Chapter

Technical Requirements for Connecting Solar Power Plants to Electricity Networks

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Abstract

This chapter discusses basics of technical design specifications, criteria, technical terms and equipment parameters required to connect solar power plants to electricity networks. Depending on its capacity, a solar plant can be connected to LV, MV, or HV networks. Successful connection of a medium-scale solar plant should satisfy requirements of both the Solar Energy Grid Connection Code (SEGCC) and the appropriate code: the Electricity Distribution Code (EDC) or the Grid Code (GC) as the connection level apply. Connection of a large-scale solar plant to the transmission network should satisfy the requirements of both SEGCC and GC. For Small-Scale Photovoltaic (SSPV), the connection should satisfy both the SSPV Connection Code and the EDC. The objectives are to establish the obligations and responsibilities of each party; i.e. operators and all network users, thus leading to improved security, higher reliability and maintaining optimal operation. The technical specifications include permitted voltage and frequency variations in addition to power quality limits of harmonic distortion, phase unbalance, and flickers. Operational limits and capability requirements will be explained and discussed. Solar power grid connection codes of Egypt are explored first. Finally, brief comparisons of PV codes and related codes of UK, Germany, USA, and Egypt are presented.

Keywords: solar energy, PV power plants, grid connection codes, technical requirements and criteria, electricity networks, power quality

1. Introduction

The share of renewable resources for generating electric energy is increasing worldwide to cope with increasing demand. Current generation expansion plans of various countries expect increasing share of renewable energy resources in the electricity generation mix. By 2020, utilities set a target to reach a ratio of 20% renewable energy of the total energy required for electricity generation. Other utilities forecasted a higher share reaching about 50% by 2050. Wind energy and solar energy are the most promising resources and proven to be efficient in real applications with decreasing competitive costs of generated electric energy. The increasing share of renewable energies to be integrated to electric power systems has resulted in technical issues such as power quality requirements, capacity limits, safety measures, security, protection systems, synchronization process, lower system inertia, etc.

Electricity regulator authorities and electric utilities have issued necessary regulation rules for connecting sources of renewable energy to power networks at distribution and transmission levels according to the source capacity. A general overview of grid connection codes for integrating photovoltaic (PV) power plants to grids is presented in [1]. It presents a useful survey of grid codes, regulations, and technical requirements for connecting PV systems to low-voltage and medium-voltage networks, including issues of power quality and anti-islanding. An interesting guide dealing with PV interconnection requirements [2] has been developed and issued by the Interstate Renewable Energy Council, North Carolina Solar Center, USA. The guide covers all steps required for connecting a small-scale renewable energy system to the electricity network, including technical, contractual, rates, and metering issues. PV connection codes to medium-voltage power grid in Germany are discussed in [3]. A comparison of the processes of connecting PV systems in Germany and California is explored in [4]. Standards developed by the Institution of Engineering and Technology (IET) named "Code of Practice for Grid Connected Solar Photovoltaic Systems" are available in [5]. In South Africa, the National Energy Regulator has approved the "Grid Connection Code for Renewable Power Plants Connected to the Electricity Transmission System or the Distribution System" as detailed in [6]. Generally, utilities around the world either modify their grid codes to include technical requirements for integrating renewable energy resources to grids or issue separate but complementary codes for renewable resources.

This chapter describes the technical design specifications and criteria, technical terms, and equipment parameters for successful connection and operation of medium- and large-scale solar energy systems to the electricity networks in Egypt. The aim is to provide basic information and background on the technical design specification and criteria, in addition to technical terms and equipment parameters that are required to connect solar power plants to the electricity networks. Connection and successful operation of a solar power plant must satisfy the requirements of the Solar Energy Grid Connection Code (SEGCC) [7], and in the meantime the solar energy producer should comply with the requirements of the Electricity Distribution Code (EDC) [8]/Grid Code (GC) [9], according to the case of connection the MV distribution network/the HV transmission network.

