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Comparative Analysis and Considerations for PV Interconnection Standards in the United States and China

David Wenzhong Gao
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Errata

This report, originally published in January 2017, was revised in February 2017 to reflect on the reasons for references to German standards, highlight the considerations for future revisions to photovoltaic interconnection standards, and include an appendix on case studies of high-penetration photovoltaic planning strategies in the United States.

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List of Acronyms

AC	alternating current
DC	direct current
DER	distributed energy resources
IEEE	Institute of Electrical and Electronics Engineers
kW	kilowatt
MW	megawatt
MVA	Megavolt ampere
p.u.	per unit
PF	power factor
PG&E	Pacific Gas and Electric Company
PV	photovoltaic
SDG&E	San Diego Gas & Electric

Executive Summary

The main objectives of this report are to evaluate China's photovoltaic (PV) interconnection standards and the U.S. counterparts and to propose recommendations for future revisions to these standards. This report references the 2013 U.S.-China Renewable Energy Partnership report *Comparative Study of Standards for Grid-Connected PV System in China, the U.S. and European Countries*,[1] which compares U.S., European, and China's PV grid interconnection standards; reviews various metrics for the characterization of distribution network with PV; and suggests modifications to China's PV interconnection standards and requirements. The recommendations are accompanied by assessments of four high-penetration PV grid interconnection cases in the United States to illustrate solutions implemented to resolve issues encountered at different PV sites. PV penetration in China and in the United States has significantly increased during the past several years, presenting comparable challenges depending on the conditions of the grid at the point of interconnection; solutions are generally unique to each interconnected PV installation or PV plant, but general recommendations can be drawn for best practices in integrating PV into the grid system.

[1] The report is a joint study conducted by Underwriters Laboratories, the China Electricity Council, and the China Electric Power Research Institute under the U.S.-China Renewable Energy Partnership. It can be accessed free of cost at: http://www.uschinaecp.org/Downlond/StandardsintheUnitedStatesandEuropeandthecomparativestudyofPV.pdf

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1 Introduction

As the level of distributed generation increases significantly, operating a distribution network becomes more challenging, and the power flows not only from the centralized substation feeder to the customers but in the reverse direction: the level of photovoltaic (PV) generation on a rooftop can sometimes be higher than the level of consumption at the customer point, and power flows back from the customer to the grid. This reverse power flow makes it difficult to control the voltage level at the customer site. Other challenging issues include line overloads, increased line losses, voltage fluctuations, and system unbalance.

Grid codes appear in many places and in different languages, with various allowable ranges, limits, and formats. The content of a typical grid code is tabulated in forms, with a range of numbers in the cells for each column and row. These numbers might be supplemented with context and descriptions to increase ease of understanding. Thus, this report describes the meaning behind the numbers in the grid codes in order to provide the necessary technical background knowledge.

This study is based on ongoing collaboration between the United States and China in the area of renewable energy under the U.S.-China Renewable Energy Partnership. The partnership seeks to strengthen the relationships among engineers, scientists, and researchers with the mutual goal of removing the barriers to renewable energy deployment in both countries.

The preceding 2013 U.S.-China Renewable Energy Partnership report on U.S. and Chinese PV grid interconnection standards, *Comparative Study of Standards for Grid-Connected PV System in China, the U.S. and European Countries*, is a high-level comparison in which an analysis of PV standards was conducted across nine selected aspects [1]. The present report extends this study in more detail by reviewing metrics for the characterization of distribution networks with significant PV generation, and it provides some suggestions for future revisions to China's PV interconnection standards and requirements. An update to the PV interconnection standards can reduce the impact of variable generation on the grid, streamline the interconnection process and thus decrease the cost of interconnection, and promote higher standards for suppliers and manufacturers.

The recommendations are accompanied by summaries of PV grid interconnection case studies in the United States [2], [3]. Challenges and solutions for the integration of four high-penetration PV plants are highlighted so that certain technical aspects can be considered for future revisions to China's standards. Germany, which has experienced high penetrations of PV on parts of its grid, offers standards that are referenced to provide a more comprehensive overview of international solutions for PV grid interconnection.

2 Metrics to Characterize the Distribution Network and Implications to Standards

In a conventional power system, the distribution network is the part of the electricity network in which the utility generators deliver electricity to the customers. At this point of utilization, the loads connected to the grid must be served satisfactorily while incurring minimal possible damage to customer loads.

With the high growth of distributed generation, the distribution network not only delivers power to the customer, but in many cases the customers deliver power, generated by distributed energy resources (DERs) such as PV, back to the distribution network [4], [5]. Thus, customer-sited DER systems need to coordinate and integrate with the utility grid to maintain the integrity of power delivery and safety.

In some cases, PV installations are connected to a small system or a small "island," which has a limited number of generators serving the loads, and connection to the major grid is not available. In these cases, balancing load and voltage may be harder to maintain. The frequency and voltage may vary over a wider range than in a large, interconnected system. Thus, a PV inverter must be able to sustain large voltage and frequency variations, and at the same time it must be able to support the grid to keep the voltage and frequency variations to a minimum. The Institute of Electrical and Electronics Engineers (IEEE)/American National Standards Institute Standard 446, "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications," is a good reference for this type of application [6].

In the majority of cases, the PV installations are connected to a large, interconnected grid that has very tight interconnection requirements and a very narrow allowable range of voltage and frequency variation. PV interconnections in this type of environment should consider IEEE Standard 1547 (IEEE 1547) and the rules and regulations set by the North American Electric Reliability Corporation, the regional reliability organization, and regulations established by the local utility to which the PV generation is connected [7]–[9]. This paper focuses mainly on non-island system integration.

2.1 Power Quality

Power quality is the metric used to measure the quality of power at the point of utilization. Power quality becomes a very important metric as the size of the grid and the power delivered through the grid increases. Good power quality ensures that the compatibility between the grid and the equipment connected to it can be maintained continuously without causing any damage to the equipment. Although power quality covers both transient and steady-state conditions, this report considers only steady-state power quality.

The equipment connected to the grid may vary in physical size, power ratings, immunity to disturbances, and from one type of industry to another. Bad power quality may disrupt wafer production in the electronic industry, cause disturbances to medical equipment during a major surgery in a hospital, or cause a glitch in mission-critical computer calculations. Major power quality issues can lead to millions of dollars of equipment damage, disruptions of transportation or information systems, or threats to human lives.

Table 1 below lists the typical range of input power quality and load parameters for a major computer manufacturer [10]. Figure 1 illustrates typical design goals of power-conscious computer manufacturers, showing that the computers they manufacture should be able to withstand voltage variations within the tolerance specified by the upper and lower limit of the curves presented. As shown in Table 1 and Figure 1, the range of values presented is very generous compared to most available national and regional grid codes used to regulate the allowable voltage and frequency of the grid.

Table 1. Typical Range of Input Power Quality and Load Parameters for a Major Computer Manufacturer [10]

Parameters	Range
1. Voltage limit, steady state (all phases)	+6%, -13%
2. Voltage disturbances (all phases)	Surge: +15% for 0.5-second maximum Sag: -18% for 0.5-second maximum Transient overvoltage: 150%–200% for 0.2 millisecond
3. Harmonic content	5% maximum with equipment operating
4. Electromagnetic compatibility	1 V/m maximum
5. Frequency limits	60 Hz ±0.5
6. Frequency rate of change	1 Hz/s (slew rate)
7. Three-phase voltage unbalance	2.5% of arithmetic average
8. Three-phase load unbalance	5%–20% maximum for any one phase
9. Power factor	0.8–0.9
10. Load demand	0.75–0.85 (of connected load)

Notes: Parameters 1, 2, 5, and 6 depend on the power source. Parameters 3, 4, and 7 are a function of the interaction of the source and the equipment load. Parameters 8, 9, and 10 are a function of the equipment. The harmonic content of the voltage is computed as the sum of all harmonic voltage added vectorially.

