 [24], FERC revised regulations to bring up competitions in the sale of primary frequency response services. FERC is concentrating on other frequency services and response problems in Order No. 842 [31]. FERC Order 661-A [25] can be applied to wind energy and PV systems in some cases.

3.4 Reliability Impacts by Variable Renewable Generation

Integrating large quantities of variable energy resources into North American bulk power system requires significant changes to electricity system planning and operations to ensure continued reliability of the grid. The section focuses on considerations that all system planners and operators must address to reliably integrate significant quantities of variable energy resources into the bulk power system, including: inertia, frequency response, regulation, load-following, active power control, reactive power and voltage control, disturbance ride-through tolerance, steady-state and dynamic stability modeling, and load and generation forecasting.

The increasing integration of renewable energy is displacing conventional power plants, which brings major challenges to maintaining the stability of power systems all over the world. For instance, 72 GW of conventional generation retired in the last 10 years in North America, and more than 120 GW of variable generation has been integrated into the power grid. The integration of VRE is introducing more and more inverter-based energy, which is making significant challenges to frequency regulation. The challenges come from two aspects: (1) the control and generation of VRE is not sensitive to load-generation balancing; and (2) the synchronous spinning inertia with respect to the overall generation is reduced drastically within a balancing area. Based on the basic principle of conventional turbines, the turbine and the rotating parts inside each power plant can store tremendous kinetic energy. Because of this, the extra energy can be absorbed into or extracted from the synchronous generators to counteract the system fluctuation. Thus, the frequency deviation can indicate the imbalance condition and the total amount of rotating mass (inertia) directly reflect the ability of the interconnected system to handle fluctuations. On the contrary, a low level of inertia means the system is vulnerable to deviations.

Solar, wind, and energy storage are totally different from conventional power plants. The generation produced by VRE sources cannot be connected to the current AC power grid directly. The power output from VRE is DC and needs to be converted to AC before connecting to power grids. The inverter [9] is a power electronics device, which is the interface between VRE and the AC power grid. Inverters convert DC power to AC power and control the flow of electricity by managing semiconductor devices. Based on the definition of an inverter, we can tell that an inverter does not comprise any rotating mass and therefore there is no inertia in an inverter. Basically, there are two types of inverters: the grid-following inverter, which control the output by tracking the voltage angle, and the next-generation grid-forming inverter, which can actively control their frequency output. It is questionable that an inverter-based power system can merely relay on grid-following control to achieve system stability. To address this issue, a next-generation grid-forming inverter [10] is necessary. Researchers and engineers have developed methodologies of mimicking various physical characteristics with inverters to achieve virtual synchronous machines or virtual inertia; therefore, the inertial responses are realized through carefully programmed controllers on inverters.

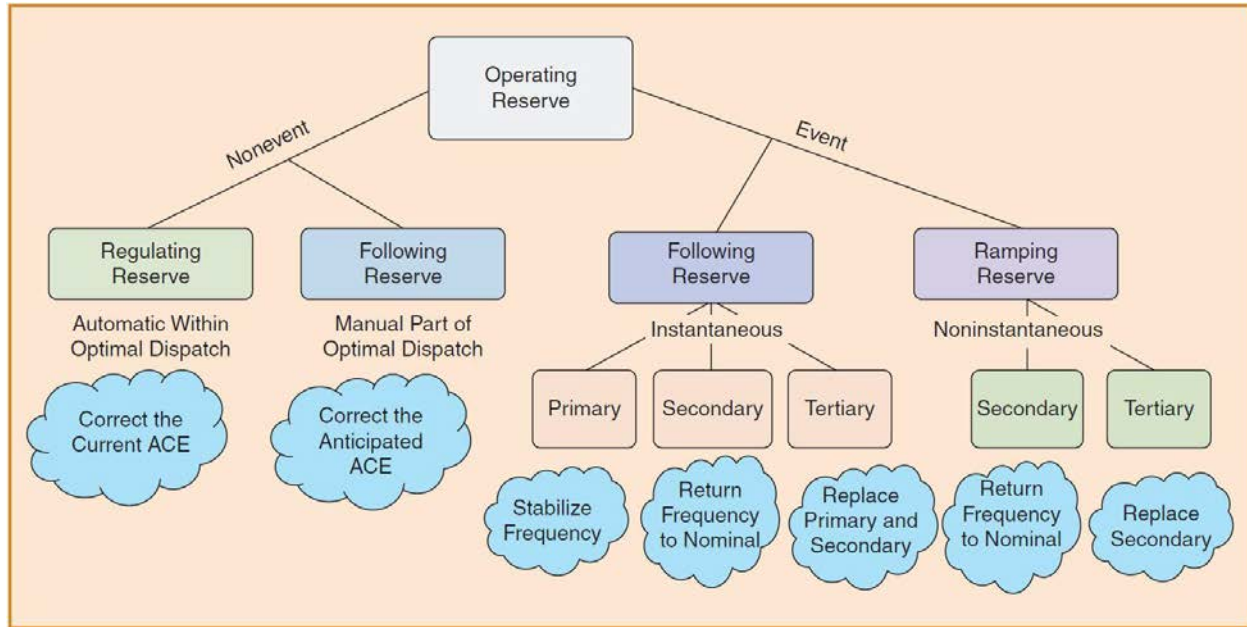


Figure 3- 6. Types of operating reserve

Source: [3]

The power system is a dynamic system, which means the load, generation, and transmission availabilities are balanced at real time. All three factors are variable and hard to predict. Additional capacity is reserved to keep the frequency stability during an imbalance event; however, the variable characteristics of VRE make it hard to determine the operating reserve and increase the importance of the operating reserve at the same time. Another shortcoming of the VRE is the inertia reduction [11], which will also further cause other power system stability issues. For example, the first step is to arrest the frequency changing rate during a frequency deviation event and further stabilize the frequency at the primary frequency response stage. Later, the grid frequency will be brought back to its prefault level so the area's control error equals zero at the secondary frequency response stage. Wind, solar, and energy storage can offer any kind of operating reserves to participate in different stages of frequency response [3]. The challenge here is that accurate generation forecast at various time horizons is required to secure the availability of the corresponding reserves. Energy storage can be implemented as backup generation and help balance the imbalance in case of error of prediction.