The SEGCC specifies the special requirements for connecting both Medium-Scale Solar Plants (MSSPs) and Large-Scale Solar Plants (LSSPs) to the distribution networks or to the transmission network according to the capacity of the solar power plant. The capacity of MSSPs' range is from 500 kW to less than 20 MW. The LSSP range is greater than or equal to 20 MW. MSSPs may be connected either to the MV distribution networks or to the HV transmission networks. However, LSSPs are normally connected to the HV or extra-HV transmission networks. Successful integration of a MSSP shall comply with the technical requirements of both the SEGCC and the EDC, when connected to the distribution networks (or the GC when connected to the transmission network level). Similarly, the connection of a LSSP to the HV/EHV transmission networks shall satisfy the technical requirements of both the SEGCC and the GC. Technical requirements and terms stipulated in these codes should be clearly understandable in order to properly implement the rules and procedures of theses codes.

The EDC consists of the technical regulation rules and procedures to control technical and legal relationships between the licensed distribution system operator (DSO) and all users of the distribution network. The GC specifies the rules and procedures in order to control technical and legal relationships between the transmission system operator (TSO) and the users of the transmission network. The aim of the codes is to ascertain the obligations and responsibilities of each partner, i.e., TSO, DSO, and all users, namely, electricity producers, bulk-load customers, MV/

LV subscribers, etc. This will result in maintaining optimal power system operation, enhanced system security, and higher reliability.

The stipulated technical specifications of connecting MSSPs and LSSPs to the distribution networks or to the transmission network comprise the permitted limits of voltage and frequency variations in addition to power quality evaluation criteria such as limits of phase unbalance, limits of total and individual harmonic distortions, and limits of flicker severity. Operational limits and capability of solar power plants will be explained and discussed in this chapter.

It is important to mention here that the technical requirements for connecting small-scale photovoltaic (ssPV) systems to the low-voltage distribution networks are specified in the ssPV connection code [10]. Even though the ssPV code is considered to be all the complementary documents that involve compulsory requirements for a LV subscriber seeking installation of ssPV system, the subscriber shall also satisfy the technical requirements of the EDC. For more details, interested readers may refer to [11] for exploring technical background of connecting ssPV systems to LV distribution networks in Egypt.

The remainder of the chapter is structured as follows: Section 2 discusses briefly basic solar energy systems; Section 3 presents the codes of connecting solar power plants to electric grids in Egypt; Section 4 describes the technical requirements and criteria for connecting medium- and large-scale solar parks to the MV distribution networks or to the HV/EHV transmission networks; Section 5 briefly reviews terms and criteria of power quality referred to in the SEGCC; Section 6 presents comparisons of some rules of PV grid connection codes of three countries, namely, the UK, Germany, and Egypt; Section 7 summarizes the main conclusions and recommendations; and the Appendix at the end of the chapter lists the main IEC technical specification standards for solar park grid connection codes.

2. Solar energy: a brief introduction

Solar energy is the radiant light and heat from the Sun that is harnessed using solar heating, photovoltaics (PV), concentrated solar power (CSP), solar architecture, and artificial photosynthesis. Solar power is the conversion of the energy from sunlight into electricity, either directly using PV, indirectly using CSP, or a combination. The Sun is 1.3914 million km in diameter, and the radiated electromagnetic energy rate is 3.8 × 1020 MW. **Table 1** shows yearly renewable energy (RE) resources and human consumption. **Figure 1** shows the world annual solar insolation [12].

As shown in **Figure 1**, Egypt is one of the countries that possess the highest solar insolation. **Figure 2** shows the average direct solar radiation in kWh/m^2/day in

Yearly RE resources and human use of energy (EJ)	
Solar energy	3,850,000
Wind energy	2250
Biomass energy (potential)	Circa 200
Primary energy use (in year 2016)	Circa 557
Electricity generation (in year 2016)	Circa 89
Exajoule (EJ) = 10^{18}, J = 278 TWh.	

Table 1.
Annual renewable energy resources and human use of energy.

