ELECTRIC POWER RESEARCH INSTITUTE

# Supplement to EPRI Power System Dynamics Tutorial (1016042, July 2009)

**3002010757**

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Technical Update, December 2017


EPRI Project Manager
A. Del Rosso



ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Principal Investigators
N. Bhatt
A. Del Rosso
A. Gaikwad
A. Tuohy
J. Boemer
V. Singhvi

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# ABSTRACT

In 1989, EPRI developed the first version of the Power System Dynamics Tutorial, with the goal of developing training material for power system operations staff. Since then, the tutorial has been revised in 2002 and 2009 to add new industry developments and issues such as mandatory compliance with reliability standards in North America. From its original 1989 publication, this tutorial has been well received around the world, with thousands of copies used globally for training power system practitioners across the entire spectrum of operations, planning, engineering, and design. Since the 2009 version, renewable generation resources—utility-scale wind and solar generation connected to the bulk power system—have experienced tremendous growth, which is expected to continue. Similarly, distributed energy resources (DER)—small-scale energy resources connected to the distribution system—have also seen tremendous growth in recent years; this growth is also expected to continue. These utility-scale renewable resources and DER have presented challenges and opportunities to bulk power system operations and planning engineers. In response, new tools and techniques are being developed for efficient and effective interface/integration of these resources with the bulk power system.

In light of these developments, this supplement to the 2009 Power System Dynamics Tutorial was prepared to provide an overview of renewable generation and DER technologies, discuss the challenges faced by system operators and planners in integrating such generation into the bulk power system, and summarize the industry efforts to address these challenges. The material in this report will be included in a new version of the Power System Dynamics Tutorial, to be published in 2018.

**Keywords**
Distributed energy resources (DER)
Observability/monitoring/control
Ramping/flexibility
Renewable generation
Variable energy resources (VER)
Voltage/frequency support and ride-through capabilities

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# Supplement to EPRI Power System Dynamics Tutorial (1016042, July 2009)

**PRIMARY AUDIENCE:** Transmission operations and planning staff

**SECONDARY AUDIENCE:** Distribution operations and planning staff, reliability standards development bodies, R&D community, EMS vendors

## KEY RESEARCH QUESTION

What challenges and opportunities are posed to the bulk power system by the increasing penetration of wind and solar generation, also known as *variable enegy resources* (VER) and *distributed energy resources* (DER)? What new tools and techniques must be developed for effective and efficient interface and integration of VER and DER with the bulk power system?

## RESEARCH OVERVIEW

A global literature review was performed to comprehend the state of the art in VER and DER and their potential impact on the bulk power system. The findings are summarized in this report for the benefit of transmission operators and other stakeholders.

## KEY FINDINGS

- The penetration of VER and DER has increased significantly in recent years. This growth of VER and DER is expected to continue.
- An increased penetration of VER creates challenges for system operators and planners because of the unique characteristics of VER technologies and fuel sources: variability (that is, generation output constantly varies with time) and uncertainty (generation output cannot be predicted and forecasted accurately).
- VER/DER integration into the bulk power system creates various challenges and opportunities: ramping (that is, the sudden increase or decrease in VER generation must accompany other supply- and demand-side resources that can ramp up/down quickly to maintain energy balancing; flexibility (flexible resources for steep ramping, operating reserves, and minimum generation operating levels); advanced VER forecasting techniques; voltage/frequency support and ride-through capabilities; VER modeling for operations and planning studies; planning considerations (that is, a thorough planning process to include all potential challenges); observability and control (visibility, observability, and control of DER by the operators of the bulk power system can allow them to schedule, dispatch, or curtail DER); understanding the role of VER/DER in system restoration; and data sharing between transmission/distribution entities.
- The industry has been improving its operations and planning processes, tools, and techniques for effective and efficient interface and integration of VER and DER into the bulk power system.

## WHY THIS MATTERS

To maintain reliability of the bulk power system, the industry must address the challenges posed by the increasing penetration levels of VER and DER.

## HOW TO APPLY RESULTS

EPRI members can compare their own processes, tools, and techniques for integrating VER/DER with those summarized in this report.

## LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI Program 173 performs R&D to address the VER/DER integration challenges mentioned in this report. The contents of this report will be included in a new version of the Power System Dynamics Tutorial, expected to be published in 2018.

**EPRI CONTACT:** Alberto Del Rosso, Principal Project Manager, adelrosso@epri.com

**PROGRAM:** Grid Planning, P40



**Electric Power Research Institute**
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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# 1
# INTRODUCTION

In 1989, EPRI developed the first version of the Power System Dynamics Tutorial, with the goal of developing training material for power system operations staff. Since then, the tutorial has been revised in 2002 and 2009 to add new industry developments and issues such as mandatory compliance with reliability standards in North America. Ever since its original 1989 publication, this tutorial has been well received around the world, with thousands of copies used globally for training power system practitioners across the entire spectrum of operations, planning, engineering, and design.

Since the 2009 version, renewable generation resources—utility-scale wind and solar generation connected to the bulk power system—have experienced tremendous growth, which is expected to continue. Similarly, distributed energy resources (DERs)—small-scale energy resources connected to the distribution system—have also seen tremendous growth in recent years, and this growth is expected to continue. These utility-scale renewable resources and DERs have presented challenges and opportunities to bulk power system operations and planning engineers. In response, new tools and techniques are being developed for efficient and effective interface/integration of these resources with the bulk power system.

In light of the above development, this supplement to the 2009 Power System Dynamics Tutorial was prepared with the following objectives:

- To provide an overview of renewable generation and DER technologies.
- To discuss the challenges faced by system operators and planners in integrating such generation into the bulk power system.
- To summarize the industry efforts to address these challenges.

Chapter 2 focuses on renewable generation, and Chapter 3 focuses on DERs. The material of this report will be included in a new version of the Power System Dynamics Tutorial, to be published in 2018. **The objective of the future versions of tutorials will be *to provide background technical information for various operational issues faced by transmission system operators and operations engineers.***

# 2
# RENEWABLE GENERATION

Renewable generation has seen tremendous growth during the past decade and now represents a significant portion of total generation in many parts of the world. This chapter focuses on wind and solar generation, often referred to as *variable energy resources* (VERs). It provides an overview of wind- and solar-generation technologies, discusses challenges faced by transmission operators in integrating such generation into the bulk power system, and summarizes industry efforts to address these challenges.

## 2.1 Growth of Wind and Solar Generation (Variable Energy Resources)

The amount of renewable generation installed globally is presented in Table 2-1 [1, courtesy of International Renewable Energy Agency]. Within the U.S., total installed wind generation capacity has increased over the years, as shown in Figure 2-1, and amounted to 82,183 MW at the end of 2016 [2, courtesy of American Wind Energy Association]. Per the forecast shown in Figure 2-2 (courtesy of Global Wind Energy Council), global wind generation capacity in 2021 is expected to be 800 GW [3]. During real-time operation, high instantaneous penetration levels of wind generation have been reported in the United States and Europe. For example, in February-March 2017, the Southwest Power Pool (SPP) and the Electric Reliability Council of Texas (ERCOT) experienced 50% penetration of wind generation [4, 5], and on February 23, 2017, Denmark generated enough wind energy to power all its electricity needs [6].

**Table 2-1**
**Global renewable capacity statistics – 2016 year-end installed capacity (MW)**

| | 2016 Year-End Installed Capacity (MW) | | | |
|---|---|---|---|---|
| **Renewable Technology** | **World** | **Asia** | **Europe** | **N. America** |
| Total[1] | 2,006,202 | 811,590 | 486,693 | 329,703 |
| Wind – Total | 466,505 | 184,489 | 155,350 | 96,739 |
| Onshore Wind | 452,424 | 182,909 | 142,879 | 96,710 |
| Offshore Wind | 14,081 | 1,581 | 12,471 | 29 |
| Solar – Total | 295,664 | 139,321 | 104,471 | 37,824 |
| Solar – PV | 290,791 | 139,074 | 102,163 | 36,067 |
| Solar – Concentrated | 4,873 | 248 | 2,308 | 1,758 |

1. Includes wind, solar, hydro, marine, bio, and geothermal.

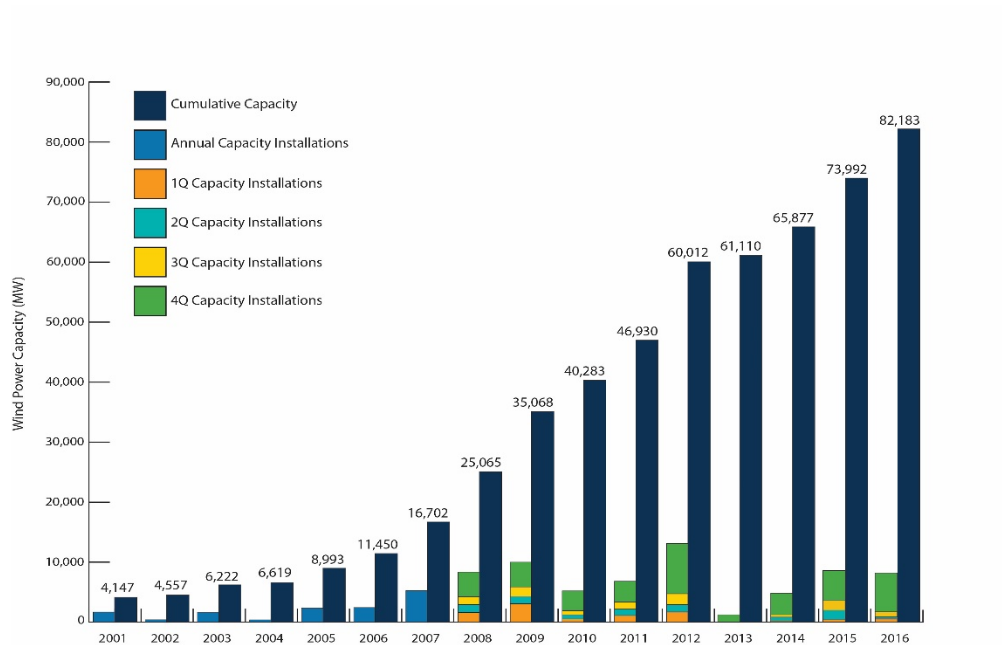


**Figure 2-1**
**Total U.S. installed wind capacity (MW) through end of 2016**


**Figure 2-2**
**Global wind generation market forecast for 2017-2021**

## 2.2 An Overview of VER Equipment

### *2.2.1 Wind-Generation Technologies*

Figure 2-3 shows a wind turbine generator (WTG) [7]. It typically has 3 blades, each 40 to 50 meters (130 to 160 feet) in length. Its rating ranges from 1.5 to 3 MW, while a 9-MW unit is available for offshore application. The turbine rotates in the range between 10 and 20 RPM. The tower height can be 90 meters (295 feet) or more. A wind power plant may consist of tens or hundreds of WTGs spread over several square miles.