From regulation perspectives, the frequency should be maintained at a nominal level at any time. Major frequency deviations can cause load shedding, equipment damage, and even blackouts. Concerns are rising with the retirement of conventional generators and increasing VRE integration because the reduction of system inertia can impair the system's ability to absorb the deviation. VRE energies can offer primary, secondary, and tertiary response if they are controlled correctly. The advantage VRE has over conventional generators is the response speed [62]. Wind turbines can provide frequency responses easier than other VRE due to the rotating mass, such as wind blades. For primary frequency response, wind turbines have the capability to provide droop-like response and improve the frequency nadir and the steady-state frequency. In Orders 755 and 784, FERC required improving the mechanisms by which frequency regulation services are procured and enabling compensation by fast-response resources, such as energy storage. In addition, FERC recently issued a notice of proposed rulemaking to enable the aggregation of distributed storage and distributed generation [26]. The combination of PV system and energy storage can offer stable frequency response. Even the PV system solely can provide ancillary services if its output is curtailed. Figure 3- 7 shows a PV plant providing primary frequency response (3% and 5% droop).

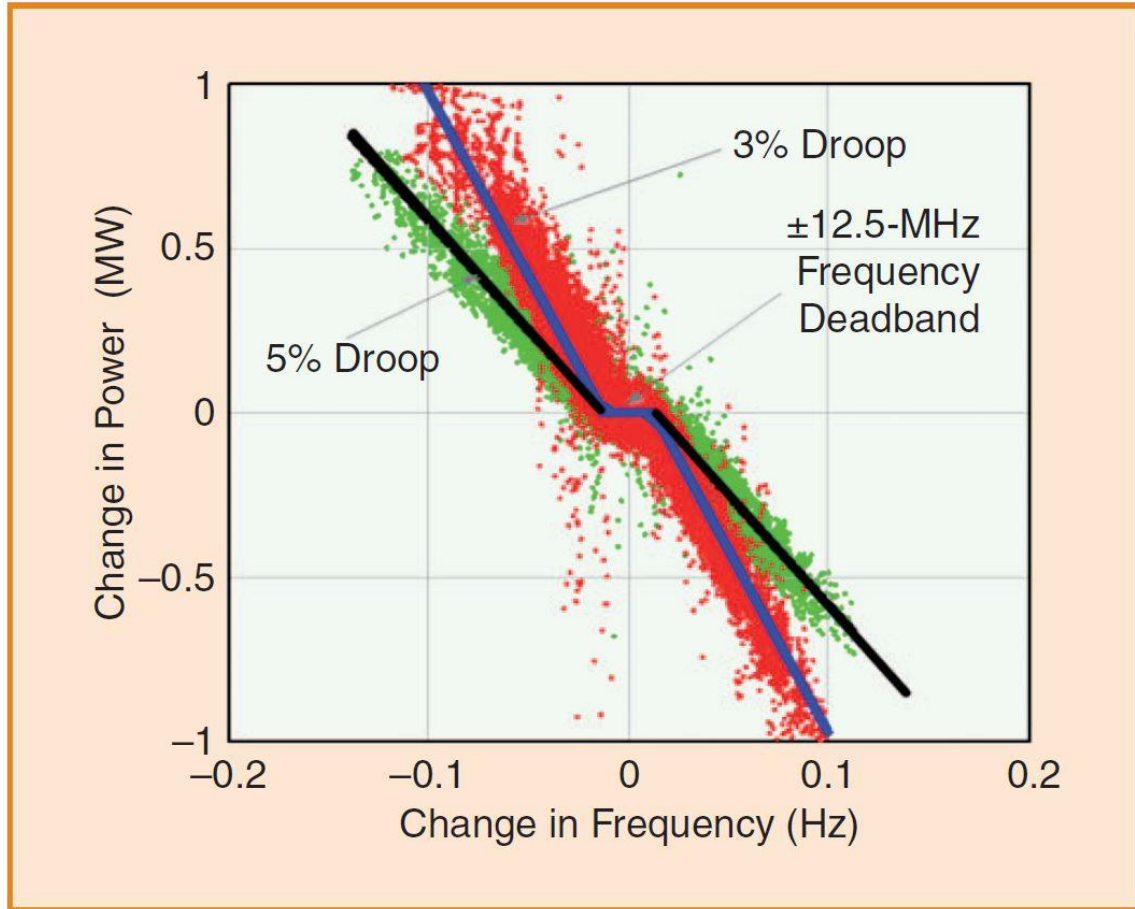


Figure 3- 7. A plant providing primary frequency response

Source: [3]

Another aspect that all system planners and operators must pay attention to is steady-state and dynamic stability modeling. Due to the variability of VRE and the evolution of power systems, FERC stated that there is an urgent need for a refined understanding of the system services to maintain the system's reliability and efficiency [27]. The current system simulation and modeling are only taking tests at several crucial time points. If test results are good at these crucial points, the system can be stable; however, the increasing VRE causes increasing system variability. Thus, dynamic stability modeling is needed to ensure the power system is balanced and stable at all times, particularly when the output of solar PV and wind is ramping up or down; therefore, the dynamic modeling is very important to the power system stability research. One important part of dynamic modeling is accurate load and generation forecasting, especially the generation forecasting. To obtain better PV generation forecasting, more variables should be included, such as location, angle, and weather information. If carefully designed and fully developed, the ride-through capability of VRE is high, and VRE can even inject reactive power to the power grid to help voltage recovery. In short, with appropriate converter design, solar PV, wind, and electrical storage can ride through different kinds of unbalanced load, voltage fluctuation, and frequency deviation, thus enhancing the reliability of a power grid.

3.5 Reliability Services by Renewable and Energy Storage

Electrical energy storage (EES) systems are going to help researchers and electrical engineers solve the challenges with the increasing integration of VRE and improving the power reliability by increasing the response speed and operating capacity. The application of EES systems is growing fast, and various sets

of applications have been developed and implemented, such as frequency regulation, voltage support, energy management, grid stabilization, and load shifting. Currently, the major EES all over the world is pumped-storage hydropower, which is playing an important role in providing ancillary services. But the growth of pumped-storage hydropower is slow, and battery energy storage systems (BESS) dominate the investment in terms of installation capacity and monetary values.