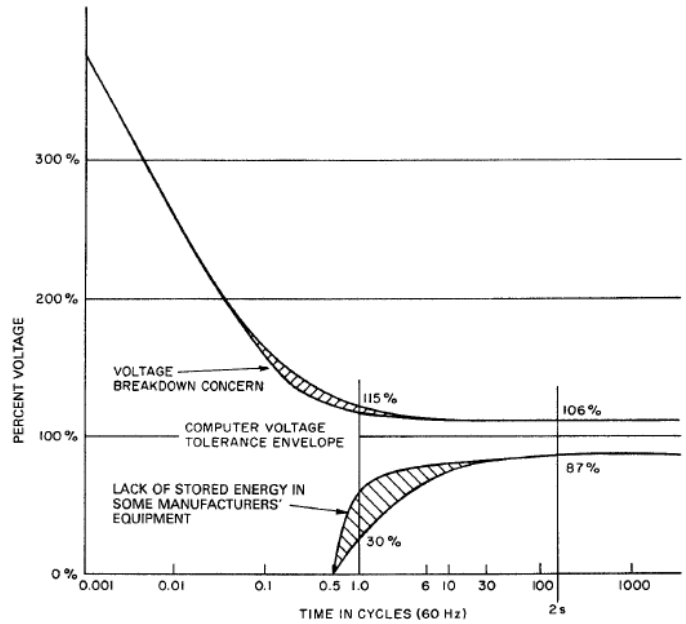

Figure 1. Typical design goals of power-conscious computer manufacturers [11][2]

IEEE 1547 is intended to ensure that renewable energy generation does not violate some of the basic rules of the distribution system, and it ensures the safe and reliable operation of the distribution system. Conventional power flows from a generator into residential and commercial loads. With the increase of distributed generation such as PV installations, the power flow may reverse direction for the duration of a day when there is excess generation from a rooftop PV generating unit. Another concern is for the safety of utility service engineers who may perform repairs in the distribution network because of islanding when the PV generation keeps parts of the feeder energized after the circuit breaker disconnects the load from the main distribution network.

2.2 Harmonics

Harmonic currents may generate harmonic voltage drops and thus harmonic voltage components at the point of common coupling. Similarly, harmonic voltage may generate harmonic currents within the distribution network. The presence of large harmonic currents can produce additional losses in the line feeders, electromagnetic interference, and radio frequency interference. The presence of harmonic currents in the motors and generators can generate torque pulsation, vibration, noise, and extra losses in the copper windings and additional iron losses. Harmonics become an important issue when nonsinusoidal currents or voltages are present in power system operations. Harmonics are generated by nonlinear systems or loads such as operation in the high saturation of magnetic fluxes in the transformer, industrial processes such as aluminum smelters, or by the contribution from power electronics equipment within a power system network. Harmonic voltage imposed on sensitive equipment connected to the grid may induce harmonic currents if a resonance circuit is naturally formed by the combination of inductance and capacitance found in the network (overhead lines, cables, capacitor banks, motors, etc.), and it may interfere with the equipment's performance. Similarly, harmonic currents generated by

[2] Newer data are expected to be included in the next revision of IEEE Standard 1100-1992.

equipment may travel through the network, producing unintended power line losses, electromagnetic interferences, and harmonic voltage drops across the lines and corrupting the power quality at the terminal of other equipment connected to the same grid.

In a distribution network, it is common to use tap changer transformers to adjust the voltage at the customer side as close as possible to the nominal value (1.0 p.u.). Similarly, capacitor banks are also used to support voltage regulation by changing the amount of capacitance applied at certain buses via switches. Underground or overhead lines inherently consist of inductance and capacitance as well; thus, the level of inductance and the capacitance varies during the day from one place to another, and a certain part of the network may inadvertently resonate at a certain harmonic frequency. The presence of harmonic sources and the resonant circuit may amplify unwanted harmonics within the circuit. Some references [12], [13] provide a good background on issues related to harmonics.

Some in China reference an interharmonic injection current similar to that specified in Germany's Low Voltage Grid Code, Standard VDE-AR-N4105. A requirement regarding harmonic currents of the 35th order and above, as recommended by IEEE 1547 in the United States, could also be considered.

According to the harmonic injection current specifications of IEEE 1547, the current harmonic caused by a voltage harmonic should not exceed the following limits: <11 times (4%), 11–17 times (2%), 17–23 times (1.5%), 23–35 times (0.6%), >35 (0.3%), and total harmonic distortion (5%). These limits can be considered in China's standards.

2.3 Flicker

Flicker is usually applicable to lighting. Flicker, triggered by the presence of unwanted voltage variations across the terminals connecting incandescent light fixtures to the grid, causes the perceived light intensity generated by a lightbulb to quickly fluctuate. Severe light flicker may interfere with the ability of a person to perform specific tasks requiring focused attention and eyesight. Thus, for example, for the safety of workers and the accuracy of production, it is important to minimize flicker in a factory where workers operate heavy machinery.

New equipment such as PV inverters and wind turbine generators are often tested for the flicker level that they may generate. For example, International Electrotechnical Commission Standard 61400 is used to test wind turbine generators during the certification process before entering the commercial market to ensure that the level of flicker generated is lower than the specified acceptable values [14].

Compared to the U.S. standard, China has a set of definite, quantitative requirements and classifications according to the voltage levels at the connection points, so no modification is suggested for China's standard.

2.4 Voltage Unbalance

A large manufacturing plant may have a well-balanced incoming supply voltage, but unbalanced conditions can be developed within the plant from its own single-phase power requirements if the loads are not uniformly spread among the three phases. An unbalanced condition can also be caused by an unsymmetrical transformer winding or transmission impedances (e.g., open wye, open delta), an unbalanced load in the transmission lines, and many other causes [15]–[18]. Further, DERs have impact on increased voltage imbalances on distribution feeders. Single-phase PV installations can lead to increased voltage imbalances, which could lead to increased losses and reduction of life in three-phase loads.

Unbalanced voltage is often overlooked because the impact is usually long term. It may continue for several months undetected. In a single-phase environment, voltage unbalance is not an issue. The impact of an unbalanced system on a transformer is not of a major concern. However, large machines (generators or motors) are commonly designed in a three-phase configuration. Voltage unbalance on three-phase induction machines, for example, can produce torque pulsation, increased losses, vibration, audible noise, and, more importantly, unequal distribution of the line currents among the three-phase windings. Thus, unequal heating in the stator windings can develop hot spots within the windings, and during the long run the hot spots within the windings may lead to insulation failure. For example, 3%–5% of unbalanced voltage may generate 10%–20% of unbalanced currents. Failures often occur to unattended motors/generators in isolated locations (e.g., water pumps for irrigation, compressors operating at night).

No detailed requirement in this regard is specified in the U.S standards. But according to Germany's Standard VDE-AR-N4105 (Section 5.4.5 and Section 5.5), the three-phase power deviation should not be larger than 4.6 kVA. This can be referenced in China's standards.

According to American National Standards Institute Standard C84.1-1995, utilities should limit the maximum voltage imbalance to 3% measured under no-load conditions, although utilities may adopt a different threshold (e.g., Pacific Gas and Electric's requirement described in Rule 2 mandates that "the voltage between phases will be maintained by PG&E as close as practicable to 2½ percent maximum deviation from the average voltage between the three phases" [10]). The National Electrical Manufacturers Association in the United States suggests not operating motors if the supply voltage is in excess of 5% unbalance. The National Electrical Manufacturers Association MG-1 and International Electrotechnical Commission 34-1 suggest derating motors if the supply voltage has an unbalance more than 1%.