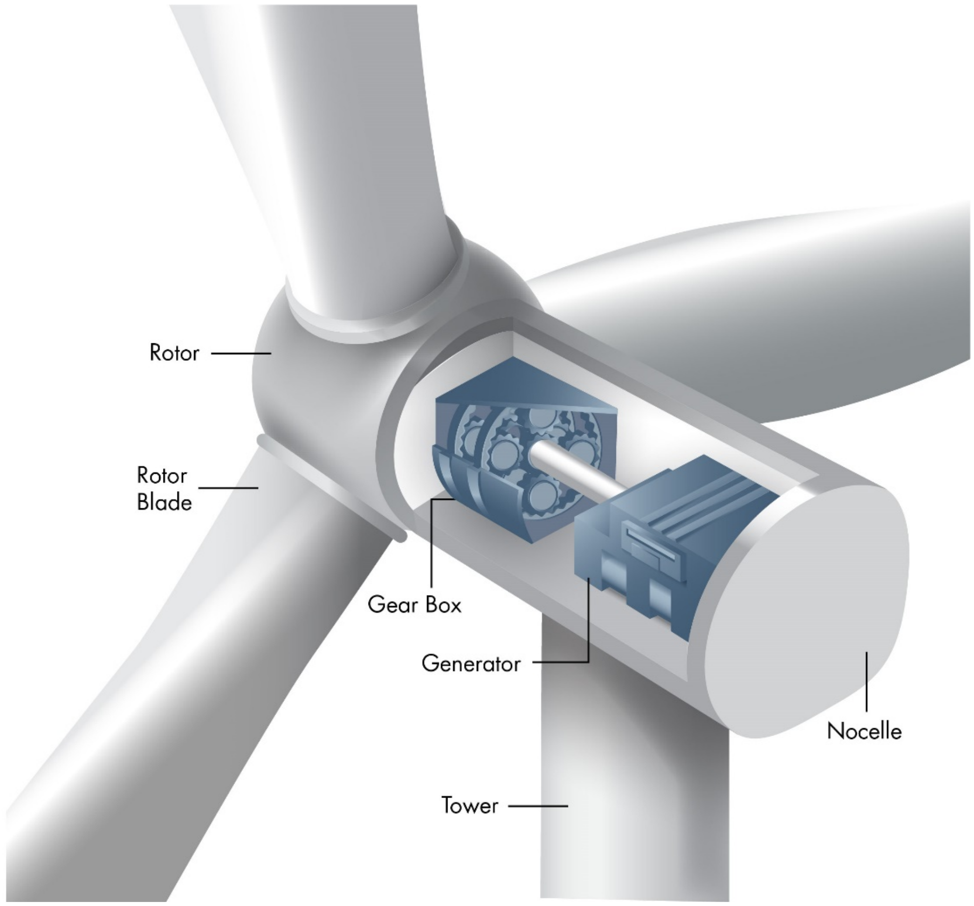


**Figure 2-3**
**A typical wind turbine generator**

Wind turbine generators can be divided into four main types, as shown in Figure 2-4 [8]. Type 1 WTGs use a conventional induction generator directly connected to the grid. The electrical generator runs at a relatively fixed speed, which is about 1% above the nominal system frequency. The power system electrical frequency, together with the number of magnetic pole pairs on the generator, determines the machine's actual mechanical speed [9]. Larger WTGs may have relatively slow-acting blade pitch controls to control the turbine's mechanical speed.

Type 2 WTGs have wound rotors with externally connected variable resistance. The relatively fast-acting variable-resistance control works with the pitch control to change the turbine speed by a few percent. Thus, these units have a small variable-speed range.

Type 3 and 4 wind turbines are variable-speed machines [9] that are connected to the grid through an inverter interface that includes an AC-to-DC-to-AC conversion. The inverter interface allows flexible speed control and enables independent control of active and reactive power outputs [10]. For Type 3 WTGs, the rotor is connected to the grid through a power converter, while the stator is connected directly [9]. For Type 4 WTGs, the generator is interfaced through a full-rate power converter. The speed of the generator rotor is thus decoupled from the grid frequency, and the rotor speed can vary according to the wind speed [9]. It should be noted that the modern WTGs are either Type 3 or Type 4, and the percentage population of Type 1 and Type 2 WTGs, which were installed in early years of wind generation, is dwindling.

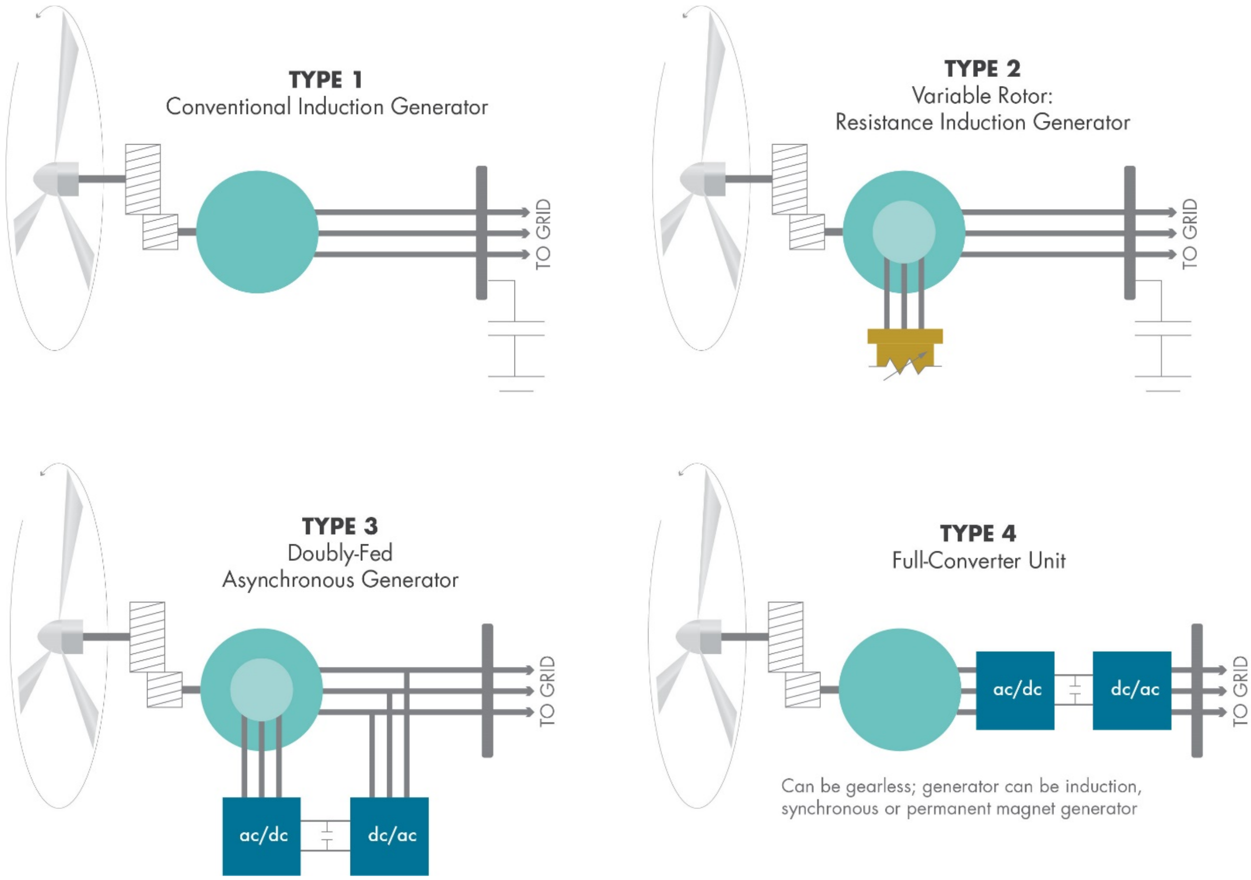


**Figure 2-4**
**Types of wind turbine generators**

### *2.2.2 Solar Technology*

**Photovoltaic (PV):** As shown in Table 2-1 above, PV solar plants represent over 98 percent of total solar power installation. PV devices generate electricity from sunlight via an electronic process that occurs naturally in semiconductor materials such as silicon. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid [11]. Thus, PV devices use semiconductor materials to convert sunlight to direct current (DC) electricity. Figure 2-5 is an example of a PV solar plant.

**Figure 2-5**
**A PV solar plant**

Utility-scale photovoltaic solar plants are similar to the wind power plants with Type 3 and Type 4 WTGs because they aggregate numerous inverter-based solar cells. The solar cells are connected to the grid by a DC bus (capacitor) through power electronics and an isolation transformer, as shown in Figure 2-6 [10, 12]. The inverter-based electronics provide control flexibility, with the added benefit of no moving parts compared to the WTGs. A plant-level control strategy is employed to coordinate with individual solar cells, in order to take advantage of equipment capability, solar irradiance, individual array status, and grid operating conditions [10]. Thus, the plant-level control provides various reference signals to individual PV cells so that the inverter control of each PV cell can accomplish the plant-level control goal. This coordination between the plant-level control and the individual solar PV cell controls ensures satisfactory plant-level performance from voltage and frequency viewpoints.

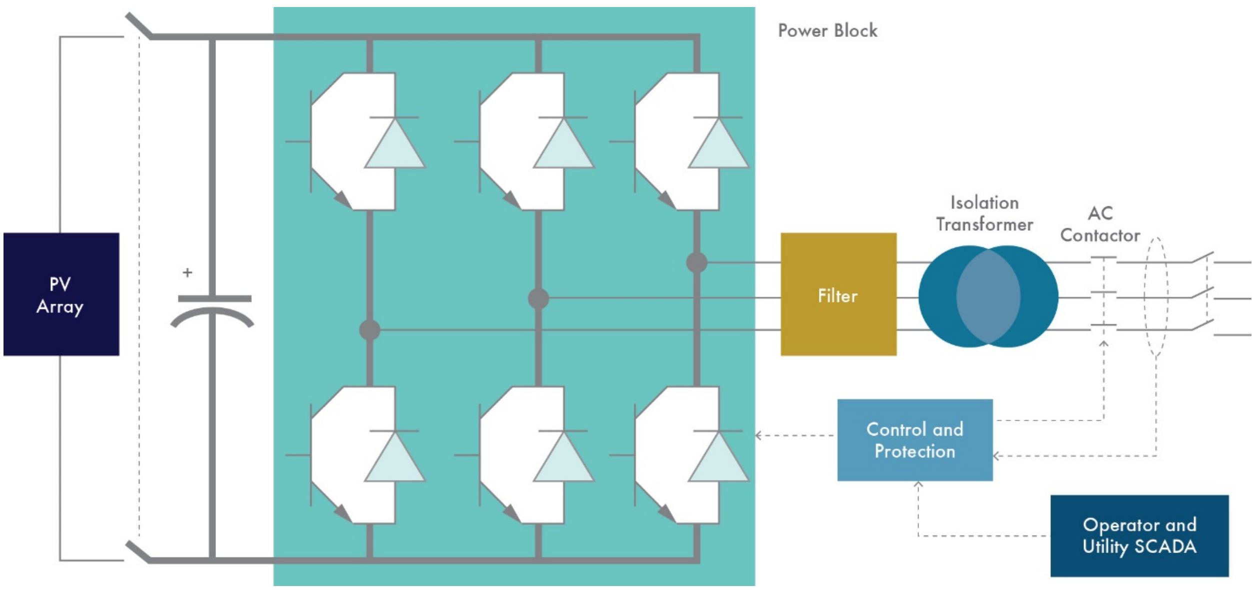


**Figure 2-6**
**Typical topology of a utility-scale PV solar power plant**

**Concentrating Solar Power (CSP):** Per Table 2-1 above, CSP plants account for less than 2 percent of total solar power installations. CSP arrays use lenses and mirrors to reflect concentrated solar energy onto high-efficiency cells. Such installations require direct sunlight and tracking systems to be effective [11]. The concentrated solar energy heats a high temperature heat-transfer fluid, which is then fed to heat exchangers that produce superheated steam that powers a conventional steam-turbine generator to produce alternating current (AC) electricity [13]. Figure 2-7 shows an example of a CSP plant design, which is for the 125-MW Dhursar Plant [14]. Due to inherent thermal inertia, CSP has less output variability and slower ramp rates than PV. CSP has inherent capability for on-site thermal energy storage (TES), which increases the time value of solar power for peaking duty or over-night operations [14].