Over the last decade, the development and implementation of EES has proven its potential to provide ancillary services for the electrical power system, and, in turn, to facilitate the integration of VRE. EES can offer tremendous support for the integration of VRE to mitigate variability and uncertainty [12]. The large-scale implementation of energy storage can effectively reduce the wind and PV output limitation caused by various factors such as line congestion and overgeneration. The U.S. government continuously focuses on the development of EES technologies, and the U.S. Department of Energy (DOE) also set the long-term goals for EES as the following:

- Compared with other technologies, EES should be cost-competitive.
- The related regulatory environment is crucial to utilizing the potential of EES.
- Proper compensation for EES should be proposed for long-term benefits.
- Seamless EES integration is essential for vast implementation.

FERC has focused on the regulations related to EES for a while, thus facilitating the implementation of EES technologies in different kinds of markets such as energy, capacity, and ancillary services. In 2011, Order No. 755 was issued by FERC to raise the payments for fast-responding resources. Later in 2013, FERC issued Order No. 784, which guides ISOs to reward services provided by fast-responding resources, including EES. Order No. 819 was issued by FERC to facilitate the competition of primary frequency response services.

3.5.1 Application Demands of Energy Storage for Large Power Grids With High Penetration Renewable Energy: Grid Frequency Control, System Flexibility

This section will discuss the role of electric system flexibility options in the large-scale deployment of renewable energy using enabling technologies such as energy storage. Key factors in improving grid flexibility include: (1) increasing the ramp range and rate of all generation sources to follow the variation in net load; and (2) the ability to better match the supply of renewable resources with demand via increased spatial diversity, shiftable loads, or energy storage. Overall system flexibility largely depends on the mix of generation technologies in the system (For example, a system dominated by gas or hydro units will likely have a higher level of flexibility than a system dominated by coal or nuclear generators.) Even with a completely flexible system, achieving very high levels of variable generation requires enabling technologies such as energy storage to address the fundamental mismatch of supply and demand.

Utility-scale EES systems provide various services as follows:

- Power system ancillary services
- Store and shift electric energy
- Manage peak load
- VRE ramping support and load following
- Increasing renewable energy usage
- Frequency regulation (inertia response, FFR, and primary frequency response)
- Spinning and nonspinning reserves

- Increase supply capacity
- Supplemental reserves
- Reactive power and voltage support
- Ability of black start
- Load support during contingencies
- EES equipped with inverter can increase grid stability.
- Power plant implementation
- Stacked services.

In the United States, the amount of installed battery energy storage was about 658 MW as of 2017. 63% of the installation aimed to help with frequency regulation, 20% was about spinning reserves [28]. Among all ancillary services, frequency regulation is probably one of the most critical services. In the United States, EES is conceived to have the potential to be the first choice for frequency regulation in the future power system. The plan for EES to provide peak/valley load following was also proposed in the United States for some island systems. Figure 3- 8 shows an example of BESS coupled with wind farms in Hawaii. This particular BESS was controlled to provide ramp-limiting service to the wind power plants in the small island system.

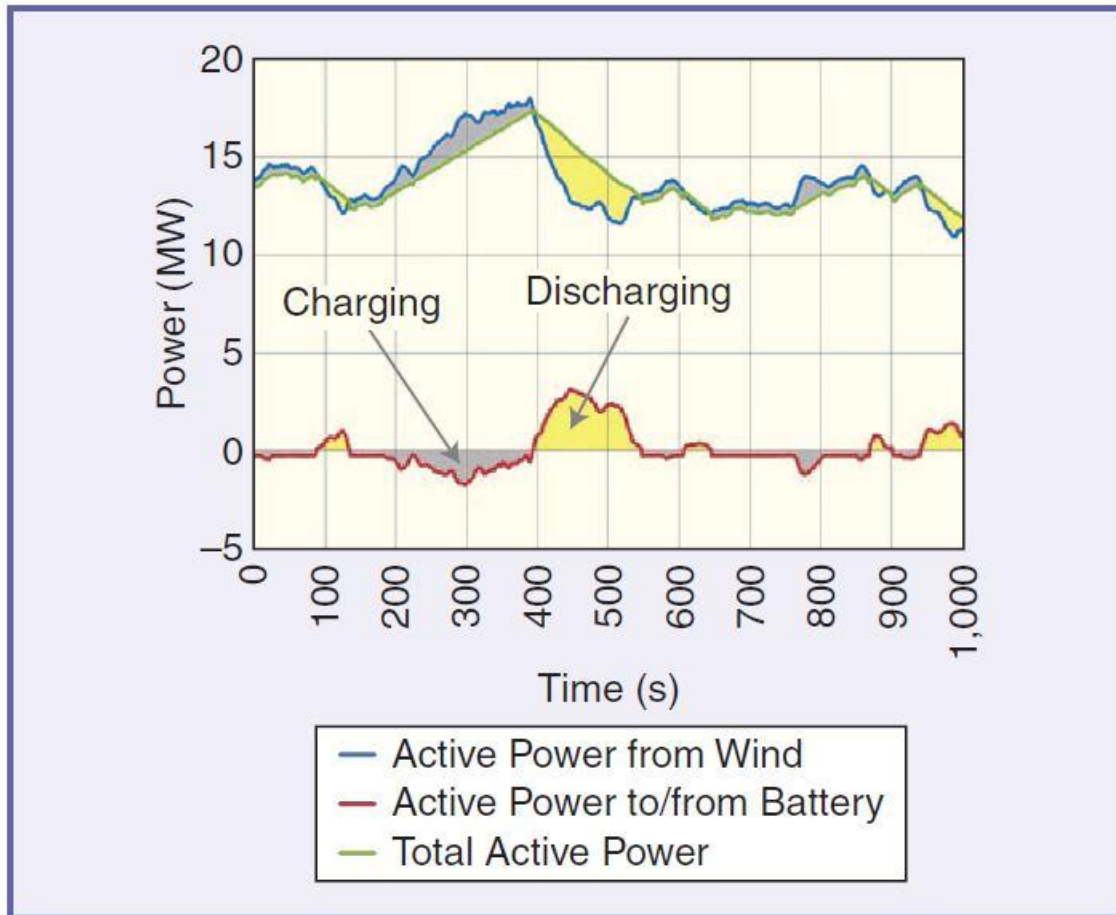


Figure 3- 8. A snapshot of 2-s plant active power data

Source: [29]

Figure 3- 8 shows a wind-battery storage system at Kahuku Wind Farm in Hawaii. In this project, the flow of the battery's active power are based on the trends of active power of the wind power plant [29]. The project showed that the BESS can help to significantly reduce the frequency of large ramping events. EES, especially BESS, can significantly mitigate the variability and intermittency of VRE and improve the value and viability of VRE.