2.5 DC Injection

PV inverters synthesize sinusoidal output current based on the principle of a push-pull converter; thus, it is possible that non-perfect sinusoidal currents (e.g., harmonics, DC offset, frequency bias) may be generated for various reasons (e.g., inaccuracy of the current sensors, low switching frequency, misfired logic signal, malfunction firing circuit board).

DC injection is an unintended DC offset current flowing in one or more phases of the power converter. If the size is small, the DC offset will not interfere with the operation of the transformer (or inductor); however, if the DC offset is sufficiently large, the operating point of the transformer on the magnetic B-H characteristic may grow and migrate into the unsymmetrical operating range (one side is positive or negative reaching saturation, whereas the other is below the saturation level). This condition will create a nonsinusoidal emf voltage and increase the core loss and temperature of the winding and eventual failure of the winding insulation.

China should consider DC injection requirements similar to those of the United States. For the operation of a grid-connected PV power station, the DC component injected into a public connection point should not be larger than 0.5% of the rated AC.

Germany's standard (VDE V 0126-1-1) sets a time limit for DC injection to be greater than the allowable value. More specifically, a direct current feed to the low-voltage grid because of a defective generator operation must lead to a disconnection within 0.2 second. This requirement should be considered for China's PV grid-interconnection standards.

2.6 Voltage Deviation

The International Electrotechnical Commission 60038 classifies voltages into the following levels:

- Low voltage: up to 1,000 V
- Medium voltage: 1,000 V–35 kV
- High voltage: 35 kV–230 kV
- Extra-high voltage: more than 230 kV.

Voltage deviation is defined as the voltage magnitude deviating from the normal voltage specified at the point of utilization. In the distribution network, the voltage deviation at the medium-voltage level is reflected in the low voltage at the customer sites.

In a power system, it is common to define voltage deviation by percentage or in per-unit (p.u.) value, in which 100% voltage or 1.0 p.u. voltage is considered the baseline. Voltage deviation may be classified as undervoltage deviation or overvoltage deviation.

The impact of voltage deviation on passive loads and motor loads is different. In general, passive loads show an output current that is proportional to the load impedance and an output apparent power, real power, and reactive power that is proportional to the square of the voltage level. Thus, for a passive load at voltage magnitude, $V = 0.9$ p.u., the output current will be proportional as the line current magnitude, $I = 0.9$ p.u., and the apparent power magnitude, $S = 0.9^2$ p.u. = 0.81 p.u. For example, a space heater of 1.0 kW, if connected to $V = 0.9$ p.u., will generate only 0.8 kW. As another example, for a capacitor bank exposed to an overvoltage condition of $V=1.1$ p.u., the reactive power output will scale to the square of the voltage, $Q = 1.1^2$ p.u. = 1.21 p.u., and this condition may cause an overvoltage to become even worse. Similarly, the same capacitor connected to an undervoltage grid will generate less reactive power than expected.

For a transformer, an undervoltage operation generally does not create unwanted consequences. Severe overvoltage operation, however, will bring the operating point of the transformer into magnetic saturation, and thus a nonsinusoidal current may be generated during an overvoltage operation. In addition, extra iron losses of the ferromagnetic core of the transformer may result.

For a motor, the consequence of the voltage deviation may be worse than a passive load. Because the majority of the motors in industry are induction motors, an induction motor is used in Figure 2 to illustrate the consequences of voltage deviation.

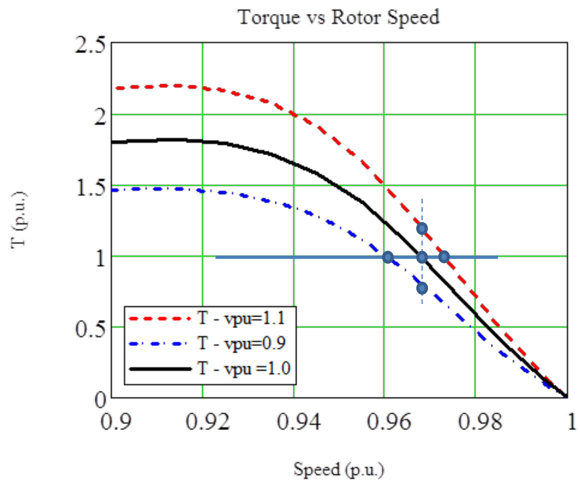

Figure 2. Torque-speed characteristic of an induction motor under varying voltage magnitudes

Consider the torque-speed characteristic of an induction motor connected to a grid with different voltages. The voltage considered is the rated voltage at 1.0 p.u. Two cases (undervoltage V = 0.9 p.u. and overvoltage V = 1.1 p.u.) are considered for comparison. Initially, the operating point is at Point A. The output torque-speed characteristic shrinks in proportion to the square of the voltage at the terminals of the motors. It is assumed that the motor drives a constant torque load. A sudden drop of voltage to V = 0.9 p.u. will move the operating point from Point A to Point A", and eventually as the motor torque is less than the load torque, and the operating point of the motor will move to match the load torque. As shown in the figure, the operation at reduced voltage will move the operating point to a higher operating slip (lower speed at Point C); thus, the motor draws more current, produces less mechanical power, generates more copper losses, and operates in a lower efficiency. If left unattended, a severe undervoltage operation may result in excessive temperatures on the stator winding and eventually cause a winding insulation failure. For a sudden overvoltage operation, the operating point of the motor will move to Point A' first, then the motor torque will match the load torque, and it will operate at a slip lower than Point A. An overvoltage at constant frequency will lead to an operation in a higher magnetic flux density or even in the saturation region, and, thus, the iron core losses will increase. Because it operates in slightly less operating slip (Point B), the copper loss is reduced.

In the United States, San Diego Gas and Electric's *(SDGE) Generation Interconnection Handbook* [19] issues a strict requirement for voltage deviation: ≦69 kV:±5.0%; 69 kV–161 kV:±2.5%; >161 kV:±2.5%. Germany's Standard VDE AR-N4105 stipulates voltage deviation at all voltage levels to be ±3%. It is suggested that the normal voltage operation range in China's standards should be established by considering the grid-connection capacity of the PV system, the contract power demand, and the voltage level.

2.7 Active Power/Reactive Power

Generally speaking, there is no present requirement for controlling or limiting the active power output of PV inverters in China. In certain areas, where very high penetrations of PV generation may be installed, curtailment may be enforced to ensure the stability of the power system. In general, if there is no regulation or rule, PV inverters should be operated at unity power factor (to minimize the output current and thus maximize the output efficiency of the inverters). The goal is to eliminate curtailment, maximizing the energy harvested by the power inverters and thus also the annual energy production.

Reactive power regulation is usually needed to help with voltage regulation on the grid. In some cases, a utility company may prohibit PV inverters from generating reactive power to the grid to avoid instability when both the PV inverters and the grid perform voltage control.

In the United States, SDG&E's *Generation Interconnection Handbook* [19] has a less strict requirement with respect to the range of reactive power capacity—with the maximum power factor of -0.90 lagging and the maximum power factor of +0.90 leading—and it does not include the duration of the reactive power adjustment. Federal Energy Regulatory Commission Order 2003 and Order 2006 state that the power generating equipment can adjust the power factor to be from -0.95 to +0.95 in accordance with the grid requirement proposed for 1 day ahead in the U.S. power market. The corresponding expenses associated with the reactive power caused by the adjustment should be paid by the grid companies.

There is no requirement regarding the reactive power adjustment for small solar power stations in China, but there are requirements for medium and large solar power plants.