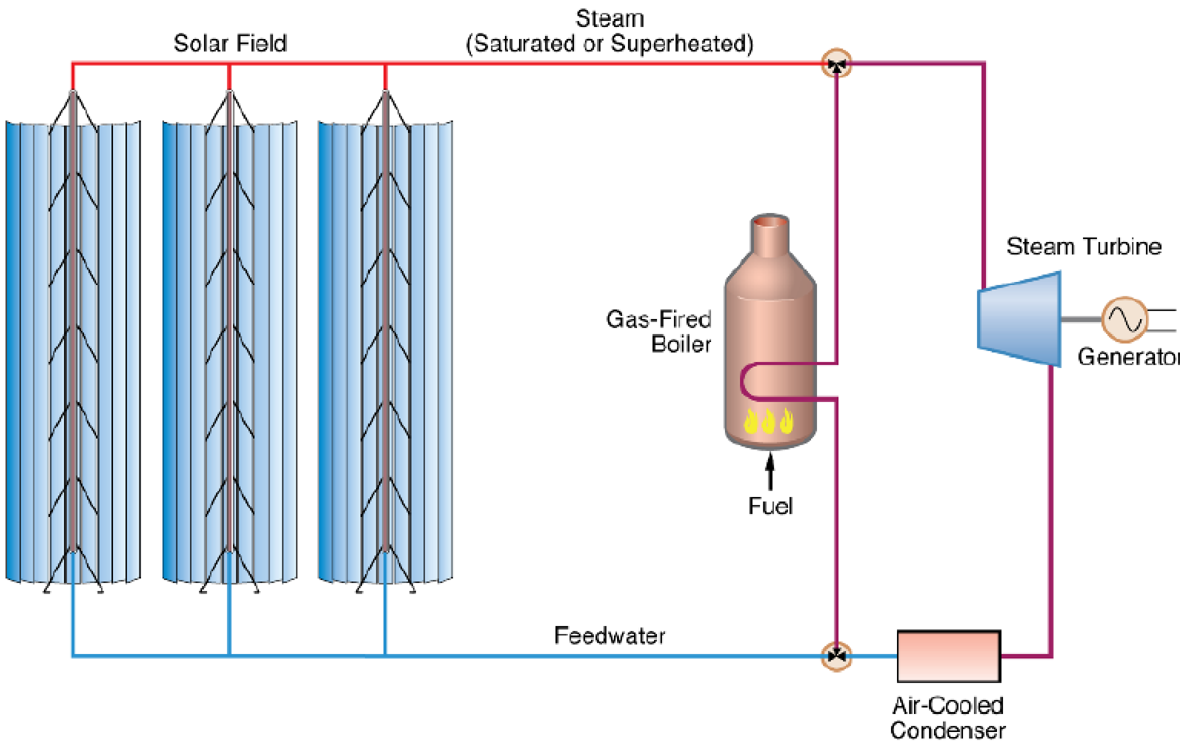


**Figure 2-7**
**Dhursar CSP plant design**

## 2.3 VER Equipment Controls

A vast majority of VERs are inverter-based resources, connected asynchronously to the grid. As highlighted below, by nature, VER controls work differently, compared to the controls of the conventional synchronous generators.

### *2.3.1 WTG Active Power (Frequency) Control*

Variable-speed wind turbine generators and photovoltaic solar are connected to the grid through an inverter, rather than a synchronous generator. These resources cannot provide inherent synchronous inertia to the system and cannot sense system frequency through its turbine speed. Therefore, these resources cannot contribute towards an automatic primary frequency response to frequency deviations *without additional controls.*

Figure 2-8 shows system frequency response following the trip of a large generator, with no wind inertia and droop controls [15, 16]. The synchronous machines connected to the system influence the rate of initial frequency decline following the event, with the frequency nadir (minimum point) occurring when the amount of frequency response from the turbine governor controls and the load variation matches the loss of generation. Eventually, the response reaches a new settling frequency. The figure shows the system frequency response with increasing penetration (15 to 40%) of wind generation, which results in corresponding reductions in the number of synchronous generators connected to the system. Without any additional controls, the increased VER penetration leads to a higher rate of initial frequency decline, a lower frequency nadir, and a lower settling frequency. Such system frequency response can potentially cause tripping of under-frequency-load-shedding (UFLS) relays, generator damage, and even cascading outages, thus posing a potential reliability risk.

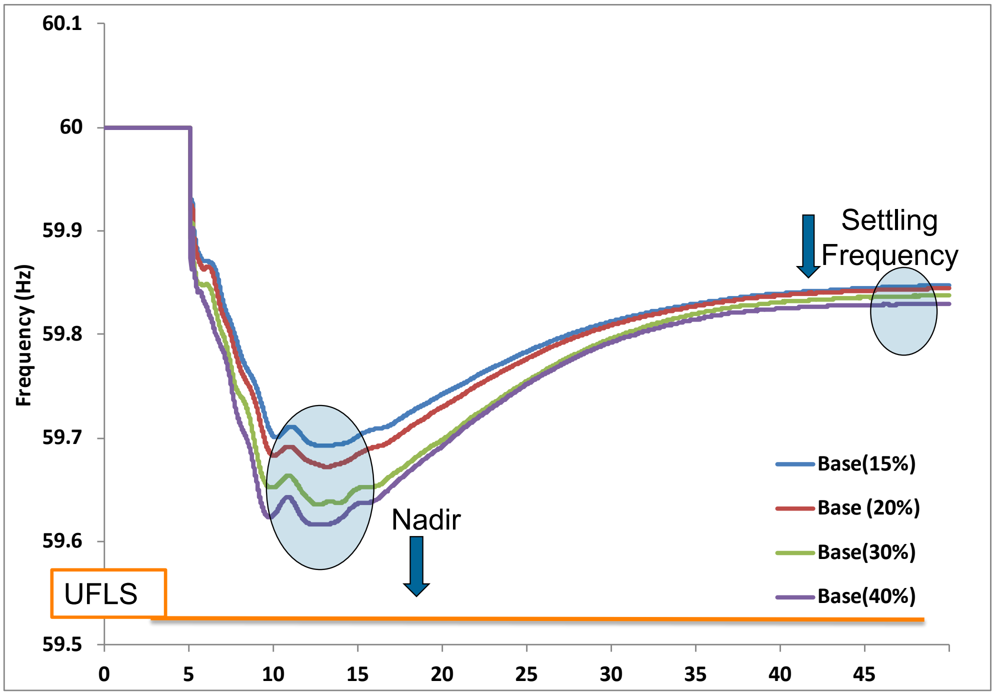


**Figure 2-8**
**System frequency response following a generator trip with wind generation penetration levels of 15 to 40% (No Wind Inertia and Droop)**

Type 3 and 4 wind turbine generators cannot inherently provide inertial response because they are tightly controlled by the power electronic converter interface. However, through supplemental controls in the power converter, they can provide "emulated" inertial response (also known as fast frequency response) by temporarily increasing the power output in the range of 5 to 10% of the rated power. This short-time and quick power injection benefits the grid by essentially restraining the rate of decline of the frequency at the inception of a load/generation imbalance event [15, 16].

Additionally, Type 3 and 4 wind turbine generators at high wind speeds can provide governor-like response. The WTG must operate in a curtailed mode to provide enough reserve for a droop or governor-like response, when the frequency drops. Under normal operating conditions with near nominal system frequency, the control can be set to provide a specified margin by generating less than WTG's rated power. The controls can be tuned to respond to a system frequency excursion using a droop curve similar to the one shown in Figure 2-9 [15, 16, 17]. For example, consider a 1-MW WTG, for which the maximum output based on available wind speed is 950 kW. To obtain a 5% margin for droop response, the Pa value shown in Figure 2-9 can be set to the maximum available output based on wind speed, or 0.95, and the Pbc value shown in the curve can be set to 0.90 per unit. This yields a reserve margin (or "headroom") of 5% of total capacity (= 0.95 to 0.90). The droop is given by the slope of the line from Point A to Point B.

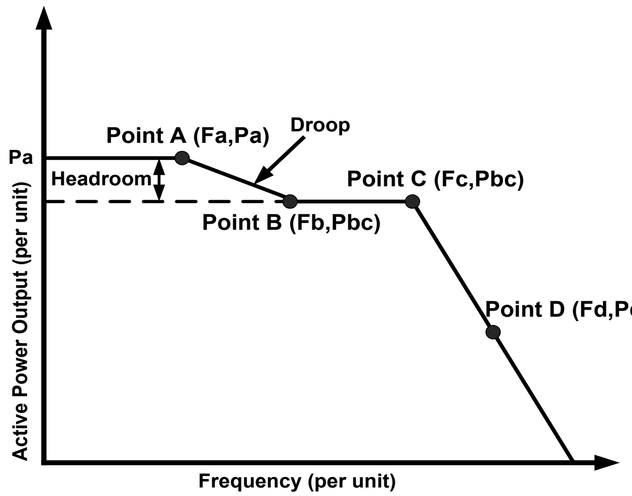


**Figure 2-9**
**Droop-like curve for active power control for Type 3 and 4 WTGs**

The impact of above WTG active power control strategies on system frequency response following a generator trip is illustrated in Figure 2-10 [15]. As can be observed, the synthetic inertia control (red curve) slightly improves the frequency nadir, while the droop control (green curve) significantly improves the overall frequency response. (Note: The red curve's slow frequency recovery (associated with inertia control) is largely because the WTGs modeled in this simulation were dispatched at 56% capacity and were operating at below their rated speed. When another simulation was conducted with WTGs dispatched at 100% capacity—not shown here—the frequency recovery improved significantly.)

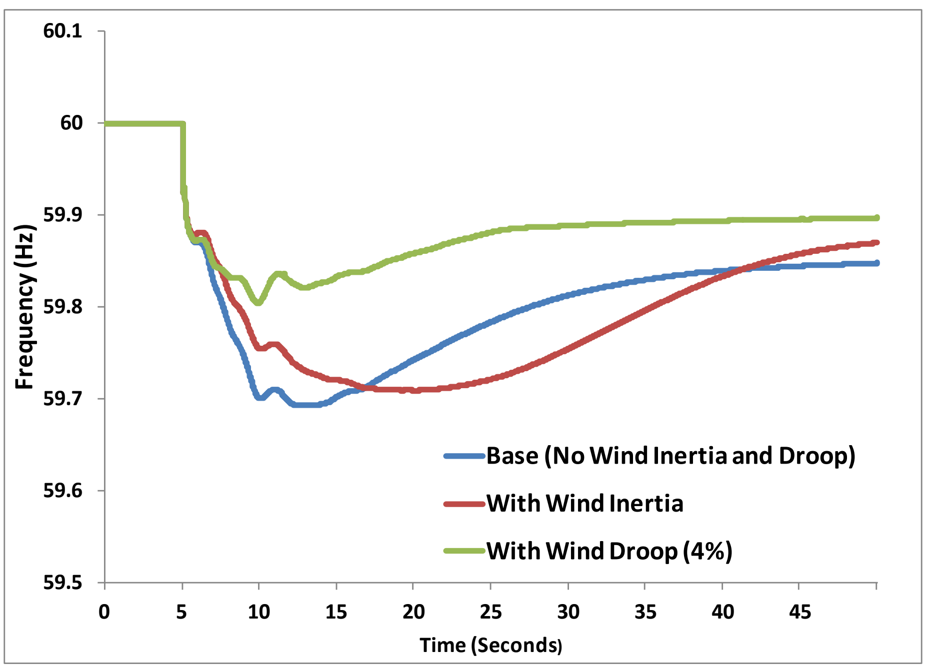


**Figure 2-10**
**Illustration of improvement in system frequency response with active power control for Type 3 and 4 WTGs**

### *2.3.2 WTG Reactive Power (Voltage) Control [9]*

Because Type 1 and 2 WTGs are based on induction generators, inherently, they cannot provide any voltage control [9]. In fact, an induction generator absorbs reactive power from the grid at all times. The amount of absorbed reactive power increases with the increase in real power output of the generator. However, with the use of auxiliary equipment, such as fixed capacitor banks, SVCs, or STATCOMs, the desired reactive power and voltage control can be achieved at the point of common coupling of the wind power plant [9].