One of the main purposes of building BESS is to help increase grid flexibility, including reducing aggregate system-level ramps caused by VRE. VRE energies can merely produce electricity when its resources are available, such as solar PV and wind energy; however, the output of VRE (such as solar PV) systems is very similar within a certain geographical area, which means their generation curves are the same. This will increase/decrease the ramp rate in a short time drastically, reduce the system stability, and increase the burden of conventional generators. Ramps should be limited to decrease the adverse impact on power system stability and enable more VRE to be integrated into the grid. Minimizing ramps can optimize the cost of ancillary services of traditional power plants. BESS can be charged during ramp-up time and discharged during ramp-down time without curtailment of generation and requirement of reserve services from other energy sources. For example, if a utility-scale PV plant is equipped with BESS, the battery system can be charged during the morning and at noon when PV outputs are ramping up or at maximum and can be discharged before sunset to compensate the ramp-down caused by PV output decreasing.

In general, the BESS controller can be designed to provide various forms of active and reactive power control. BESS can have capability to provide inertial response, FFR, and primary frequency response. In addition, the BESS can provide reactive power control in the form of kVAR-voltage droop during dynamic and fault conditions.

All BESS active power control components can be combined in a single simplified equation, so at any instant in time, the total BESS power (injecting or absorbing) is:

$$P_{bess}(t) = P_o(t) + \Delta P_{soc}(t) + \Delta P_i(t) + \Delta P_{FFR}(t) + \Delta P_{droop}(t) + \Delta P_{AGC}(t) \quad (1)$$

where $P_o(t)$ is the BESS dispatch set point; $\Delta P_{soc}(t)$ is the portion of the commanded power set point for the BESS state of charge (SOC) control; $\Delta P_i(t)$ is the BESS inertial response (or response proportional to the rate of change of frequency); $\Delta P_{FFR}(t)$ is BESS FFR response; $\Delta P_{droop}(t)$ is the BESS droop response; and $\Delta P_{AGC}(t)$ is the BESS AGC response.

Depending on the type of service that the BESS is providing, the individual components in (1) can be activated at the proper times. For example, $\Delta P_i(t)$ will start first at the beginning of the event, as soon as a large rate of change of frequency is detected; then either $\Delta P_{FFR}(t)$ or $\Delta P_{droop}(t)$ will kick in (the BESS can provide either FFR or droop response, but it cannot do both at the same time). The $\Delta P_{AGC}(t)$ component will follow the AGC set points from the system operator for secondary frequency control and frequency regulation. Equation (1) can be expanded to show components of interest in more detail:

$$P_{bess}(t) = P_o(t) + \Delta P_{soc}(t) - 2H \frac{df(t)}{dt} - \frac{f_o - f(t)}{droop} + \Delta P_{AGC}(t) \quad (2)$$

where f_o is the scheduled grid frequency, $f(t)$ is the grid frequency at any point, and H is emulated inertia constant.

It is clear that high penetration of variable generation increases the need for all flexibility options, including storage, and it also creates market opportunities for these technologies [32].

3.5.2 The Method for Analyzing the Frequency Regulation Value of Energy Storage for High Penetration Proportion Renewable Energy Integration and Case Study

Electric power system (EPS) operators use a variety of scheduling techniques to match electricity generation and demand. When the total supply of energy is different from the total demand, system operators must deploy operating reserves (including regulating, following, contingency, and ramping reserves) to correct the energy imbalance. The way they do this, and especially the way they plan for this, can affect the reliability and efficiency of the power system—particularly if it includes large amounts of variable generation. In this section, we will discuss the tools used to evaluate economic and reliability metrics when employing different operating reserve strategies, including use of energy storage technologies. Such multiple-timescale, interconnected simulation tools that include security-constrained unit commitment, security-constrained economic dispatch, and AGC submodels enable FESTIV to fully investigate the trade-offs in economic benefits, reliability benefits, and incentive structures.

There are requirements, or minimum technical requirements that utility-scale VRE shall carry out, such as solar PV, wind, and EES. Renewable generation also plays a vital role in frequency regulation of existing

and future power grids. With the increasing penetration of EES, particularly BESS, utility-scale BESS should participate in reliability controls, including:

- Low-voltage ride-through and high-voltage ride-through
- Voltage regulation
- Steady-state and dynamic reactive power controls
- Frequency fault ride-through
- Frequency response and frequency regulation
- Ramp-rate regulation
- Active power control.

According to our research, NREL's suggestions include requirements on ranges for inertial control deadbands for frequency and high rate of change of frequency and the magnitude of inertia response as a percentage of pre-fault power level or total plant capacity [12]. For instance, the inertia response can be set between 0.025 – 0.3 Hz for programmable frequency headland. The programmable rate of change of frequency deadland can be within 0.1 – 2 Hz/s. The programmable magnitude of inertial response can be in 0 – 0.15 p.u. FFR is a relative novel way to utilize BESS to deal with sudden generation or load losses [13]. With proper knowledge of loss magnitude, BESS can be controlled to change its power output. Thus, FFR can be a useful frequency response method for system operators. The key is to improve the ability of the control system to resolve the loss magnitude and send the set point to control BESS. The BESS response speed will rely on the power system stability impacts: BESS has the capability to deploy all available reserves rapidly, which can probably result in system oscillations. FFR provided by BESS can be based on frequency threshold, such as rate of change of frequency; however, it will need the information of precise FFR magnitudes. NREL recorded about 20 – 30 ms constant response time by a commercial 1 – MW/1 – MWh Lithium-ion BESS equipped with in inverter, which means that BESS can be a productive provider of FFR service.

NREL researched the topic of what frequency response services by BESS are most effective in terms of boosting power system performance during and after significant contingencies [12]. We built a power system model that comprises synchronous generators with steam, gas, and hydro governors; static loads, inertia-less wind and solar generation, and a BESS. The share of wind and solar generation took up 20%, and the BESS took up 3.5%. We conducted a significant contingency by tripping off a generator that powers 3% of the load. The average inertia constant for all conventional generator $H = 5$ s. We assumed both wind and solar generation merely supply bulk power without reliability services. The BESS ran at zero power, so it could run at full power in either charge or discharge condition. At $t = 50$ s, a generator was disconnected, resulting in reduction of the frequency of the system. The base case is only traditional generators have the ability to provide inertia and droop response, making a frequency nadir at about 59.6 Hz. The results of the experiments for this hypothetical case are shown in Figure 3- 9.