According to Germany's Standard VDE-AR-N4105, there is a power reduction adjustment point under dispatching control for each 10% of the power when the power is larger than 100 kW. When the voltage floats ±10% of rated voltage (Un) and the active power output is 20% larger than the rated power, the power factor (PF) should comply with the following requirements:

1. S ≦3.68 kVA:PF≧0.95
2. 3.68 kVA≦S≦13.8kVA:PF≧0.95
3. S >13.8 kVA:PF≧0.90.

Most installations in China are presently controlled at unity power factor. No general recommendations for active power control are suggested. However, SDG&E and German standards can be referenced if active/reactive power control issues need to be addressed.

2.8 Active Power Control for Frequency Regulation

Most modern wind turbine manufacturers include active power control capabilities for frequency regulation in the wind turbines. "Active power regulation" covers reserve, active damping, and frequency response (inertial and governor response). These capabilities can be made available by PV power plants as well.

The control of active power from PV plants to support frequency regulation and to balance the instantaneous load and generation is needed especially when the level of generation from conventional (synchronous) generators is limited and the level of inertia in the grid is low because of fewer synchronous generators connected to the grid (e.g., during weekend loads or weekdays post recovery when many large generators are separated from the grid). Obviously, PV generation can support the grid only when the available solar radiation is sufficient. There are two main conditions during which PV generation can assist in frequency regulation: overfrequency and underfrequency.

An overfrequency event implies that the level of generation exceeds the load. In this case, the output of the PV generation can be curtailed. In the United States, curtailment is usually requested by the independent system operator (e.g., Electric Reliability Council of Texas, California Independent System Operator). The size of the output reduction and the ramping rates by which the power must be reduced are regulated by the independent system operator or the regional reliability organization. This curtailment may lead to a significant loss of energy production.

An underfrequency event implies that the load is more than the level of generation. To support an underfrequency event, PV generation must be operated with part of the output as a spinning reserve. Spinning reserve operation requires that the PV generation is curtailed by a certain amount and thus generates less than the available output power (or solar irradiance). When an underfrequency event occurs, the PV plant can release the spinning reserve to the grid. Note that the spinning reserve means that the PV plant has a loss of energy production during curtailment, and in some cases the PV plant may receive proper compensation for the spinning reserve service provided to the grid.

Some PV inverter manufacturers include some of these capabilities, especially power curtailment to help regulate an overfrequency event on the grid when some of the large loads are disconnected from the grid during disturbances. However, these inverters are usually custom-designed because of the extra cost and liabilities that may be tied to these additional functionalities. Figure 3 shows an example of power compared to frequency that takes the input of the measured grid frequency and commands output power to the grid as the frequency varies. P_{MPPT} is the maximum power point tracking output of PV, and $P_{dispatch}$ is the operating point at nominal frequency. The spinning reserve operation intentionally curtails the available output power to enable additional power production to be delivered to the grid during low-frequency conditions. The ramp rate for this operation is governed by the parameter “Droop.” Similarly, overfrequency curtailment can be accomplished by using the same curve; it is governed by the parameter “$Droop_{+}$.” The operating frequency between the two deadbands, DB_{low} and DB_{high}, is the acceptable frequency deviation, and it is needed to avoid chattering (continuously moving from one state to another, especially in a small islanded system). The parameters to control the real power compared to the frequency are usually set at the plant level for a PV plant or at the PV inverter level if it is a rooftop installation. In the United States, the requirement for PV generation to perform frequency control functions is governed by a local or regional regulation.

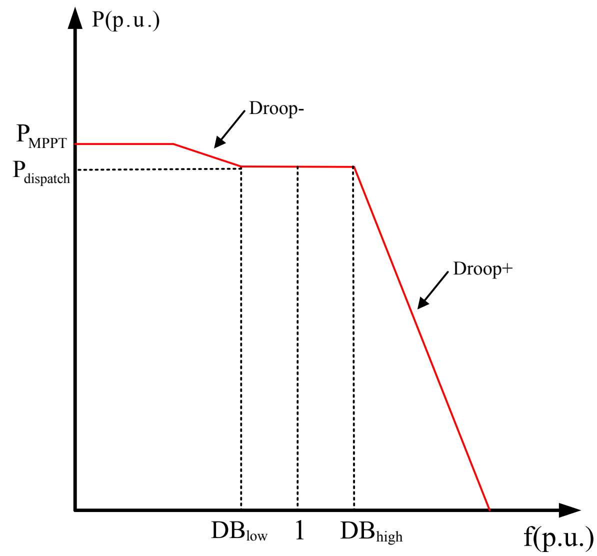

Figure 3. Variable droop characteristic curve of active power versus frequency for PV

Note that although the curve presented performs a function similar to that of governor control, in reality the PV inverter is based on a power electronics generator, and thus the response time is much faster than the governor of conventional power plants (i.e., an electronic time constant compared to a mechanical time constant). Active power control for frequency regulation should comply with IEEE Standard 519-1992, "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems." The relevant German standard (VDE-AR-N4105) specifies an operating frequency range from 47.5 Hz–51.5 Hz for small PV power stations, with a detailed technical requirement and calculation formula.

For frequencies between 50.2 Hz–51.2 Hz (VDE-AR-N4105), all adjustable PV power generation should be able to reduce output in proportion to an increase in frequency or increase output in proportion to a decrease in frequency.

According to Figure 4, the generated active power, P_M, can decrease with a gradient of 40% of P_M per Hz when the system frequency exceeds the main frequency of 50.2 Hz. If the main frequency exceeds 51.5 Hz, the PV system should be disconnected from the network immediately. Active power adjustment is not included in the U.S. standards.

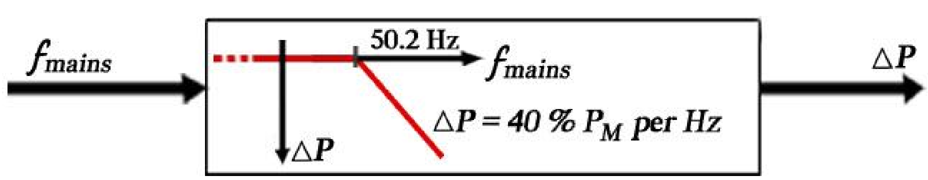

Figure 4. Active power output during underfrequency/overfrequency conditions [1]

Overall, a large-scale PV system should be allowed to actively participate in frequency regulation. Small-scale PV systems can normally operate within a relatively broad frequency range and deviation limit. This aspect of frequency regulation can be considered for future implementation in China.

2.9 Limits of Voltage Fluctuations

As previously discussed in Section 2.1, voltage variation must be limited to ensure that the operation of the equipment connected to the grid functions normally. During normal operation, the frequency of the grid is constant; however, power flows through distribution lines change with load variation during the day. Changes in the load imply changes in the real and reactive power delivered to the load. Both the real part and the reactive part of the load affect the voltage drop along the lines; consequently, it affects the voltage at the point of the delivery. There is a strong correlation between the reactive power flow and the voltage fluctuations in the transmission network, in which the ratio of reactance to resistance (X/R) ratio is very large. In the distribution network, in which the X/R ration is small, there is an additional correlation affecting the voltage at the point of the delivery. In distributed generation, the size and the direction of the real power flow also influences the voltage at the terminal of the loads or PV inverters.

PV inverter manufacturers strive to comply with IEEE 1547 [12], [13], implement anti-islanding protection, and ensure that PV inverters stay connected to the grid within the allowable operating ranges for voltage time and frequency time. Table 2 lists the operating voltages and the maximum clearing times for distributed generation. Figure 5 shows a graphical representation of the information contained in Table 2.