Type 3 and 4 wind turbine generators can control voltage by varying their reactive power at a given active power and terminal voltage, so long as the total power output is within the limits of the electrical equipment [9]. In a Type 3 wind turbine, the voltage is controlled by changing the rotor current so as to affect the stator current and produce reactive power to boost voltage. Type 4 wind turbines can control voltage by controlling the line-side power electronic converter [9].

Type 3 and 4 WTGs, due to power electronic converters, can vary reactive power over a wide range of active power conditions. However, a Type 4 WTG, due to its full-scale converter, has a higher reactive power capability as compared to the partial converter of a Type 3 WTG. Figure 2-11 shows a typical "triangular" and "rectangular" reactive capability used for Type 3 and 4 WTGs [9]. Both types of WTGs, if needed, can deliver reactive power at zero active power output. When a Type 3 WTG is off-line, the generator is disconnected and can no longer provide reactive support. However, a Type 4 WTG can provide reactive power and voltage control, even when the turbine is off-line, by keeping the line-side power converter on-line and using it effectively like a STATCOM [9].

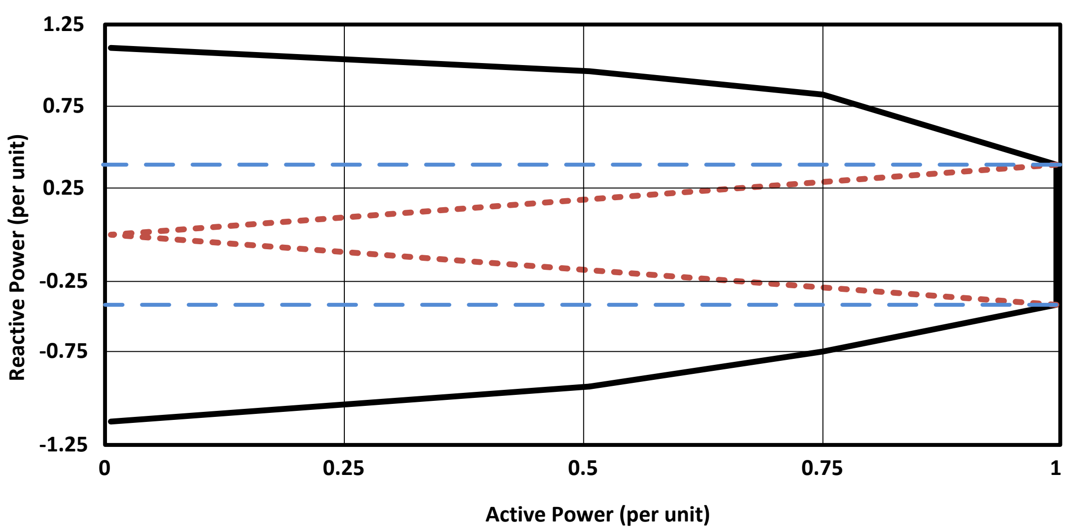


**Figure 2-11**
**Typical reactive power capability curve (triangular, rectangular, and D-shape) for Type 3 and 4 wind turbines**

In addition, the modern Type 3 and 4 WTGs can respond very quickly and inject reactive current within a few cycles after fault inception because the response is primarily driven by power electronics [9]. Many international grid codes have specific requirements on the level and amount of reactive power injections during and following transmission faults. For system stability and voltage regulation, the most important factor is post-fault recovery. In weak regions of the grid, current injection during a fault may also be important for protection equipment to function correctly. In either case, because Type 3 and 4 WTGs are not inherently a source of short-circuit current and the current injection during faults is tightly controlled, this can present a challenge for system protection (i.e., sensing and clearing faults in regions dominated by these types of WTGs) [9].

### *2.3.3 WTG Power Plant-Level Control Strategy*

The wind power plants with Type 3 and type 4 WTGs typically have a plant-level control strategy that coordinates with individual WTG controls to ensure satisfactory operation of the entire fleet of WTGs. A functional depiction of plant-level control strategy is illustrated in Figure 2-12 [10, 16]. The plant-level control generally uses a voltage and/or MW and/or MVAR reference and distributes active and reactive power setpoints to all individual WTGs. Each WTG adheres to these setpoints by deploying its own speed and power controls—such as the pitch control the inverter P/Q controls—to align with the plant-level control requirement. This coordination between the plant-level control and the individual WTG controls ensures satisfactory plant-level performance from voltage and frequency viewpoints.

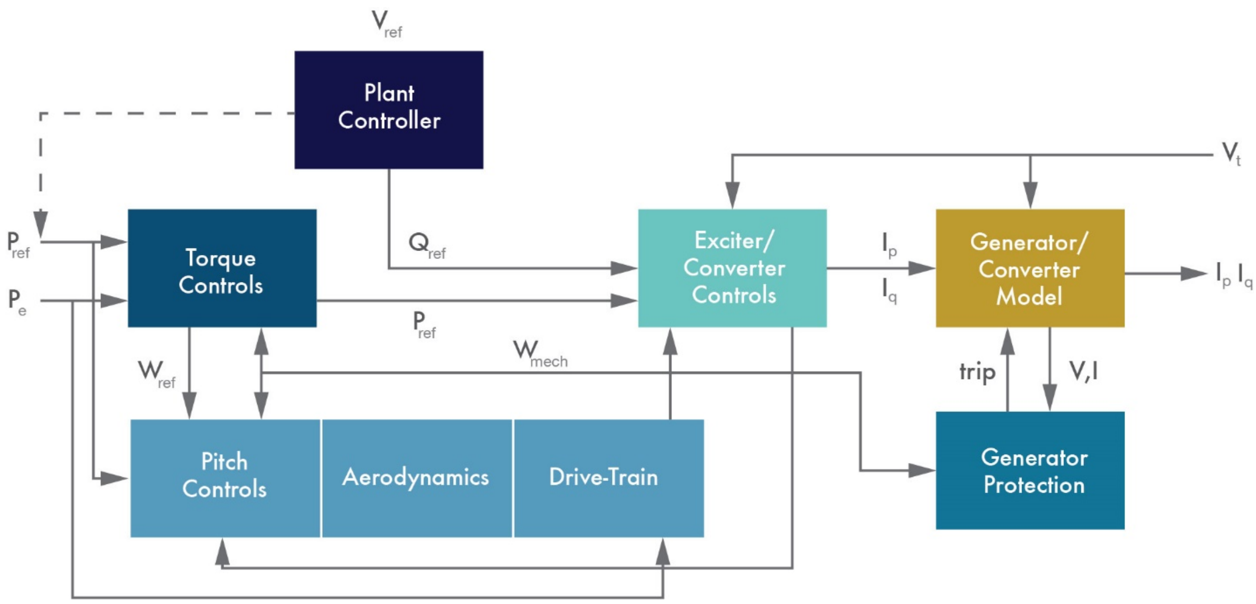


**Figure 2-12**
**A typical wind power plant-level control strategy**

### *2.3.4 Solar PV Active Power (Frequency) Control [9]*

PV systems offer an avenue for aiding in frequency regulation. At any point, the active power output of an array can be "curtailed" by appropriate action at the inverter, in combination with the maximum power point tracking (MPPT) system [9]. As shown in Figure 2-13, instead of selecting the optimal DC voltage suggested by the MPPT algorithm marked "Maximum," the inverter can select another DC voltage that produces a smaller area under the curve (marked "Curtailed") and thus lower or curtail power [9]. By curtailing its output power, PV systems can reduce their contributions to over-frequency events on the bulk system. For under-frequency events, PV systems can increase their output by moving the operating point to the one suggested by the MPPT algorithm [9].

With such capabilities, the focus should be on the overall frequency response capability of the PV plant, rather than on inertial and primary frequency responses. In general, these power electronic based devices can provide frequency response much more quickly than conventional fossil fuel power plants because the action is based on power electronic controls [9].

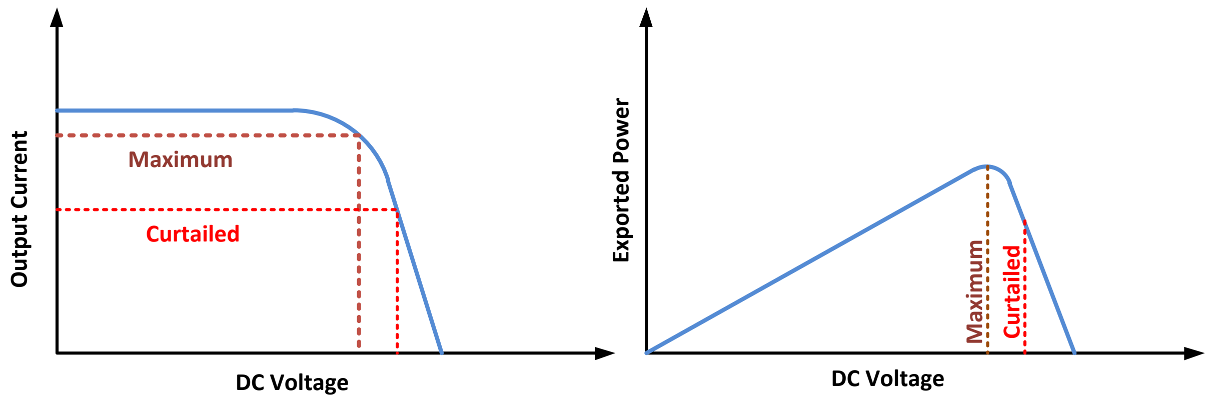


**Figure 2-13**
**An example of a PV power curve**

### *2.3.5 Solar PV Reactive Power (Voltage) Control [9]*

A utility-scale PV system, through inverter controls, can provide reactive support at any active power output level [9]. The reactive power output could be higher at low active power output levels, depending on inverter current limits and terminal voltage. PV inverters are typically designed to operate at 0.9 to 1.1 per unit of the rated terminal voltage. These voltage limits affect their available reactive capability. For nominal voltages, the PV inverters can provide reactive capability similar to wind plants. In fact, it is feasible to design a PV inverter to provide reactive support, even if the solar irradiance is zero [9].

Typically, a plant-level reactive power controller manages the reactive power output of individual inverters to meet operating requirements at the point of interconnection [9]. Different control modes, such as closed loop-voltage control, voltage droop control, power factor control, and reactive power control, are possible. For example, if the interconnection requirement is to maintain a power factor between 0.95 leading to lagging at the point of interconnection (POI), the PV inverters can operate in power factor control mode to meet the requirement [9].

### *2.3.6 VER Disturbance Ride-Through Capability*

The generation integrated into the bulk power system must continue to remain connected under disturbance conditions and must not trip prematurely. This requirement is imposed by many regulatory entities, in order to ensure that the generation continues to support the system even under disturbance conditions, in order to maintain system reliability. An example of such requirement is the NERC Standard PRC-024-2, *Generator Frequency and Voltage Protective Relay Settings* [19]. As VER penetration into the BPS increases, to maintain BPS reliability, it is essential for VERs to have voltage and frequency ride-through capabilities. Early-generation VERs did not have such ride-through capabilities because they were largely connected to distribution systems and were expected to disconnect themselves under disturbance scenarios. However, the smart inverters of modern VERs connected to the BPS are equipped with such capabilities and are capable of riding through voltage and frequency excursions, as often required by interconnection agreements.

## 2.4 Unique Characteristics of VERs

An increased penetration of VERs creates challenges for system operators and planners due to the unique characteristics of VER technologies and fuel sources, as described below.