The following cases show the impacts of BESS on system frequency:

- Case 1: BESS offering inertial response (200-ms delay)
- Case 2: BESS supplying droop response (200-ms delay)
- Case 3: BESS supplying inertial response and droop (200-ms delay)
- Case 4: BESS supplying FFR (2-s delay)

- Case 5: BESS offering inertia (200-ms delay) and FFR (2-s delay).

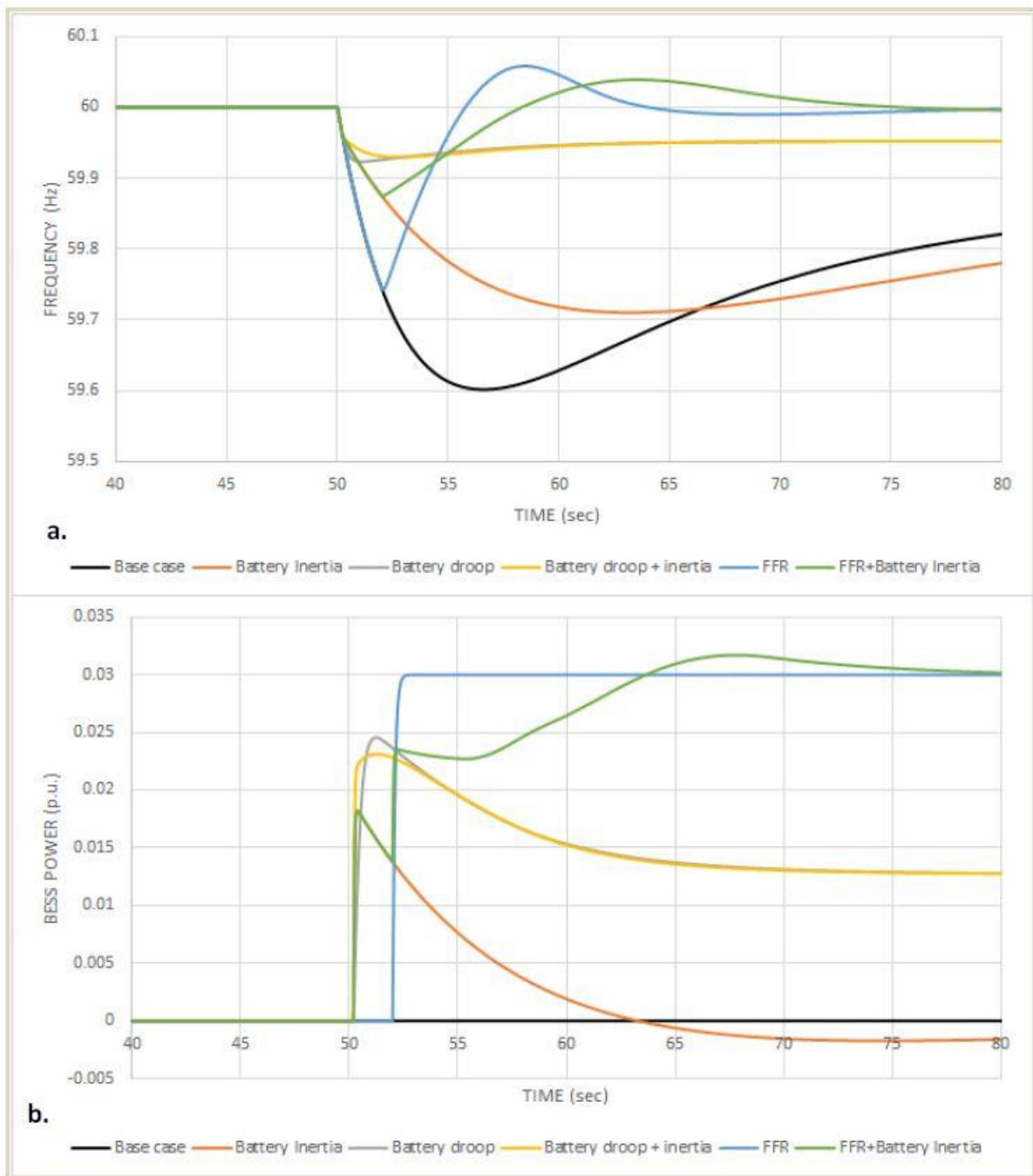


Figure 3- 9. System frequency (a) and BESS response (b)

Source: [12]

3.5.3 Value Assessment Method of Energy Storage for Improving System Flexibility

The section will discuss various methods used for examining the potential for replacing conventional peaking capacity and flexibility resource with energy storage, including analysis of the changing technical potential with increased storage deployment and the effect of PV and wind deployment. Details on

dispatch models to evaluate renewable generation as a function of system flexibility and enabling technologies like energy storage will be described.

Based on our past research and experiments, NREL proposed recommendations for the determination of minimum technical requirements [14]; such regulation and assessment should at least cover some of the following items:

- All aspects about active and reactive power services by BESS
- Black-start and grid-forming ability
- Transient fault ride-through capabilities
- Power quality regulation
- Protection regulation
- Validation of energy storage models
- Operation and control regulation
- Control and communication update.

The implementation of BESS is to mitigate the instability with the increasing integration of VRE, such as wind and solar PV systems. Meanwhile, BESS can also lower the cost of reserves provided by conventional power plants and decrease the headroom curtailed by VRE. Both utility companies and regulators want the BESS to be cost-effective; therefore, the value of BESS is determined by the services it can provide. To fully utilize the BESS, NREL proposed a list of required services by BESS and related parameters that need to be clarified for assessment [12], including:

- Inertial response capability with programmable inertia constant H
- FFR capability with response time and maximum possible
- Frequency droop control capability with programmable droop setting and deadbands
- Ability to follow 2-s active power set-point commands from AGC systems
- Voltage droop control capability with programmable droop setting and deadbands
- Steady-state and dynamic reactive power injection or absorption capability
- Short-circuit current control capability (i.e., positive-sequence, negative-sequence, and zero-sequence components) under balanced and unbalanced fault conditions
- Voltage and frequency fault ride-through capability
- Grid-forming capability
- The concept of a virtual synchronous machine is rising in the industry as a flexible option to allow operation under a wide range of system conditions, including seamless transition between grid-connected and stand-alone operation.
- Control of short-circuit current in grid-forming mode under various fault scenarios.