Table 2. Voltage Ranges and Maximum Clearing Times [12]

Voltage Range (% Nominal)	Max Clearing Time (Seconds)[a]
V<50%	0.16
50%<V<88%	2
V>120%	0.16
110%<V<120%	1

[a] Maximum clearing times for DERs ≤ 30 kW

The limits of the voltage fluctuations discussed in this section are intended to ensure safe operation of the equipment connected to the grid. It is normal during important and sensitive loads for the equipment to self-protect by disconnecting when it experiences undervoltage and overvoltage operation. The protection is programmed to the undervoltage/overvoltage relay, which will sense the voltage, compare it to the allowable operating range, and disconnect the circuit from the grid when the safe range is violated. PV inverters with power electronics components are more sensitive to severe voltage violations than regular electrical generators.

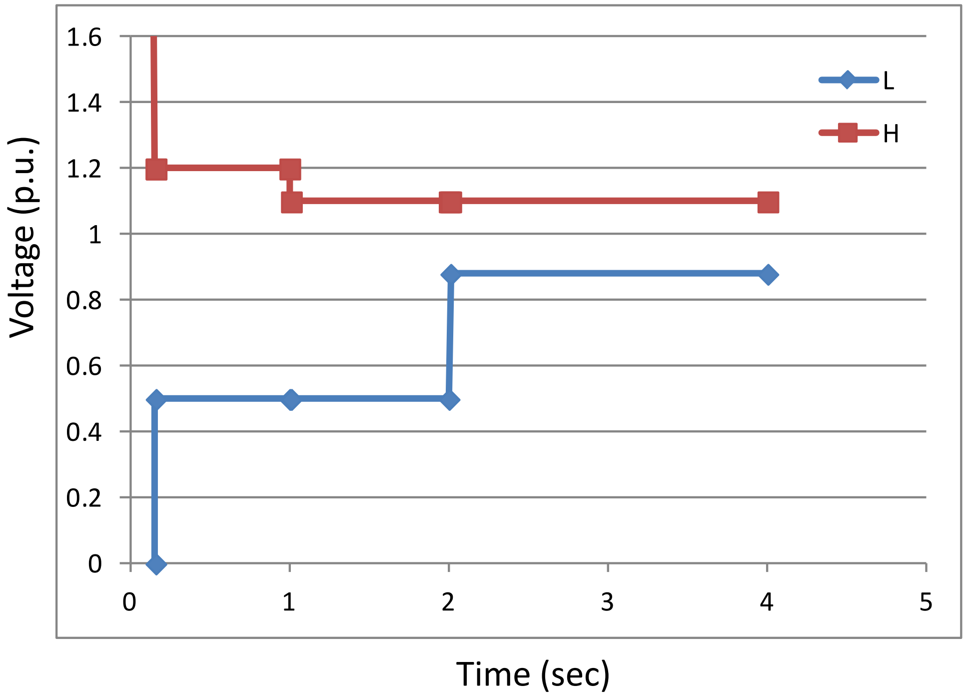

Figure 5. Representation of voltage versus maximum clearing time as described in IEEE 1547 [12]

As the level of PV penetration on the modern grid increases significantly, there is greater need to have voltage ride-through or fault ride-through capabilities included in the grid code. This is discussed in more detail in subsequent sections. Ride-through capability is included in grid codes to protect the reliability and stability of the grid to which a PV inverter or PV plant is connected. Thus, to satisfy the grid code, and not only to protect their own PV inverter, PV inverter manufacturers should consider how to protect power system operation. In some cases, this means that PV inverters must be designed to accommodate power system disturbances. A balance between the technical capabilities and cost will need to be considered. Note that grid conditions are different for different locations and different regions, and thus the grid code may vary from one place to another. To be competitive and cost-effective, some PV manufacturers may market different capabilities to different market sectors.

Voltage limits and disconnection times are similar in the relevant standards in China and the United States.

U.S. standards (IEEE1547 and SDG&E *Generation Interconnection Handbook* [19]) simply require that PV power stations with a power capacity larger than 30 KW adopt specific requirements for small PV power stations as a reference only, and relevant grids can propose their own requirements to comply with actual situations.

The relevant German standard (VDE-AR-N4105) stipulates that PV power stations should be disconnected from relevant grids after withstanding high or low voltage for a specific period of time. In addition, Germany's standards have different requirements for both the power generation side and the grid connection point along with different requirements for single-phase and multiphase undervoltage conditions. Note that the relevant standards for China and Germany have quite different requirements for the specific time.

2.10 Limits of Frequency Fluctuations

To maintain the constant frequency of the grid, the balance between generation and loads must be maintained at all times. It is necessary to know the level of the loads and the generation at all times. Load forecasting and resource forecasting are conducted regularly to minimize disruptions and imbalances. Although load forecasts have been done regularly by utility companies for many years, since the invention of the electric generator, renewable energy resource forecasting is new and developing. Although significant progress is being made in this type of forecasting science and technology, there are situations when the forecast does not match the actual generation. To make up the difference, spinning reserve generators are usually made available by the utility company and can be called upon when needed to support the loads.

Because the majority of the generators are synchronous generators, the frequency fluctuations reflect the rotational speed of the generators connected to the electric grid. To analyze the impact of the frequency fluctuations, consider the following voltage equation:

$$E = K_v \phi$$

For a transformer connected to a grid with rated voltage, a sudden overfrequency operation means that the transformer is in an underflux operation; however, an underfrequency operation means that the transformer is in an overflux operation, commonly known as operation in magnetic saturation. The magnetic saturation causes a nonsinusoidal current, additional iron core losses, vibration, and noise (hum). If it goes unnoticed, this condition may eventually shorten the life of the transformer.

$$E = K_e \phi \omega_m$$

For a synchronous generator, a sudden overfrequency operation means a sudden speed increase and output voltage increase, and thus the field excitation controller of the generator must reduce its field current to maintain the voltage at the terminal of the generator constant. On the other hand, a sudden drop in the operating frequency means that the output voltage decreases, and thus the field excitation controller of the generator must increase its field current to compensate for the voltage on the grid.

$$\phi = \frac{E}{K_e f}$$

In an induction motor, the flux level is determined by the voltage and frequency of the grid to which it is connected. It is proportional to the voltage divided by the frequency. Thus, the magnetic flux density of the iron core is proportional to the ratio of V/Hz. If the V/Hz is higher than normal, the induction motor (or generator) may be operating in a higher saturation region. Figure 6 illustrates the impact on the torque speed characteristic of a motor because of the variation of the frequency at constant voltage.

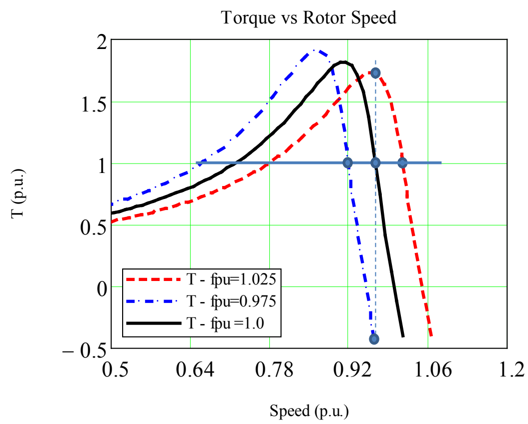

Figure 6. Torque-speed characteristic of an induction motor under varying frequency

It is assumed that the motor is driving a constant load torque. As shown, an event of overfrequency at constant voltage will reduce the magnetic flux and move the peak of the torque-speed curve to the lower right. Initially, the frequency is normal and the operating point resides on Point A. When the frequency increases (e.g., 1.025 p.u.), the inertia of the motor will keep the speed the same temporarily, and the operating point moves from Point A to Point A'. As the motor torque becomes higher than the load torque ($T_{A'} > T_A$), the operating point eventually moves from Point A' to Point B, thus increasing the "new slip" (the operating point is closer to the peak torque), and the stator current will rise. If the frequency increases significantly, ($\Delta f >> 2.5\%$) and the frequency deviation goes uncorrected, this condition may lead to excessive overload (i.e., the stator winding experiences overcurrent) and eventual insulation winding failure. This condition is most likely to happen in a small system with limited resources to make an instantaneous correction to the balance between the loads and generation.