### *2.4.1 Variability [20]*

Because the fuel sources of VERs—i.e., wind speed and solar irradiance—vary with time, wind and solar generation constantly varies with time. Figure 2-14 presents one-day output of a 250-MW wind power plant. The output continues to vary throughout the day between zero and close to its capacity. To accommodate such short-term variability, other system resources must ramp up and down and may need to change their commitment status instantly and often. If adequate system ramping capability is not available, the system could be at reliability risk due to potential for energy imbalance and frequency drift scenarios.

Note that system ramping needs are not based on variability of a single VER but are based on resultant variability from all VERs across the footprint, combined with daily load variation, as discussed later in Section 2.5.3. Also, as the footprint covered by the installed VERs increases, the resultant variability decreases because of lack of correlation among variabilities of the VERs within the footprint.

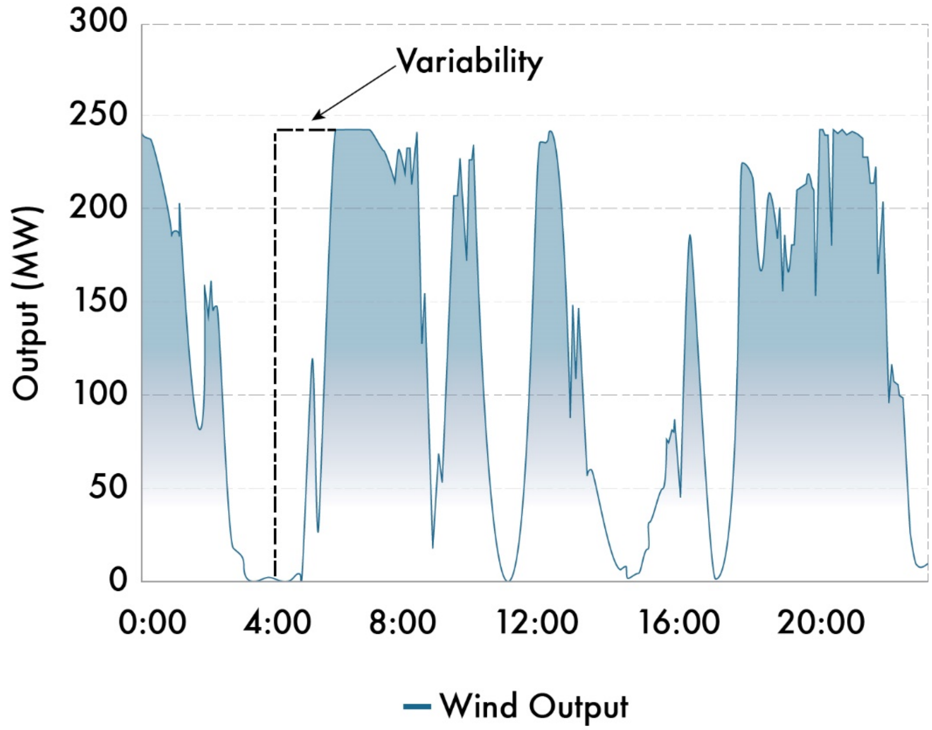


**Figure 2-14**
**Variability of a 250-MW wind power plant over a 24-hour period**

### *2.4.2 Uncertainty [20]*

Because wind speed and solar irradiance cannot be predicted accurately, wind and solar generation can also be not predicted or forecasted accurately. Figure 2-15 shows a 24-hour profile of a solar power plant, including actual power output and day-ahead forecasted output. While the day-ahead forecast called for a clear sky, the day turned out to be partly cloudy. This resulted in significant differences, in terms of magnitude and volatility, between the forecasted and actual plant output levels, as exemplified by the dotted vertical line. (Note that when such individual VER uncertainty is combined with uncertainties associated with other generation sources and with the daily load cycle, the resultant uncertainty will be different.) Such an uncertainty can lead to a mismatch between the needed versus the available generation resources because the system resources are typically scheduled in advance based on forecasts. The mismatch can produce energy imbalance and frequency drifts, which could potentially pose a reliability risk. Addressing the mismatch during real-time operations could be challenging because some thermal plants require advance notice (of hours or even days) to commit to be online and produce power. Also, addressing the mismatch would likely require going off the economic generation dispatch, which could lead to inefficiency.

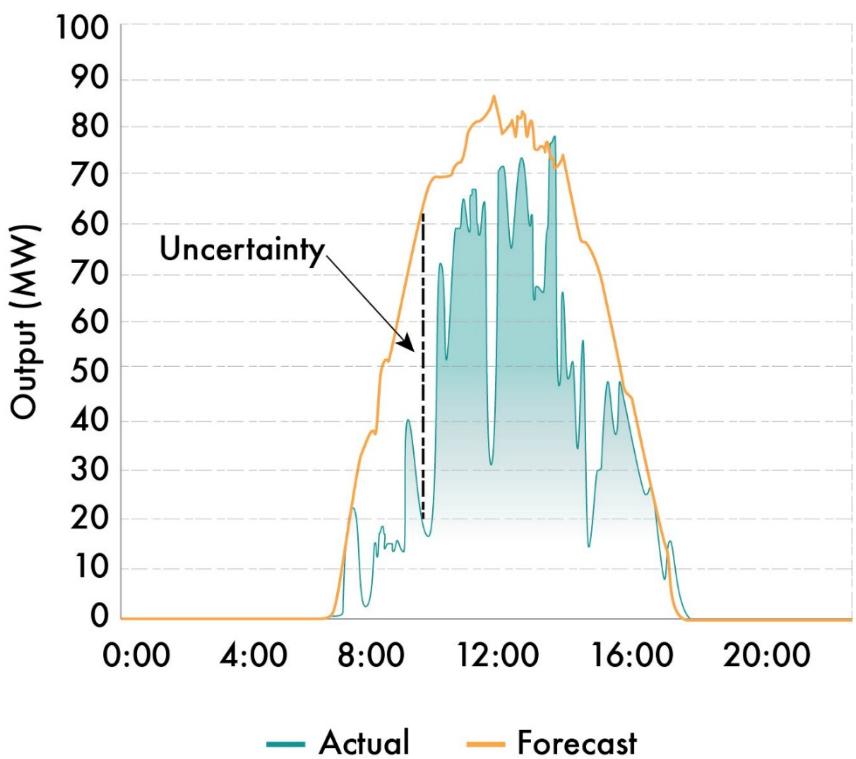


**Figure 2-15**
**Uncertainty of a solar power plant over a 24-hour period**

Generally, the longer the forecasting period, the higher the uncertainty. Thus, uncertainty for day-ahead forecast is greater than that for the hour-ahead forecast. In general, as the footprint covered by the installed VERs increases, the resultant uncertainty decreases because of lack of correlation among uncertainties of the VERs within the footprint.

## 2.5 VER Integration into the Bulk Power System (BPS): Challenges and Industry Response

VER integration poses challenges in short-term operations and in long-term planning horizons. Therefore, solutions in both time horizons are essential. A summary of specific challenges and industry efforts is provided below.

### *2.5.1 Geographic Diversity and Footprint*

Geographic diversity, where VERs are spread out across a large geographic area as compared to a concentrated area, helps reduce the negative impact of variability [21]. Also, the wider the footprint of a balancing authority area, the lower the negative impact of variability and uncertainty associated with VERs. This has led to increased balancing area sizes, as well as increasing coordination between balancing areas. The Energy Imbalance Market in the Western Interconnection operated by California ISO, where a large number of western utilities now pool balancing resources in real time (but not yet day ahead), is a good example of a recent market development in this area.

### *2.5.2 Ramping*

To offset the variability of VERs, sufficient ramping is needed from other resources over multiple hours. The ramping need can be identified by calculating net load, equal to total load minus VER, which represents the net effect of variabilities of all VERs as well as the variability of load. Figure 2-16 illustrates such a net load curve, also known as the CAISO duck curve [22], in which VER is predominantly solar power. It is evident that as solar generation penetration increases from 2012 to 2020, the ramping needs also grow.

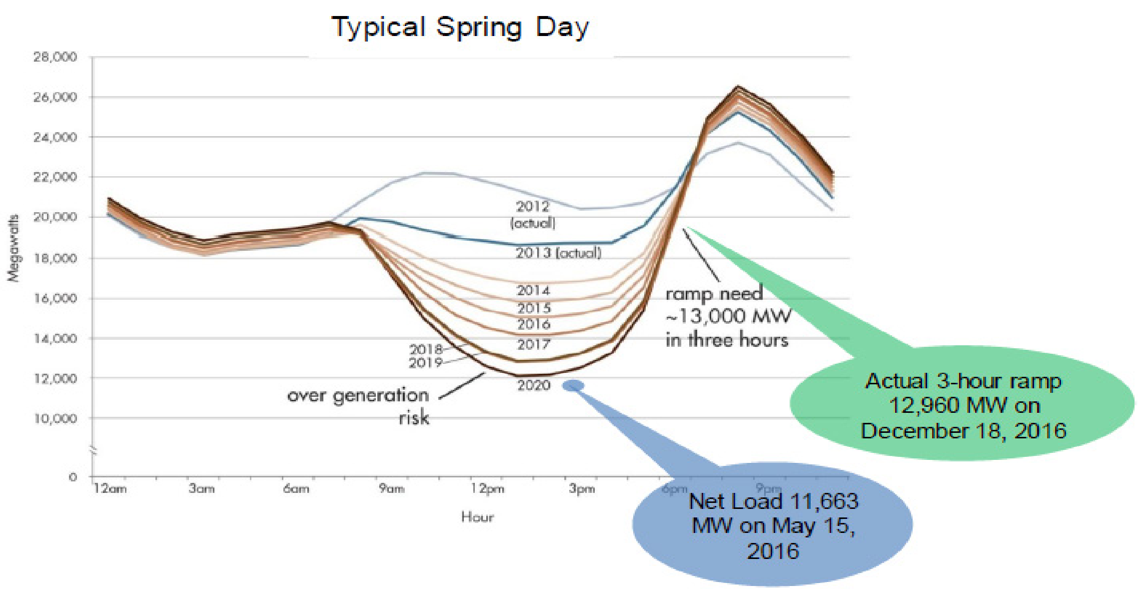


**Figure 2-16**
**Net load or duck curve from CAISO**

Figure 2-16 also indicates the challenge of managing low demand periods of the day in an area with high solar generation penetration. The traditional generation would need to be curtailed, while maintaining enough flexibility (i.e., reserves) of supply- and demand-side resources, in order to ensure adequate ramping capability and energy balance requirements.

As discussed previously, both wind and solar power can provide flexibility to manage issues associated with ramping by enabling active power controls. For example, most United States ISOs/RTOs now have the ability to dispatch wind (and increasingly, bulk system connected solar) in their real-time markets. This can be used to relive transmission congestion or help system balancing by providing price signals to wind plants to dispatch down. This is an important source of flexibility for managing the variability and uncertainty. However, it also results in loss of zero marginal cost generation, and may make it more challenging to meet renewable policy targets.

### 2.5.3 Flexibility

Flexibility is the key to successful integration of VERs into the BPS [23]. Larger penetration of VERs will require steeper ramping requirements from dispatchable generators and demand response resources, lower minimum operating levels of traditional generation resources, and higher levels of generation reserves. In addition to this physical flexibility, process flexibility must exist in real-time operational processes for scheduling and dispatching of these resources in sub-hour timeframe. To facilitate such flexibility, efforts are underway to revamp ancillary services with the objectives to quantify the amount of flexibility needed, to locate the specific generation and load resources available to provide the flexibility and to remunerate the flexible resources for providing these services [20].