3.6 Reliability Services by Modern Transmission Technologies

Flexible AC transmission systems (FACTS) are used to increase power transfer capability, stability, and controllability of the networks through series and/or shunt compensation. These devices are also employed for congestion management and loss optimization. FACTS technology is an energy conversion,

transmission, and control technology that uses high-power semiconductor switching devices. Facing EPS, it integrates manufacturing technology, modern control technology, and the traditional power grid technology, and has become the core of FACTS. This section will provide an overview of modern FACTS devices and their uses for reliability services in transmission grids.

A FACTS is a system consisting of static equipment used for AC transmission of electrical energy. A FACTS aims to improve controllability and enhance transfer capability of the electrical grid [15]. A power system dominated by FACTS devices is an electronics-based system. Incentivized by the goals of greenhouse emission reduction and increasing electric demand, the integration of renewable energies is increasing in recent years. In turn, the increasing VRE generation also creates novel challenges in power grids, such as dispatch of active and reactive power, voltage and frequency stability, sub synchronous resonance, and power quality. Thus, the VRE has the potential to compromise the stability and safety of the power systems. Recent research shows that FACTS devices are good at solving these kinds of problems. The key to FACTS is to incorporate power electronic devices at the transmission level to make the system electronically controllable. The controllers inside FACTS enable FACTS to control one or more parameters to alter the operation of transmission and enhance the power system stability and power quality. The incorporation of FACTS can increase the ability to control dynamic power flow and decrease the power oscillations. Besides that, FACTS devices are also capable of increasing availability of power transfer and capacity of existing transmission lines and voltage support.

The Thyristor Controlled Series Capacitor is one of the FACTS devices. The Thyristor Controlled Series Capacitor enables fast and continuous change of transmission-line impedance. Therefore, the active power flowing in the transmission line should be maintained at a predefined value under various system conditions. The figure below shows a configuration of a Thyristor Controlled Series Capacitor, which contains a series capacitor bank in parallel with a reactor controlled by thyristor.

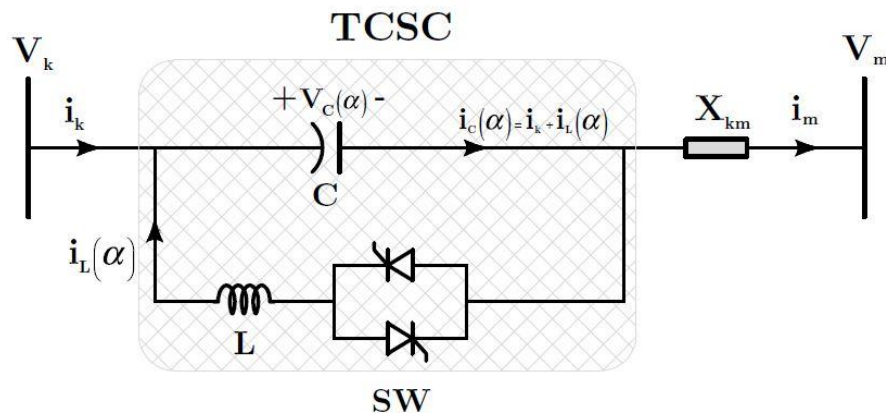


Figure 3- 10. Thyristor Controlled Series Capacitor schematic

Source: [12]

The Static Synchronous Compensator is another FACTS device, which can provide voltage support without large banks of capacitors and reactors to supply or absorb reactive power. Static Synchronous Compensators can be used as a controlled current source, which supply or absorb reactive power. Figure 3- 11 shows the scheme of a Static Synchronous Compensator.

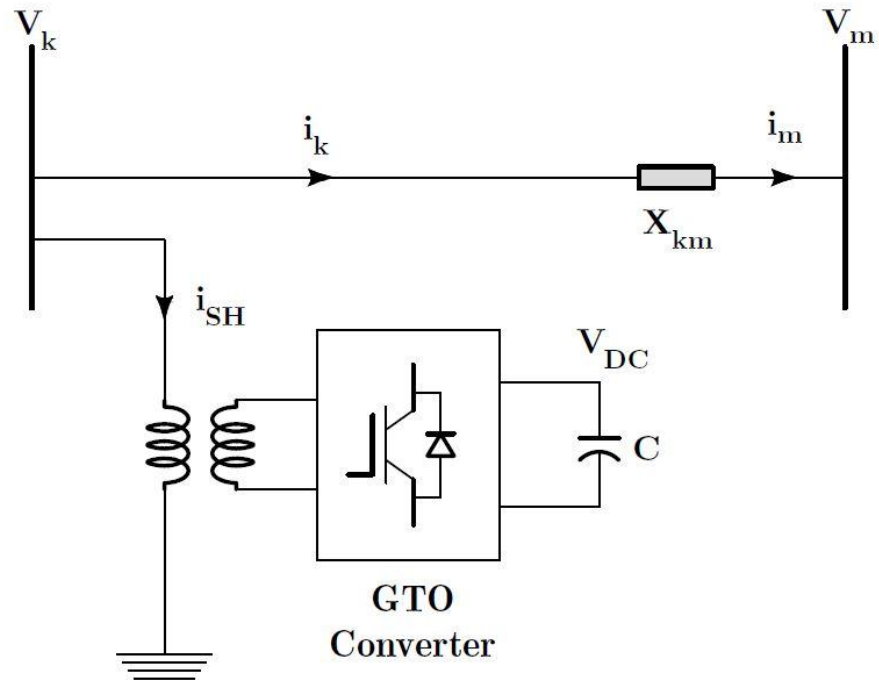


Figure 3- 11. Static Synchronous Compensator schematic

Source: [15]

The Unified Power Flow Controller is the integration of shunt and series converters, which are equipped on the DC side through a common connection. A Unified Power Flow Controller enables bidirectional exchange of active and reactive power between the two devices on its two sides, thus realizing controlling the compensation of the active and reactive power. The schematic of a Unified Power Flow Controller is depicted in Figure 3- 12.