On the other hand, a decrease in frequency (e.g., 0.975 p.u. = 2.5% drop from normal) will move the operating point from Point A to Point A". When the motor torque is lower than the load torque ($T_{A''} < T_A$), the operating point will move to Point C. The "new slip" at Point C is less than the original slip, and it is not likely that the overload will occur; however, the operating flux will be higher, the iron core losses will increase, and the iron core will produce more heat, which may lead to higher temperature on the core. By heat conduction, the winding temperature may also rise and may threaten the integrity of the winding insulation.

In a large interconnected system, the range of allowable frequency variation is very narrow. As shown in Figure 7, the nadir (the lowest point of the frequency) is shown to reach 59.85 Hz (0.25% drop from normal). This measurement was recorded in the National Wind Technology Center at the National Renewable Energy Laboratory in Boulder, Colorado, which is located in the Western Interconnection system. As shown during the period of observation (60 seconds), the frequency flattens during the post-recovery event. Eventually, as time progresses, the frequency will be returned to as close as possible to 60 Hz by the governor's action and the availability of the spinning reserve from other generators.

Table 3 lists the operating frequencies and the maximum clearing times for distributed generation as specified in IEEE 1547 [12], [20]–[21]. Figure 8 shows a graphical representation of the information contained in Table 3.

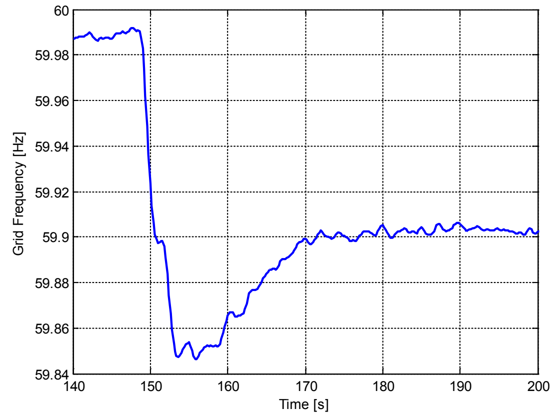

Figure 7. An example of frequency dip caused by a loss of generation—recorded at the National Wind Technology Center of the National Renewable Energy Laboratory

Table 3. Frequency Ranges and Maximum Clearing Times [12]

Frequency Range (Hz)	Max Clearing Time (Seconds)
f >60.5	0.16
[a] f <57.0	0.16
[b] 57.0<f <59.8	0.16-300

[a] 59.3 Hz if DER≤ 30 kW; [b] For DER >30 KW

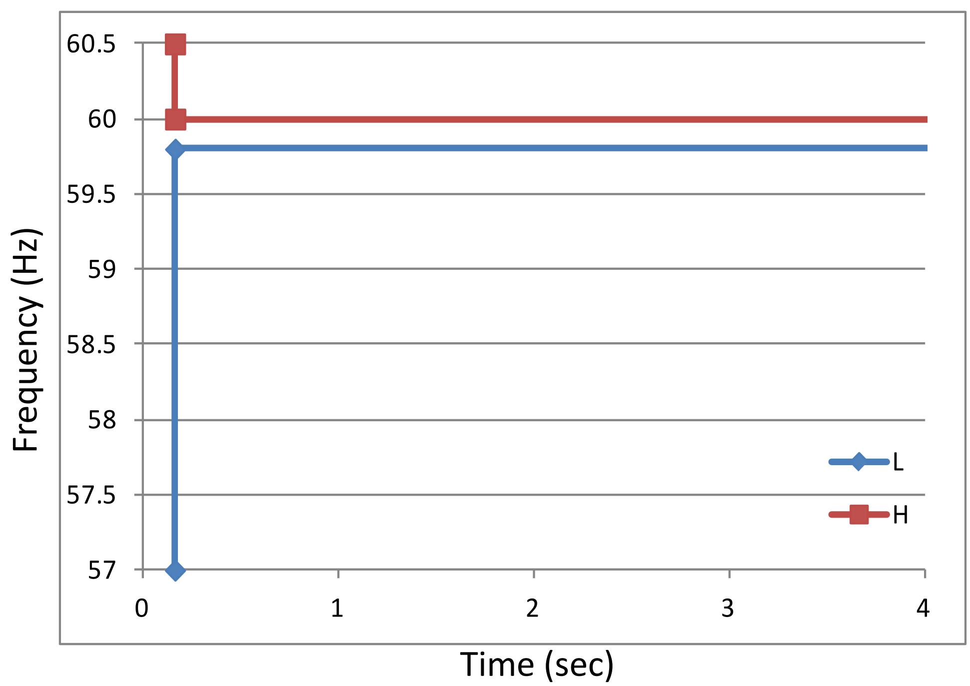

Figure 8. Representation of frequency versus maximum clearing time as described in IEEE 1547 [12]. H = upper frequency limit, L = lower frequency limit.

For small PV power stations, quick disconnection is required in case of overfrequency or underfrequency. The U.S. relevant standards (IEEE 1547 and SDG&E's *Generation Interconnection Handbook* [19]) specify that the disconnection time should be shorter than 0.16 second. (In China, it is shorter than 0.2 second.)

The German relevant standard (VDE-AR-N4105) requires the specific operating range of the frequency to be from 47.5 Hz–51.5 Hz (-5%–+3%).

In China, determining frequency fluctuation limits may be addressed in a future national standard.

2.11 Reconnect Time

The reconnect time is defined as the time duration a PV inverter is allowed to be offline before reconnecting to the grid. In a large wind power plant with induction generators (Type 1 wind turbines), the process of reconnection or start-up is usually done in a staggered manner by a group of turbines to avoid a large inrush of start-up currents. In PV inverters, there is no inrush current during start-up because the output current is usually controlled not to exceed the maximum limit (usually limited to 1.1 p.u.). However, it may be necessary to follow ramping rate requirements based on the local or regional grid code.

The disconnection from the grid must be compatible with the fault ride-through standard applicable to the local grid code (discussed in Section 2.7).

No relevant standards for reconnection time exist in the United States and Germany for large, centralized PV power stations. For small PV power stations, the relevant standards in China and the United States have almost the same requirement. The normal voltage range in the relevant standards in China (GB/T 19964, Q/GDW 617, and GB/T 29319) is 85%–110% rated value; in the United States (IEEE 1547 and SDG&E's *Generation Interconnection Handbook* [19]), it is 88%–110% rated voltage.

Normal frequency in China is 49.5 Hz–50.2Hz; it is 59.3 Hz–60.5 Hz in the United States.

2.12 Fault Ride-Through

A top priority is to support grid voltage through the full implementation of a PV system's low-voltage ride-through capability. Fault ride-through is intended to support power system stability. Consider a situation in which the level of PV generation is very high and the available synchronous generators connected to the grid are very limited. If the PV inverters are allowed to be taken offline at the slightest deviation of voltage or frequency, the large number of PV inverters will be disconnected by the undervoltage and underfrequency relay protection. The level of generation becomes less than the load. As a result, the frequency of the grid will drop even further, and the voltage at the terminal of the generator drops with the frequency decline. The voltage of the grid can be increased only by increasing the excitation of the generator, but because the generator must produce more power to compensate for the loss of the generation from the large number of PV inverters, without additional generation the frequency continues to drop, the excitation of the synchronous generators reaches its limit and can no longer support the voltage, and the voltage continues to decline. One by one, the undervoltage and underfrequency relay protections of the remaining generators will disconnect them from the grid. This sequence of events is called the cascading effect, in which the loss of one generator triggers a condition that leads to the loss of other generators. Eventually, all the generators will be disconnected from the grid, and a blackout will follow.