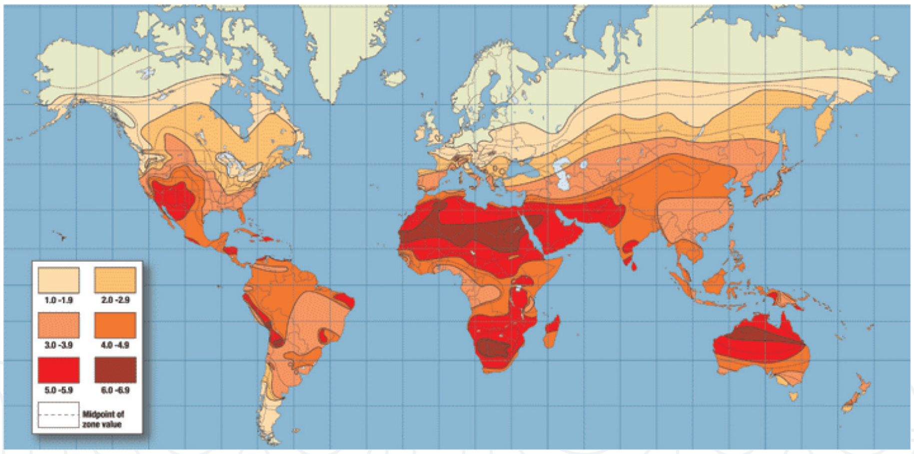

Figure 1.
Annual solar insolation worldwide [12].

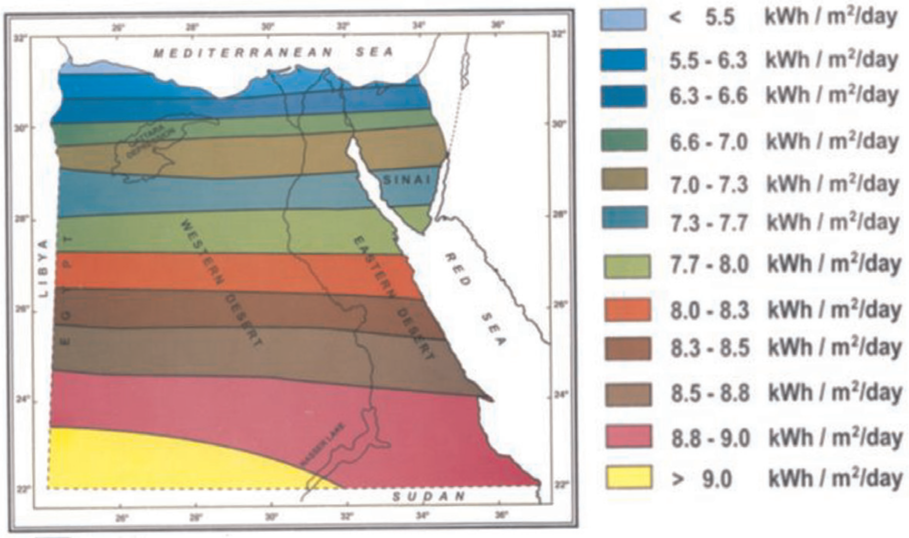

Figure 2.
Egypt solar atlas [13].

various regions in Egypt [11]. It can be noted that the southern regions have higher solar radiation than northern coastal regions. The region which has the highest solar radiation (>9.0 kWh/m^2/day) is shown in yellow in the figure.

Figure 3 shows the existing 1500 MW solar PV power plant located in Tengger Desert in China. It has been considered the largest PV power park in the world until now. Currently, Egypt is constructing a solar power plant of 1800/2000 MW in

Figure 3.
1500 MW Tengger Desert solar power plant in China.

Benban near Aswan [13]. It will comprise 40 PV stations of about 50 MW each. **Figure 4** shows an aerial view of part of the Benban PV solar power park [14]. Upon completion, Benban will be the worlds' largest PV power plant without energy storage.

Recent high concentration PV system is being developed by the IBM and the Air Light Energy Solutions using a parabolic dish to concentrate sunlight up to 2000 times onto new triple junction solar PV system. Each small (1 × 1 cm) chip can convert 50 W at 80% conversion efficiency, using liquid cooling process. **Figure 5** shows the concept of this new PV technology employing a tracking system to follow the sun.

Figure 6 shows the existing world's largest CSP plant (Ivanpah) located in California, in the Desert of Nevada in the USA. The installed capacity of this CSP plant is 392 MW [16]. The plant was commissioned in year 2014. Other larger CSP plants are currently under development in different countries. For example, Morocco's Ouarzazate solar power plant [17] will deliver about 580 MW of power once it is accomplished in year 2020. Also, Dubai authorities approved a CSP project to generate 1000 MW by 2020 and to be upgraded to 5000 MW by 2030.