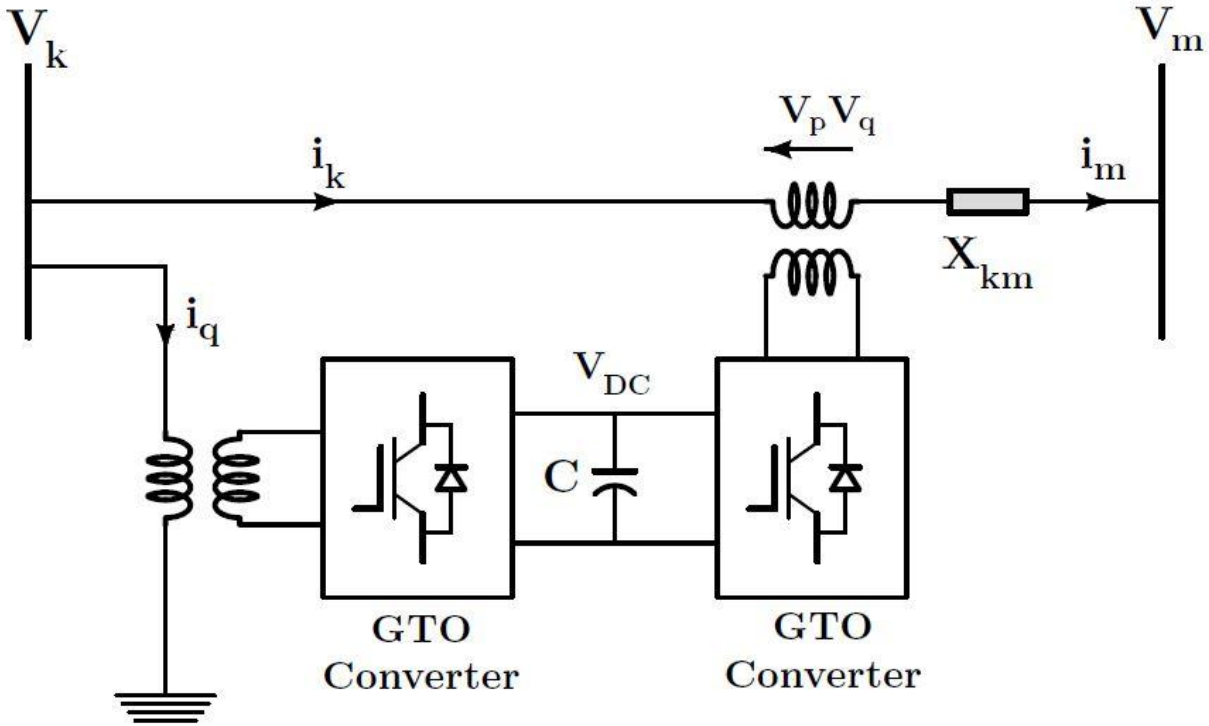


Figure 3- 12. Unified Power Flow Controller schematic

Source: [15]

According to NREL's research, the Thyristor Controlled Series Capacitor and Unified Power Flow Controller can mitigate the transmission-line congestion, which allows the control of active power to keep the active power at the same level when the load increases. In terms of voltage regulation, the Static Synchronous Compensator and Unified Power Flow Controller can provide good control results and maintain the voltage at its nominal level. Meanwhile, shunt compensation devices can provide better performance over series devices in improving voltage profiles of buses.

3.7 Examples of Field Demonstration Projects

In this section, we will provide a description and results of several pioneering demonstration projects involving provision of system-level reliability services by utility-scale wind, solar PV generation, and energy storage. Holistic demonstration on an actual, large, utility-scale, operational renewable power plant and dissemination of the obtained results is essential for closing gaps in perspectives that exist among various stakeholders in the U.S. and China grids. If wind and PV-generated power and energy storage can offer a supportive product that benefits the power system and is economic for power plant owners and customers, this functionality should be recognized and encouraged.

The first project is the Kahuku Wind Farm BESS Project in Oahu, Hawaii. Location is in the North Shore of Oahu [16]. The Wind Farm has twelve 2.5-MW wind turbines and a 15-MW/10-MWh BESS. The goal of BESS is to decrease ramps of the wind power output. From an economic aspect, ramp reduction can reduce the frequency of ancillary services provided by conventional generation and its corresponding cost. The test was conducted in November 2011 for 11 days, and the frequency of a large ramping rate was declined greatly and even eliminated. At some critical points, more than an order of magnitude in the frequency of 1-minute ramp rates was observed.

Another project we want to introduce is in Texas [17]. The system comprises a 156-MW wind power plant and a 36.-MW/24Mwh battery system. The purposes of this project include: (1) mitigate the wind power intermittency issues; (2) verify the viability of utility-scale BESS; and (3) and increase the viability of wind generation. As expected, the BESS showed favorable performance in fast-responding regulation services; however, the performance of the lead-acid battery degraded due to fast charging and discharging.

The third project we want to introduce as an example is the rebuilding and upgrading of the Puerto Rico Electric power grid [14]. The original power system in Puerto Rico was damaged by Hurricane Maria on September 20, 2017. The Puerto Rico Electric Power Authority wanted to upgrade the original power system so it could meet the electricity demand by 2035, and new legislation called for 100% renewable energy by 2050. Modern PV and wind power plants, together with battery systems, have the potential to realize the goal. There is 6 GW of installed capacity in Puerto Rico so far, and 200 MW is renewable generation. We investigated the most valuable frequency response that BESS can provide during and after major contingencies. The simulation power system was like the Puerto Rico Electric Power Authority [14]. The BESS capacity was 3.5% of the overall demand. The performances of BESS were good in all different testing cases.