In this aspect, the relevant U.S. PV standards (IEEE 1547 and SDG&E's *Generation Interconnection Handbook*) have no specific requirements for low-voltage ride-through.

From IEEE 1547, Table 4 shows that the clearing-time trip settings should be mutually agreed upon between the utility and the PV plant operator based on the regional regulations. Figure 9 shows a graphical representation of the information contained in Table 4. The shaded blue area shows the variability for the limits depending on the regional grid codes. Note that IEEE 1547 is intended for generation smaller than 20 MW; however, as the level of rooftop PV penetration has become very high in recent years, it is not unusual for some utilities to require PV inverter owners to set the inverter to follow the same rules to ensure the reliability of the power system.

Table 4. Voltage Ride-Through as Defined in IEEE 1547 [12]

Default Setting[a]		
Voltage Range (% of Base Voltage)	**Clearing Time (Seconds)**	**Clearing Time: Adjusting Up to and Including (Seconds)**
V<45	0.16	0.16
45≤V<60[b]	1	11
60≤V<88	2	21
110≤V<120	1	13
V≥120	0.16	0.16

[a] Under mutual agreement by the electric power system and demand response operators, other static or dynamic voltage and clearing-time trip settings shall be permitted.
[b] Base voltages are the normal system voltages stated in Table 1 of the American National Standards Institute Standard CB4.1-2011.

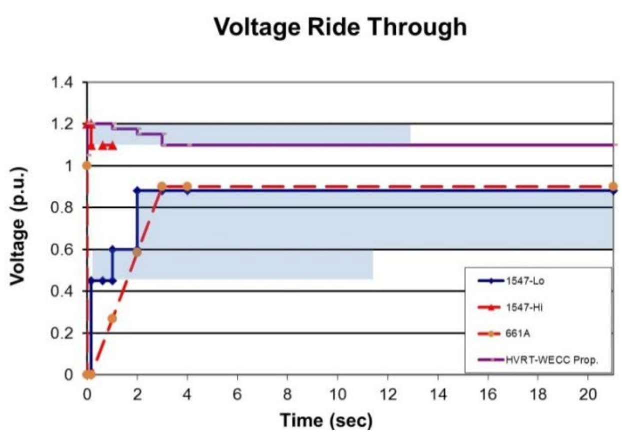

Figure 9. Graphical representation of voltage ride-through as defined in IEEE 1547 [12]

The latest relevant standards in Germany and China have basically the same zero-voltage ride-through requirements for PV power stations and slightly different voltage requirements for low-voltage ride-through [1]. (The relevant standard in China requires 0.625 second under a voltage of 0.2 p.u., whereas that of Germany is 0.625 second under a voltage of 0.3 p.u.)

The latest relevant standard in China requires a restoration speed of 30% of rated power [1], whereas the relevant Germany standard requires 10%.

In terms of dynamic reactive power support, the latest relevant national standards in China (GB/T 19964, Q/GDW 617, and GB/T 29319) require the reactive current response time to be no longer than 30 milliseconds and propose detailed technical requirements and a calculation formula for dynamic reactive current. The relevant standard in Germany (VDE-AR-N4105) does not have a requirement for the corresponding time of dynamic reactive current, but it proposes qualitative requirements rather than quantitative requirements for dynamic reactive support.

The future Chinese standard will evolve with the increasing level of variable generation.

2.13 Communications Requirement

The communications requirement is of utmost importance. Communications are used to pass the information data from the measuring devices to the individual generators and loads so that each individual generator and the loads may be able to make rational decisions regarding whether to stay connected to the grid or to disconnect for the safety of the remaining grid. In this context, communications must be made available instantaneously and accurately. The decision control must be supervised and must cover a large area of the interconnected power system.

All the relevant standards in China, the United States, and Germany do not incorporate specific communications requirements for small PV power stations; however, they all propose communications requirements for medium and large PV power stations.

China's communications requirements are more detailed with respect to the method, channel, and information transmission as well as signals, but the U.S. and German communications requirements are very simple, requiring details to be discussed by grid companies and PV power generation parties.

2.14 Anti-Islanding Requirement

When a power system outage occurs, PV systems should stop generating power to prevent damage to the equipment; hence, anti-islanding protection is required. The requirements are as follows:

For small PV stations, anti-islanding protection is specified in the relevant standards in China, the United States, and Germany. China's standard has a clearing time of 2 seconds, and Germany's standard has a clearing time of 3 seconds.

China's standards specify an anti-islanding protection for medium and large PV stations, but the U.S. and German standards do not. However, China's anti-islanding protection standard conflicts with the low-voltage ride-through requirement and may need to be revised.

3 Summary and Considerations for Future Revision

This report presents a comparison of the rules, requirements, and standards for PV systems in China, the United States, and Germany. A number of metrics are employed to characterize the distribution network, and the implications for the relevant standards are discussed. Although the list of metrics can be expanded, the most commonly used measures are included in this report. Some background information and the technical reasons behind the requirements are also discussed and included in each section.

Although the majority of the requirements among the three countries are similar, there are several differences that result from the characteristics of the electric grids. Some of China's technical requirements are more rigorous, whereas others are not as prescriptive; however, in recent years China added a significant amount of renewable energy—especially PV—generation to its grid, so enhancing China's distribution network requirements to be more resilient to disturbances will benefit grid performance for even higher levels of PV penetration.

Based on this comparative analysis, the following is a list of additional considerations for future modifications to China's standards, including industry standards set by the grid companies and national standards proposed by designated institutions and implemented by the National Energy Administration, certification bodies, and other relevant parties:

1. There is concern about the ability of conventional power plants to handle the ramp rates of large PV power plants; thus, China's standards could consider stipulating the limit of the ramp rates of PV plants, which may be assisted by energy storage systems. Utilities can impose limitations on ramp rates, and PV system output can be curtailed to help enhance system dispatch capabilities and reduce integration costs caused by reducing the variability and uncertainty of solar generation.
2. Rules, requirements, and standards could consider different specifications for different PV penetration scenarios (e.g., ≤2%, ≤10%, ≤30%, ≤50%).
3. Rules, requirements, and standards could consider the following aspects for distribution and subtransmission integration impact studies: voltage regulation, fault currents, protection coordination (overall circuit protection coordination, potential reverse power flow, coordination with inverters), ground fault overvoltage, and islanding.
4. For the reactive power level, an appropriate control method could be selected to support system voltage stability. These range from fixed volt ampere reactive, fixed power factor, closed loop voltage control, to volt/volt ampere reactive droop.
5. Requiring anti-islanding protection conflicts with the low-voltage ride-through requirement; hence, some revisions to these grid codes are needed.
6. The accuracy of a PV plant's output forecast is an important factor to determine a grid-connected PV power plant's capacity and its operation and control, but there is no forecast accuracy specification in the current PV standards. A new section could be added to the standards.
7. Rules, requirements, and standards should be revised as newer PV generation technology develops—for example, the active power requirement in the PV standards could be improved according to an advanced power output forecast of a PV plant.

8. Rules, requirements, and standards could consider the development of validated generic dynamic and power flow models of distributed and central-station PV power plants for large-scale simulation studies and to establish relevant integration guidelines. The Western Electricity Coordinating Council's generic PV and wind models provide a good foundation.