### 2.5.4 VER Forecasting

VER forecasting, where in-house meteorology experts or external forecasting companies provide system operators with a prediction of VER output using meteorological information and statistical techniques, can reduce the uncertainty associated with VERs [24]. VER forecasting is especially important for the day-ahead, hour-ahead, and minutes-ahead timeframes, in order to allocate, dispatch, and schedule non-VER resources to address potential negative impacts of VER variability and uncertainty. Significant improvements have been seen in the past decade, with errors on the order of 5% or less of capacity now typically seen for many balancing areas.

### 2.5.5 Voltage/Frequency Support and Disturbance Ride-Through Capabilities

During early years of VER integration, the need for VERs to have voltage and frequency support capabilities was recognized. As described in Section 2.3, voltage and frequency support capabilities can now be integrated within Type 3 and 4 WTGs and solar PV devices. It should be noted that for utility-scale VERs to be integrated into the BPS, voltage and frequency support requirements imposed by transmission entities are becoming increasingly common.

As discussed in Section 2.3.6, another early concern was the inability of VERs to ride through disturbances, which was investigated by the NERC Integration of Variable Generation Task Force [25]. Type 3 and 4 WTG and solar PV equipment are capable of riding through voltage and frequency disturbances. Also, VER disturbance ride-through has been included in interconnection requirements by transmission entities.

### 2.5.6 Transmission Planning Considerations

Wind generation is generally located remotely from load centers, often requiring transmission buildout to transmit the wind generation to load centers and to avoid area transmission overloading. Solar PV plants are generally located close to load centers, while concentrated solar generation plants may need transmission buildouts due to the likelihood of their remote locations. Additionally, VERs may be located in a weak portion of the system, characterized by scant transmission network and few synchronous generation resources. Such an integration may require special attention to investigating potential concerns for voltage stability and control interaction issues [10, 26]. This emphasizes the need for a thorough transmission planning process, taking into consideration all integration issues discussed above.

### 2.5.7 VER Modeling

Transmission planning studies for integrating VERs require modeling to represent VER equipment's behavior under steady-state and dynamics conditions. Industry efforts have been underway to develop VER models that are standard (i.e., a defined model structure used by all commercial software tools), generic (i.e., not specific to any particular design), and publicly available [7, 8, 12]. To keep pace with evolving VER technologies, VER models for system dynamics studies have evolved over time through cooperative efforts among VER equipment vendors, software vendors, NERC, WECC, U.S. National Labs, IEC, IEEE, CIGRE, and R&D organizations such as EPRI. Generic/standard VER stability models are available in commercial software tools such as GE PSLF® and Siemens PTI PSS®E. These generic models are suitable for use in screening studies (also referred to as *feasibility studies* sometimes) performed to assess the impact of accommodating VERs and to address any negative consequences on BPS. However, vendor-supplied customized models are more suitable for interconnection studies of a specific VER project and for operational planning studies.

### 2.5.8 Evolution of Ancillary Services

To address VER variability and uncertainty, the industry has been reviewing and revising their generation dispatch and scheduling processes. This has led many transmission operations organizations to adjust the ways to define, procure, and compensate for ancillary services. This revamping of ancillary services has the underlying goals of maintaining power system reliability and efficiency, while providing incentives for market participants to provide the services [20]. The scope of these global efforts includes splitting some of the existing services to redefine the existing ancillary services set and adding new services. In some cases, the existing services are renamed and rebranded to align with the evolving dispatching, scheduling, and ramping needs. A few examples of the types of ancillary services being proposed, but not necessarily implemented, are as follows:

- Short-term flexible ramping product, defined as rampable capacity reserved within the real-time dispatch interval that can be used at a subsequent dispatch interval when ramping is needed.
- Synchronous Inertia defined as the response that is immediately available from synchronous generators, synchronous condensers, and some synchronous demand loads (when synchronized) because of the nature of synchronous machines.
- Redefined regulating reserves, with emphasis to increase the reserves to address VER variability and uncertainty as well as a focus on rewarding those resources that can respond quickly and accurately to regulation signals.

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# 3 DISTRIBUTED ENERGY RESOURCES

Distributed energy resources (DERs) are the relatively small-scale energy sources connected to the distribution system. Literature defines DERs broadly to comprise supply-side and demand-side resources such as solar and wind generation, combined heat and power facilities, demand response, electric vehicles, energy storage, and end-use efficiency programs [1, 2, 3, 4]. The resource size could range from tens/hundreds of watts to tens of MWs, with the upper range determined by the distribution system's ability to support the resource [3]. Rapidly expanding DER deployment has led to increased interactions among the customers, the distribution system, and the transmission system. There is growing likelihood that significant amounts of load may be supplied locally. Power flow patterns may be different from the traditional patterns anticipated by bulk power system operators [2, 5]. Thus, the increasing DER penetration has prompted an attention to its potential impact on the bulk power system (BPS). This chapter provides an overview of DERs and discusses potential challenges and opportunities posed by DERs on operational aspects of the BPS. Some of these challenges, particularly related to distributed wind and solar generation, can be similar to those described for VERs in the previous chapter.

## 3.1 Distributed Energy Resources

Various resources classified in the literature as DERs are as follows [1, 2, 3, 4]:

- Distributed generation connected to distribution system: Solar PV, wind, fuel cells, combined heat-and-power (CHP), and natural gas-fired micro-turbines.
- End-use energy efficiency: Permanent load reduction due to end-use efficiency improvements such as through implementation of LED lighting programs.
- Demand response: Temporary load reduction under capacity-constrained conditions such as through interruptible load programs.
- Energy storage: Distribution-level or customer-side energy storage, including batteries and thermal energy storage.
- Flexible loads: Temporary load increases or decreases under flexibility-constrained conditions such as electric vehicle charging during times of high solar PV generation.

There are three types of DERs, based on how they are connected [6]:

1. Transmission connected resources: They are connected directly to the transmission systems through step-up transformers.
2. Utility-scale DERs: This is a term defined by NERC, which refers to DERs connected to a distribution substation either at the substation itself or through a dedicated feeder.
3. Retail-scale DERs: This is again a term defined by NERC, which refers to behind-the-meter DER, which will be at the customer location (rooftop PVs for example).

This chapter focuses on #2 and #3, while Chapter 2 focuses on #1.

A large portion of DERs consists of commercial and residential solar PV installations. Figure 3-1 shows the expected growth in solar generation around the world and across the United States. By

2019, the commercial and residential solar PV installations could reach 250 GW globally and 28 GW in the United States.

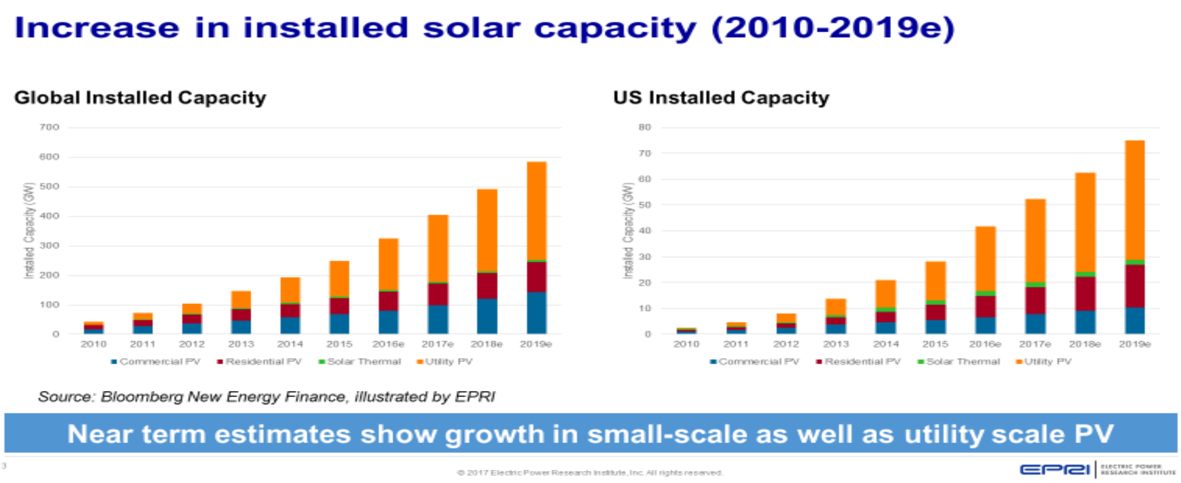


**Figure 3-1**
**Solar generation capacity 2010–2019**

## 3.2 Impact of DERs on the Bulk Power System

During an early stage of DER growth through the 2000s, DER impact was largely confined to the distribution system. DERs were required to be disconnected during abnormal conditions. In recent years, however, the DER penetration has been increasing, thus requiring an attention to the DER impact on the BPS.

An overall impact on the BPS of supply-side DERs, especially solar PV, is described below. Table 3-1 summarizes DER impact on BPS planning and operations [7].

**Table 3-1**
**Summary of potential impact of DERs on bulk power system**

## Characteristics of DER that Impact Ops & Planning

| DER Characteristic | Potential Benefits | Potential Challenges |
|---|---|---|
| Point of Interconnection | • T&D deferral<br>• Congestion & losses<br>• Supply capacity | • Protection<br>• Voltage regulation<br>• Disturbance ride-thru<br>• Utility rates/revenues |
| Visibility & Control | | • Ops awareness/control<br>• Power flow mgmt.<br>• Balancing |
| Inverter Interface | • Voltage & Frequency | • Protection<br>• Voltage & Frequency<br>• Power Quality |
| Variability & Uncertainty | | • Voltage & Frequency<br>• Other resource O&M<br>• Reserves & Flexibility |
| Emissions & Fuel Costs | • Low fuel costs<br>• Low emissions | |

**Not all Benefits & Challenges apply equally to all DER resource types**



- Deferral/congestion/losses [1, 7]: DERs serve local load, and therefore could reduce burden on the T&D infrastructure. This can potentially reduce congestion and losses on T&D facilities. DERs also may help in potentially deferring distribution, generation, and transmission investments in the short term.
- Protection [8,9,10]: With increased penetration of DERs, it may be necessary to evaluate the impact of DERs on protection performance requirements. However, DER data required for such evaluation may be limited. Also, increasing levels of inverter-based solar and wind generation have the effect of decreasing short-circuit current levels, thus making it difficult to detect and clear faults.
- Ride-through capability [8, 9, 10]: To maintain reliability of the BPS, the NERC PRC-024-2 standard defines requirements so that generators can remain connected during frequency and voltage excursions [11]. An EPRI investigation concluded that high penetration of distributed PV without low voltage ride-through capability can impact BPS voltage performance [10]. The impact is exacerbated when the potential for air conditioning (A/C) stalling is coupled with the distributed PV drop out [10]. Therefore, as DER penetration increases, to maintain BPS reliability, it is essential for DERs to have voltage and frequency ride-through capabilities. Accordingly, IEEE standard 1547 is being revised to require DERs to have ride-through capabilities [12].

Early-generation DERs did not have such ride-through capabilities because they were connected to distribution systems with insignificant impact on the BPS and were expected to disconnect themselves under disturbance scenarios. However, the smart inverters of modern solar and wind generation devices are equipped with the ride-through capabilities, as discussed in Section 2.3.6.

Thus, smart inverter-based DERs are capable of riding through voltage and frequency excursions.