3.8 Grid-Forming Inverters

The successful integration of wind power into the power system worldwide was made possible by the use of conventional grid-following power converters, which provide a number of essential reliability services to the grid. In some cases, combining variable generation with energy storage will increase flexibility and enhance the ability of wind and solar power to provide such services; however, one fundamental limitation of grid-following converter technologies is their inability to ensure stable grid operation when the voltage source generation capacity diminishes. This fact is rarely discussed by the greater renewable integration community, but adequate capacity of grid-forming sources has proven more important for stable grid operation than the emulation of large inertia constants by current source converters. The network cannot stably operate without sufficient voltage sources, regardless of how much inertia is present. Alternatively, systems without inertia and high rate of change of frequencies but with enough grid-forming capacity can still operate in a stable manner if proper controls are implemented, from which we can conclude that in future scenarios grid forming may be more important than inertia (concept is explained in below figure). Grid-forming inverters are also capable of providing all existing and future advanced reliability similar to or better than any conventional technology, and they help to enhance grid resiliency and security by provision of other services such as islanded operation, black start, and so on [4]; however, the important questions waiting for answers by the research community are:

- How should the fundamentals of grid-forming operation and transient stability theory be applied when power converters mimic basic characteristics of synchronous machines such as power sharing, synchronizing and damping torques, and so on?
- How do we design and control future wind and solar power plants so that they can provide adequate grid-forming capability combined with the full range of essential reliability and resiliency services, along with dispatchability and flexibility of conventional sources?
- What is the role of energy storage in this wind and solar power transformation?
- How can other “beyond batteries” solutions help with this transformation?

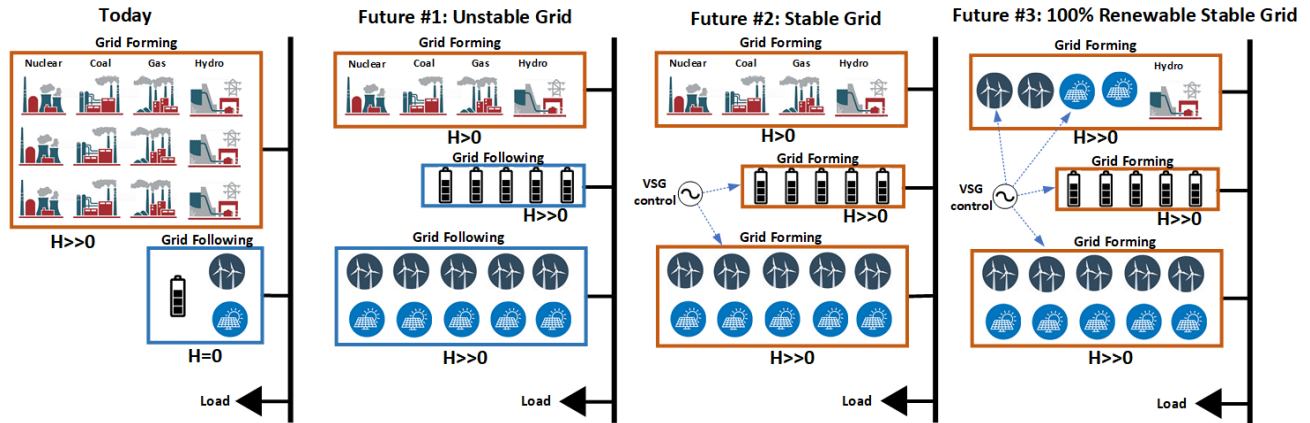


Figure 3- 13. Grid forming: essential for stable operation

Source: [30]

The basic difference between grid-following and grid-forming operation of IBRs is shown in Figure 3- 13. In a grid-following operation, the inverters do not directly set grid voltage and frequency. Instead, they act as current sources, injecting commanded levels of active and reactive power. In grid-following mode, the measured variables are grid frequency and voltage, and the controlled variables are active and reactive power. Grid-forming inverters can directly set the grid voltage and frequency and operate essentially as synchronous generators with automatic load tracking, as long as the current limit of the inverters are not exceeded. Unlike grid-following inverters, the grid-forming inverters do not require phase-locked loops and can operate with fixed voltage and frequency control or droop-based controls as shown in Figure 3- 13. Such droop-controlled operation for grid-forming inverters enables power sharing similar to synchronous generators. In droop-controlled grid-forming inverters, measured variables are active and reactive power, and controlled variables are frequency and voltage.

Grid-forming inverters can have more sophisticated controls, such as virtual synchronous machine or virtual synchronous oscillator controls. Grid-forming inverters have the same fundamental limitations as grid-following inverters in the form of very low overcurrent capability, which has impacts on system protection, grid strength, and short-circuit ratio.

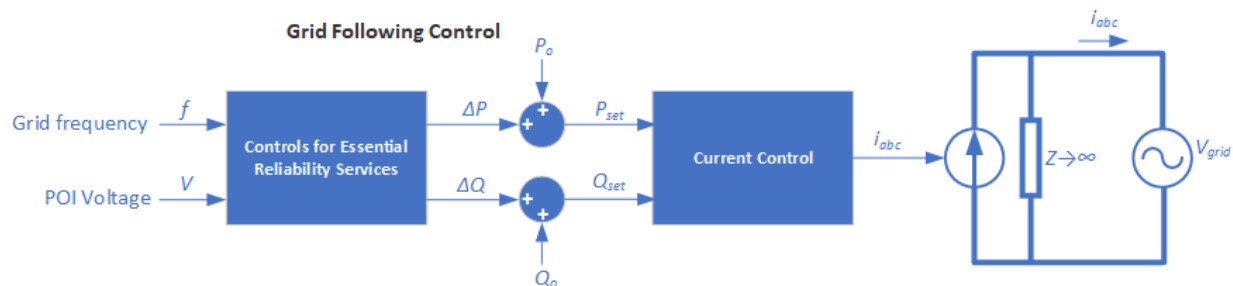


Figure 3- 14. Grid-forming inverter

3.9 Conclusion

High renewable penetration will bring different challenges to power system reliability and stability. Reduction of inertia has been of concern for more widespread unstable events; however, with the advanced control functionalities provided by power electronics interface and proper storage compensation, renewable generators are capable of providing a wide range of grid services that can

maintain and improve grid reliability and stability matrices. Many studies and tests have demonstrated those functions, and many pilot projects throughout the world have proved the concepts are working.

In the fast-changing grid technologies landscape and energy mixes, the main challenge is how to maintain reliable, resilient, and economic operation of the power system on our way to a 100% renewables-based grid, considering many uncertainties and possible scenarios that will, in turn, impact solutions to address this challenge. In addition, new reliability challenges may present themselves as the power system is evolving toward inverter-dominated systems. New stability problems, control interactions, and sub and super-synchronous oscillations, protection adequacy, and transient performance in weaker grids may become serious reliability issues if not understood and addressed in proper ways. This will require development of new algorithms, new models, and software tools allowing adequate simulations of inverter-dominated power systems with high temporal resolutions.

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