The appendix of this report also includes a review of four PV plants in the United States to highlight some practical aspects of PV generation, including challenges and opportunities. Many of these issues and their solutions are specific to the local PV installation and network; however, these examples may suggest approaches to addressing issues arising at other installations.

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Appendix

This section reviews the experience from four PV plants in the United States by evaluating the photovoltaic (PV) systems, distribution networks, issues encountered, and solutions implemented, if available. The plants have different capacities, modules, and inverters.

In each of the four cases, a high-penetration PV plant was installed to provide electricity to a distribution network. These plants are considered to be at a high penetration level based on their output power and the load profile.

Case 1: 10-MW PV Plant Near Carlsbad, New Mexico

This project aims to provide 10 MW_{DC} from a PV plant to a radial distribution network near Carlsbad, New Mexico. The PV plant is owned by Sun Edison, and the utility company is Xcel Energy. The PV plant and distribution network specifications are described below.

PV System

Trina TSM270PC14 PV cells are used in the PV plant, which has the following specifications:

- DC output power: 9.9 MW_{DC}
- DC output power of each cell: 270 W at standard testing conditions.
- Efficiency: 13.9%
- Types of inverters:
  - PVI-330-TL-EN 330 kW_{AC}
  - PVI-275-TL-EN 275 kW_{AC}
  - PVI-220-TL-EN 220 kW_{AC}.

Distribution Network

The existing substation provides power to a load that varies from 3.78 MVA–10MVA. The substation's rated voltage is 69 KV. A transformer of 69 KV/12.47 KV with rated power 28 MVA is used to connect the substation to the load. As noted above, the PV plant generates 9.9 MW. The penetration level of this PV plant is between 90%–100%, which is high; hence, Xcel Energy had some concerns about connecting this plant to the grid. Some of these concerns are:

- Significant reduction in output power of the PV plant due to the shading effect. This may cause a drop in the distribution voltage level.
- Potential problems because the PV output power is much larger (percentage wise) than the minimum load
- System energization and de-energization
- Power injections and the operation of protection relays
- Variation in voltage profile.

Issues and Concerns

Xcel Energy conducted different impact studies for interconnecting the high-penetration PV plant. Xcel Energy tested the system under fault conditions to examine the contribution of the PV plant to the fault current and to test the coordination of the protective relays. Many other tests have been done, such as studying the voltage profile during sunny and cloudy days.

Solutions

Sensitivity of the existing relays at the substation to overcurrent can be a nuisance and may trigger unnecessary trips. Additional line protection to protect the substation can be added. Reverse power flow may occur when the load is at its minimum and the output of the PV plant is high. A voltage-supervised closer was added to the breaker of the substation. High voltages may occur when interconnecting PV depending on network conditions. The following solutions were found by the utility:

1. PV owners must regulate the power factor to a fixed leading power factor.
2. Inverters must be energized in an increment manner to prevent large voltage steps.

Case 2: 5.2-MW PV Plant at Colorado State University–Foothills Campus

In this project, a 5.2-MW_{AC} PV plant is installed at Colorado State University to provide one-third of the energy to campus. The PV plant is owned by Colorado State University, and the utility company is Xcel Energy.

PV System

The PV system used in this project has the following specifications:

- Total power: 5.2 MWAC
  - Phase 1: 2 MW was installed
  - Phase 2: 3.2 MW was installed.
- Crystalline-silicon PV modules
- Array Technology Wattsun single-axis tracking system
- Advanced Energy Solaron inverters.

Distribution Network

The existing substation at the Foothills campus provides power to a load ranging from 3.1 MVA–9.1 MVA. The substation rated voltage is 115 KV, and a transformer of 115KV:13.2 KV is used to connect the substation to the distribution network. The penetration level is 47% (of the short-circuit capacity), which is considered to be high.

Issues and Concerns

Xcel Energy conducted many studies to confirm that the interconnection of the PV plant will not adversely affect the quality of the grid. Many issues and concerns were considered by Xcel Energy, and the required steps were taken to maintain the quality of the services.

Solutions

- To prevent voltage fluctuations, flicker, and frequent change of the tap changer and switches, the utility now uses:
    - A load tap changer that has the capability to boost or buck the voltage
    - A bidirectional regulator to keep the voltage within an acceptable range
    - A remotely controlled capacitor bank
    - Inverters with controlled power factor.
- Voltage swell may occur if the PV plant comes online immediately after an outage. Only one inverter at a time can come online; there is a minimum period of 230 seconds and a maximum period of 500 seconds before the next inverter comes online.
- High voltage may occur at the distribution level when the load is at its minimum and the PV power is at its maximum.
    - Use voltage regulators to maintain the voltage within an acceptable range.
    - Install 10 inverters. Each inverter will absorb from 100 KVAr–150 KVAr.
    - Disconnect part or all of the PV plants manually if Step 1 and Step 2 do not work.

Case 3: 1.2-MW Kapa'a Solar Project, Olohena Road, Kaua'i, Hawaii

This project provides a total of 1.2 MW_{DC} to a radial distribution network in Olohena, Kaua'i, Hawaii. The PV plant owner is Kapa'a Solar LLC, and the utility company is Kaua'i Island Utility Cooperative.

PV System

The Kapa'a solar PV plant has the following specifications:

- Output power: 1.2 MW_{DC}
- Self-corrosion resistance
- Direct connection to the utility grid
- Four 250-KW bipolar inverters.

Distribution Network

The existing substation provides power to the load that varies from 1.2 MW–2 MW. The substation rated voltage is 57.1 KV. A step-down transformer is used with a ratio of 57.1 KV:12.47 KV to connect the substation to the load. This PV is high penetration, at 60%. The monitoring that has been carried out by Kaua'i Island Utility Cooperative showed excellent results: the voltage is kept at acceptable level on both sunny and cloudy days. This encourages the utilities to install more PV plants with no major problems to the grid.

Issues and Concerns

The only concern that the electric utility company has is the IEEE 1547 standard for the frequency upper limit of 60.5 Hz. Because of the small load on the island and the interconnection of the PV plant, the frequency may exceed the upper limit of 60.5 Hz. The utility company and the consumer will benefit if the standard allows for an increase of the frequency operating range.

Case 4: 2-MW Plant in Fontana, California

In this project, a PV plant is installed in Fontana, California, to provide 2 MW_{AC} to consumers by interconnecting the plant to a radial distribution network. The PV plant is owned by Southern California Edison, which also owns the utility grid. This PV plant is part of a large project aimed toward providing 500 MW PV power by Southern California Edison by 2015.

PV System

The plant is a rooftop PV system with the following specifications:

- 30,472 solar modules to provide 2 MW_{AC}
- 256 DC string combiner boxes
- 12 fuse boxes
- Two 500-KW inverters
- Four 200: 480-V transformers.

Distribution Network

The existing substation provides power to a load ranging from 2.6 MW–4.2 MW. The rated voltage of the distribution network is 12 KV. A transformer of 480 V:12 KV is used to connect the plant to the grid. The penetration level of this PV plant is approximately 47%.

Issue and Concerns

Despite the high penetration of PV, a prior study and the measurements that were taken after interconnecting the PV plant showed no major technical problems; therefore, no major upgrade was done to the existing grid. There was a change in capacitor control bank settings.

Solutions

To overcome the problem of variable power generation, the delay setting was changed from 120 seconds to 30 seconds after interconnecting the PV plant. It is recommended that advanced inverter control functions such as volt/volt-ampere reactive control and curtailment can help mitigate potential negative impacts of a high-penetration PV system in a distribution network.