- Observability/control [5, 8, 9]: Telemetering, aggregation, and scheduling/dispatching of certain DERs (e.g. roof-top solar PVs) may be difficult or even infeasible. Accurately quantifying the load to be served by the transmission system in an area with high penetration of DERs could be quite challenging. For example, the local load served by solar PV varies over a daily cycle due to the variability associated with solar PV generation. Therefore, BPS operators are unlikely to have an ability to monitor and control the DERs. This would become a critical issue when DER penetration increases and adversely impacts BPS operation. For example, if DER operation causes an overloading of a BPS facility, the BPS operator would need a way to identify the specific DER causing the overloading and operate that DER to relieve the overloading.
- Ramping [8, 9, 10]: Figure 3-2 shows the daily *net* load (i.e., the total load minus solar PV generation) curve for an illustrative scenario of sizable distribution-connected solar PV. (Note: This figure is similar to Figure 2-16 described in Chapter 2.) During morning hours, as solar PV generation picks up, the remaining conventional generation will require downward ramping capability. On the other hand, during afternoon hours, the traditional generation will require quick upward ramping capability to make up for the loss of solar generation. Thus, BPS operators will need traditional generation resources or demand response resources that can provide the needed ramping capabilities.

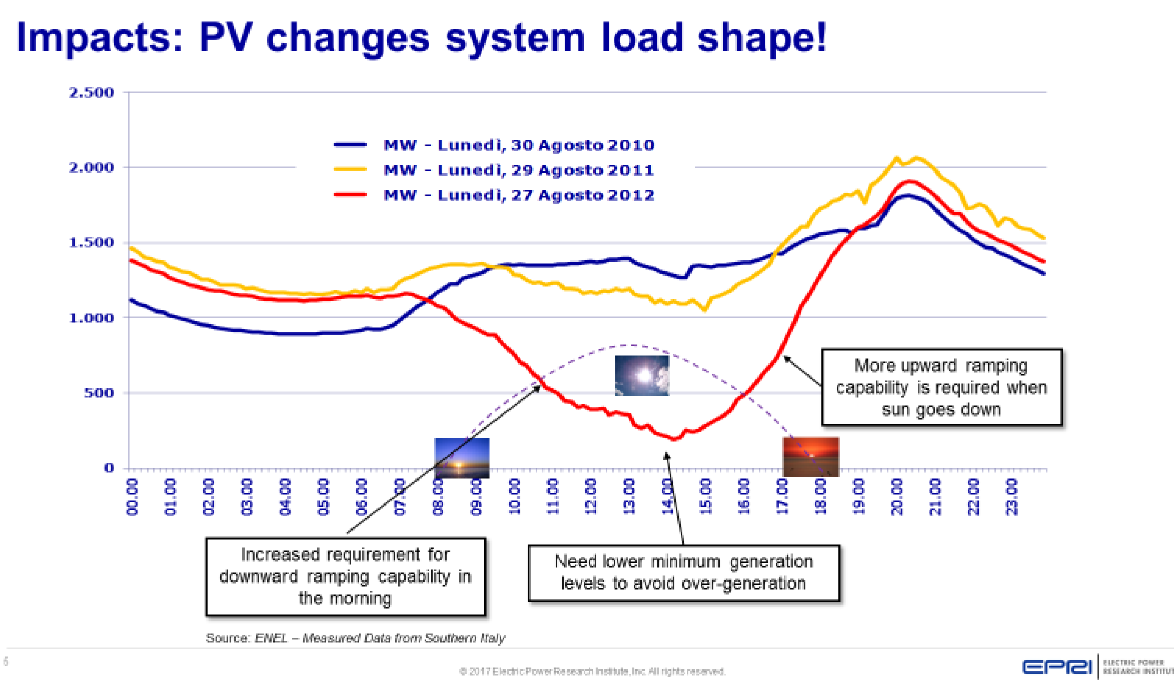


**Figure 3-2**
**Daily net load curve with solar generation**

- Reserves and flexibility [5, 8, 9, 10]: A high level of DER penetration would necessitate ramping requirements (as discussed above) from dispatchable generators and demand response resources, as well as lower minimum operating levels of traditional generation resources, and higher levels of generation reserves. As explained in Section 2.5.3, process flexibility must exist in real-time operational processes for scheduling and dispatching of these resources in sub-hour timeframe for energy-balancing purposes. To facilitate such flexibility, efforts are underway to revamp ancillary services with the objectives to quantify the amount of flexibility needed, to locate the specific generation and load resources available to provide the flexibility, and to remunerate these flexible resources for providing these services. The challenge will be to quantify the DERs that can be potentially used for balancing because some may be serving local load and may not be available for balancing purpose. Also, some DERs may not be visible to the operator and may not controllable by the operator. It can also become significantly more challenging to forecast the net load because production from DERs and DER relationship to load become more challenging to predict.

- Frequency and voltage support [5, 8, 9, 10]: With high level of DER penetration, DERs will need to have frequency and voltage support capabilities, in order to maintain BPS reliability. As discussed in Sections 2.3.4 and 2.3.5, the modern inverter-based solar PV installations inherently possess active power and reactive power capabilities to provide quick support during under-frequency and over-frequency conditions as well as during overvoltage and undervoltage conditions. However, these DER active and reactive power controls will have to be made available for BPS purpose, and they must be coordinated with the corresponding BPS-level controls so that they work together and not fight.
- Under-frequency load shedding (UFLS) and undervoltage load shedding (UVLS) schemes [8, 9, 10]: It likely that the design of these two schemes did not consider the implications of DER operation. Each scheme is designed to shed specific nominal amounts of loads connected to distribution feeders. If a particular load to be shed is served by a local DER, the amount of load actually shed during a UFLS or UVLS operation will be the net load, i.e. the nominal load designed to be shed minus the DER amount. This net load amount varies over a daily load cycle, as shown in Figure 3-2. Such scenarios could cause unexpected amount of load shedding as seen by the transmission system, which could create operational complications during an under-frequency or undervoltage condition.

Figure 3-3 provides another perspective on potential impact of DERs on the BPS [7]. As more and more DERs are added to the grid, DER impacts extend beyond the customer to the distribution feeder and eventually to the bulk power system. These impacts could be both positive (shown on the left) and negative (shown on the right).

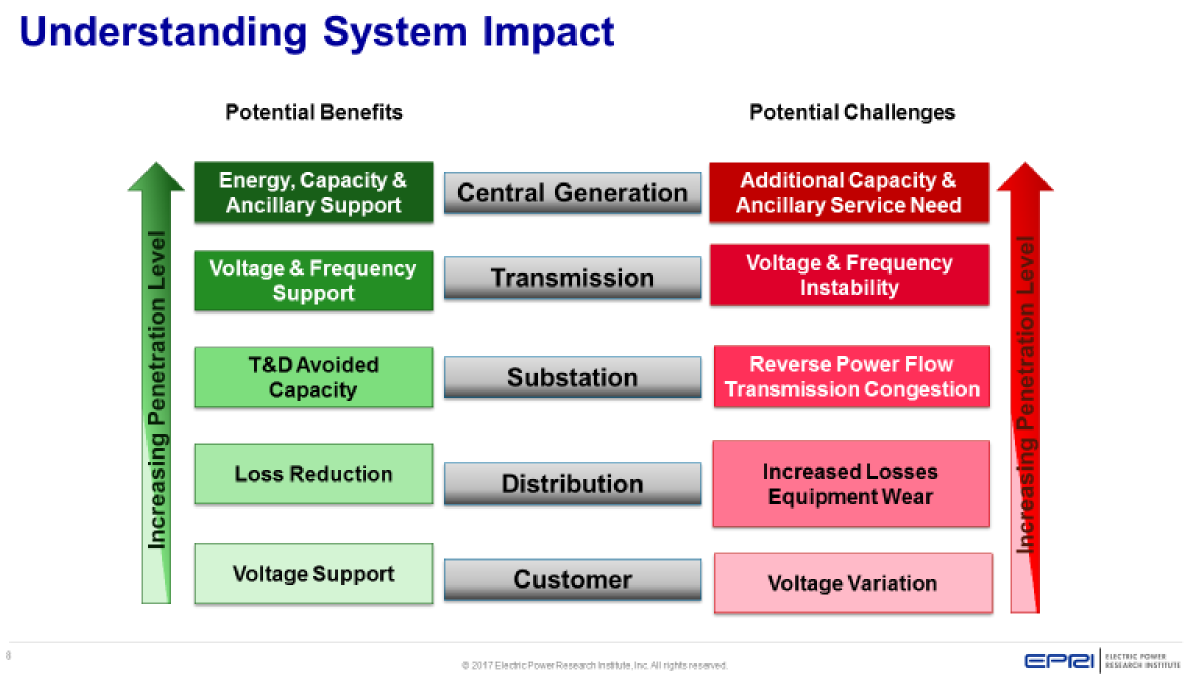


**Figure 3-3**
**DER impacts on the bulk power system**

DER benefits across the entire customer-central generation spectrum can be as follows:

- Small amounts of DER could provide voltage support at the customer.
- Small amounts of DER could reduce losses on the distribution system.
- Small amounts of DER could provide frequency support with the right kind of storage.
- The right types of DER, such as PV coupled with properly controlled storage, could help to defer or avoid substation upgrades.
- Significant amounts of DER could even defer the construction of a new central generating unit or a new distribution or transmission circuit.

On the other hand, if DERs are not properly integrated, there could be negative ramifications, as follows:

- Local voltage issues.
- Issues with reverse power flow at the substation.
- Voltage and frequency issues leading to additional generation or ancillary service cost.

This underscores the need for integrated resource planning, including comprehensive simulation studies, when evaluating the integration and impact of DERs on the BPS.

## 3.3 DER-Related Challenges and Opportunities for the Bulk Power System

### *3.3.1 Integrated Resource Planning*

It is essential to learn from the experience of various roles played by DERs in the realm of BPS operations. This will help in ensuring that DERs are supporting, as opposed to disrupting, the

BPS operation. This learning will help in incorporating DERs as potential sources of energy, capacity, and ancillary services in the integrated resources planning activities across the generation-transmission-distribution spectrum. Such broad supply-demand spectrum planning could make it possible to consider a variety of options to meet energy, capacity, and ancillary services needs more efficiently and effectively, even when facing large uncertainties.

Identifying desirable DER locations across a distribution system can be a helpful step in the integrated resource planning process. In this regard, EPRI's Distribution Resource Integration and Value Estimation (DRIVE) screening tool can be utilized to estimate the DER hosting capacity feeder-by-feeder across an entire distribution system [13].

### *3.3.2 Data/Information Sharing [2, 14]*

As evident from above discussion, the increasing levels of DERs can alter the role played by DERs in distribution system operations as well as in BPS operations. This will necessitate close coordination and information/data sharing between transmission and distribution interfaces for the existing and planned DERs. An example is the sharing of DER modeling data required for transmission planning and operations studies.

### *3.3.3 Forecasting [1, 2, 8, 9]*

Conducting future resource planning in an integrated manner will require accurate DER forecasts and advanced forecast methods. DER forecasting for long range planning will need to consider a diverse set of issues such as consumer preferences and adoption, technology cost projections, regulatory policies on tax incentives and renewable mandates, utility rate structures and business models, to name just a few. Ongoing research efforts by EPRI and others are focused on investigating, understanding and postulating these issues, with the goal to improve the existing DER forecasting tools. In real-time operations, less than desirable certainty for DER forecasting may lead to requiring allocation of more reserves for ramping and flexibility, compared to the reserves needed in response to utility-scale variable-energy resources.

DER forecasting could potentially be improved by increased monitoring of DERs and using the monitored information in forecast models with respect to underlying drivers of variability of DERs and loads. While forecasting of individual DERs at the micro level (e.g. roof-top PVs) may be infeasible, a reasonable forecasting at macro level can help the integrated planning process. This can be accomplished, for example, by sampling subsets of existing DERs and then upscaling them or by deploying sensors at DER locations and then projecting their output.

Because DERs serve local load, DER forecasting must be accompanied by the corresponding impact on load forecasting. The load forecast must take into consideration the variability of DERs, specifically solar PV, as demonstrated in Figure 3-2.

### *3.3.4 Coordinated Active and Reactive Power Controls*

DER active and reactive power controls will have to be made available to support voltage and frequency performance at the BPS level. These controls must be coordinated with the corresponding BPS-level controls so that they work together and not fight. A coordinated effort between distribution and transmission entities will be needed to determine the use of DER capabilities being proposed under revised IEEE 1547 standard [2, 12].

Active voltage control on a feeder could significantly reduce the risk of fault-induced delayed voltage recovery (FIDVR) events caused by stalling of single-phase residential air conditioners (A/Cs) due to a fault. (FIDVR phenomenon could be severe in systems with large amounts of A/Cs.) By reducing net load on the feeder and providing voltage support, the impact of FIDVR events on distribution and BPS voltage levels can be mitigated [2, 15].

### *3.3.5 DER Monitoring and Control*

Visibility, observability, and control of all or a portion of DERs to BPS operators—through aggregation, telemetering, and two-way communication—can allow BPS operators to schedule, dispatch, or curtail DERs [16]. This can help in mitigating any adverse impact of DERs on BPS such as to relieve transmission congestion by curtailing DERs. It can also help in utilizing DERs in wholesale energy and ancillary services markets to aid BPS markets and operations for market efficiency, energy balancing, operating/contingency reserves, and mitigating ramping concerns, among others [2,16]. DERs are currently being considered in BPS markets and operations by Germany, PJM, NYISO, CAISO, and Hawaii [16].

### *3.3.6 New Simulation Modeling Paradigm*

For BPS performance assessment, a classical transmission model of distribution load (i.e., netted generation and load) is not valid. The unique characteristics of DERs must be modeled separately using a modular approach to capture the DER characteristics appropriate for the system performance phenomenon or scope being assessed (e.g. steady-state or transient stability or voltage stability) [2]. In DER modeling, it is critical to capture the following interactions: 1) DER interaction with local load (e.g. motors) that may cause FIDVR and 2) DER interaction with a distribution feeder [17]. The distribution circuit, along with the load and DER, should be explicitly modeled in the power flow case for systems with significant DER penetration with respect to load [14]. The smart inverter-based DERs must be modeled in detail and must be utilized as BPS resources to maintain satisfactory power system performance.

### *3.3.7 System Restoration [5, 8, 9, 10]*

When developing a restoration plan, the impact of DERs on power system restoration must be investigated and incorporated. For example, non-controllable DERs may get automatically connected during restoration, the desirability of which must be investigated.

### *3.3.8 Standards and Requirements*

Regulatory and technical bodies have taken a proactive role in understanding the potential impact of high DER penetration on the bulk power system and setting related standards and requirements.

#### 3.3.8.1 DER Requirements in European Codes

A summary of DER-related European codes is provided in Figure 3-4 [7, 18]. As indicated by the x-axis (Time), these codes were first introduced for resources connected to the transmission system and were then transitioned to the resources connected at sub-transmission and distribution levels. All four requirements—starting from Steady-state voltage support to Dynamic grid/voltage support—address some of the potential adverse impacts and opportunities of DERs on the bulk power system, as discussed in Section 3.2.

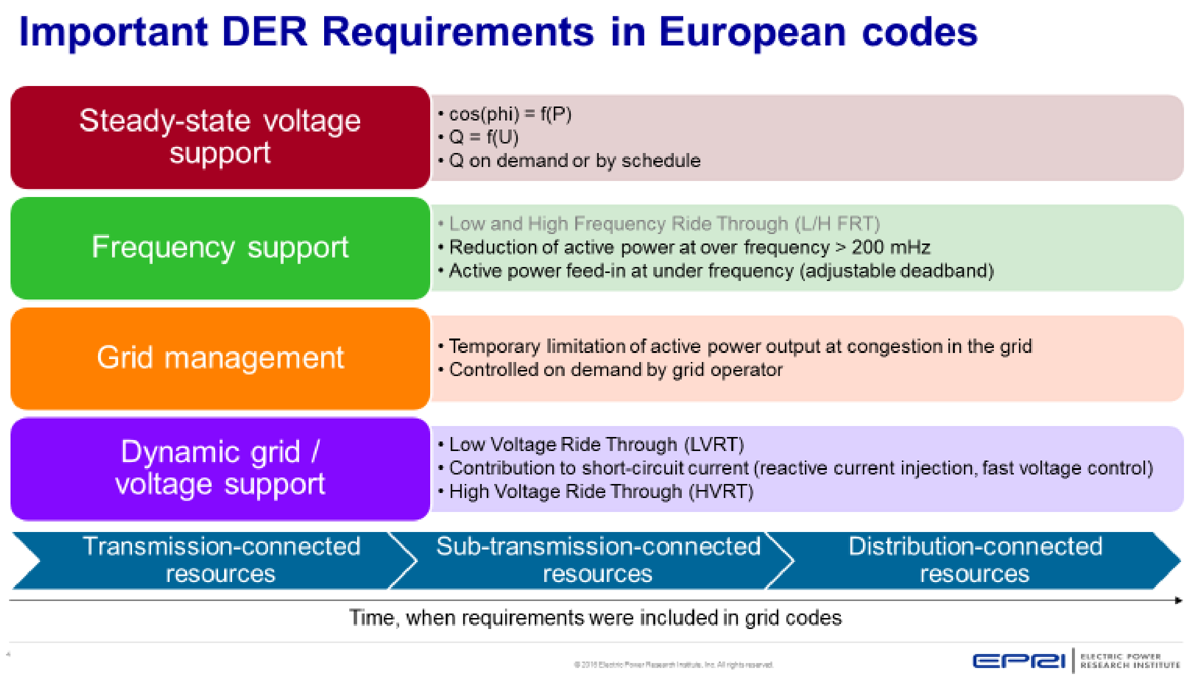


**Figure 3-4**
**DER requirements in European codes**

### 3.3.8.2 IEEE 1547 Interconnection Standard for DERs [12]

This voluntary standard was originally developed in 2003, when DER penetration into the distribution system was relatively low but was beginning to ramp up. For the past few years, extensive efforts are underway to revise 1547 to address the impact of increasing levels of DERs on the bulk power system. Figure 3-5 provides the context for these 1547 revision efforts.

- The objective is to specify and harmonize interconnection requirements for distributed energy resources.
- IEEE Std 1547 is a voluntary industry standard; Authorities Governing Interconnection Requirements (AGIR) may adopt it in legislation. CA Rule 21 may refer to IEEE 1547 in the future.
- Individual utility generator connection agreements may refer to safety standards such as UL 1741, which in turn may refer to IEEE 1547 in the future.
- Federal and state interconnection procedures may give privilege (fast track) to IEEE 1547-compliant/tested DER applications.
- The revised IEEE Std 1547 is aligned with NERC and FERC bulk system reliability standards.

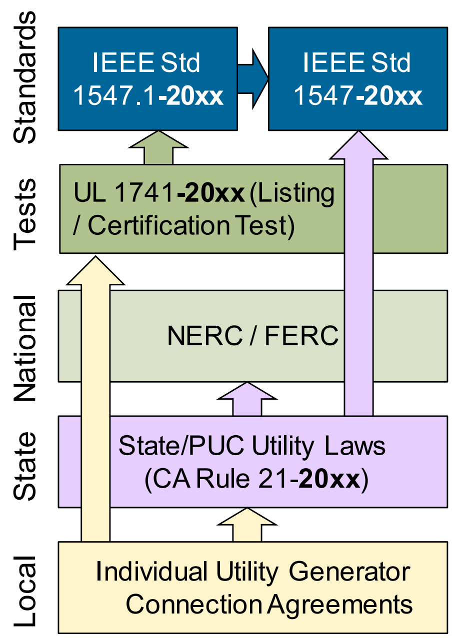


**Figure 3-5**
**Efforts to revise IEEE 1547 interconnection standards for DERs**

As shown in Figure 3-6, the revision effort focuses on four elements. First, it expands the scope of the IEEE 1547 standard by considering distribution system issues as well as bulk system aspects such as ride-through requirements. As mentioned earlier, ride-through requirements are essential to prevent widespread voltage or frequency tripping of DERs that can negatively impact bulk system reliability for a high DER penetration scenario. Second, the revision extends the requirements from the interconnection system to the whole DER, which means, for example, that DER auxiliary equipment will have to be capable of withstanding the specified voltage and frequency disturbances. Third, the revised standard will apply to the individual DER equipment as well as to all DERs aggregated at a plant-level. Finally, the revision specifies a mandatory, standardized and open DER communication interface, in addition to the electrical performance of the DER at its electrical connection point. Once communications networks are deployed, utilities or aggregators can communicate with this interface to monitor, control, and exchange information with DER.

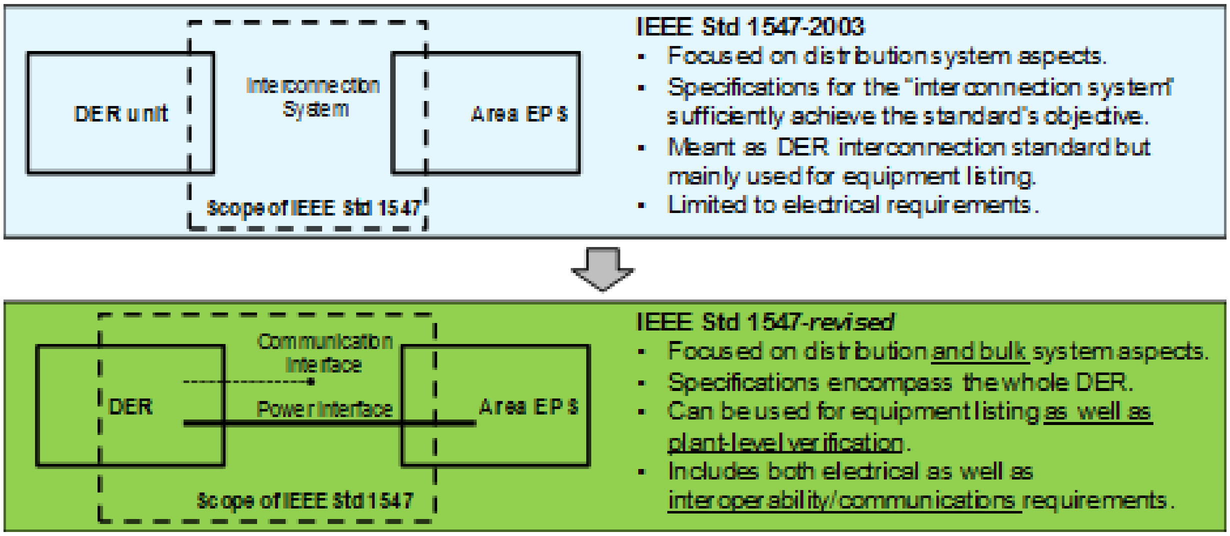


**Figure 3-6**
**Scope of IEEE 1547 Standard revision efforts**

More specifically, the new DER capability requirements include specifications for:

- Reactive power capability.
- Regulating DER's reactive power exchange to support voltage.
- Regulating DER's active power exchange to support frequency.
- Riding through abnormal voltage and frequency conditions to maintain bulk system stability, including post-fault power restoration time performance, rate-of-change-of-frequency, as well as phase angle jump ride-through.
- Wide ranges of adjustability for DER control and trip settings, including default values.
- Detecting open-phase conditions.
- Power quality requirements.
- Specifying priority of DER functions.
- Specifying minimum measurement accuracy.
- Providing a standardized non-proprietary communication interface.
- Responding to disabling permit service settings (emergency shut-down).
- Responding to active power limit set points (active power curtailment).
- Performance of DER connected to an intentional island that includes part of the utility grid.
- A new concept for testing and verification of composite DER with partially compliant components.

## 3.4 References


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