Figure 7 shows the existing world's largest parabolic-trough solar energy generating systems located in Mojave Desert in California, USA. Its capacity is 354 MW

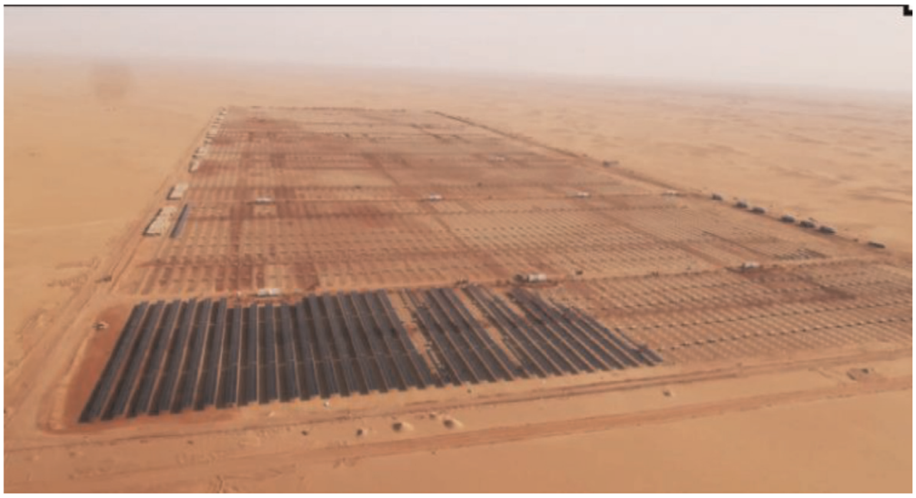

Figure 4.
Aerial view of under construction Benban PV power plant in Egypt [14].

Figure 5.
High-concentration PV system [15]. Image: www.airlightenergy.com/

Figure 6.
Ivanpah: the largest CSP plant in the world [16].

Figure 7.
Largest parabolic-trough concentrated solar system.

and includes 1600 acres. It was built in stages (1984–1990). The average capacity factor of this solar power plant is about 21%.

The concept of the solar updraft tower power plant (or solar chimney) [18] is shown in **Figure 8**. The solar chimney comprises four main parts, namely, the air collector, a tall tower, wind turbines, and an electric generator. The collector is suspended above the ground at a height of 2–20 m surrounding the tower. The solar radiation incident on the collector warms the air beneath the collector and makes it hotter than the outside air. The warmed air is drawn up through the tower, passing the wind turbine which is installed at the bottom of the tower base. The motion of air rotates the turbine and its associated electric generator.

Compared to PV systems, the solar chimney has the advantage of the possibility of operation 24 h a day even after sunset, thus overcoming the intermittency drawback of solar power. The available warm air beneath the collector can continuously operate the wind turbine and electric generator at night.

Figures 9 and **10** show the development of global solar energy generation from photovoltaic and concentrated solar power plants, respectively, up to year 2035 [19].

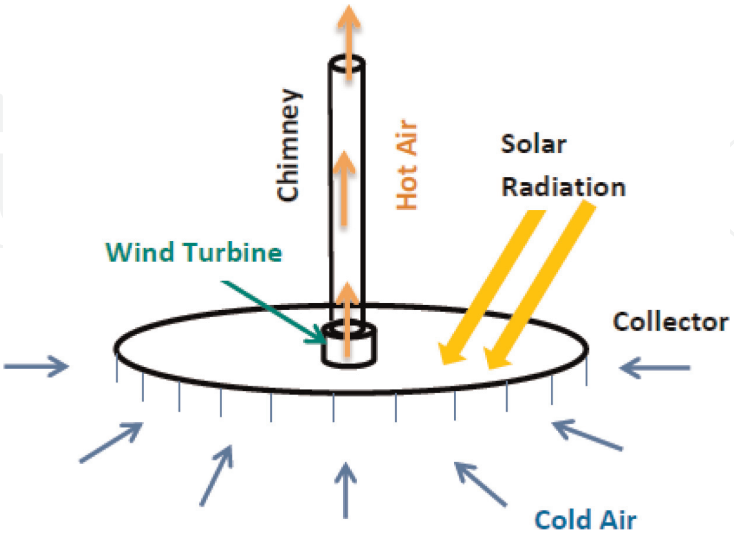

Figure 8.
Concept of solar chimney.

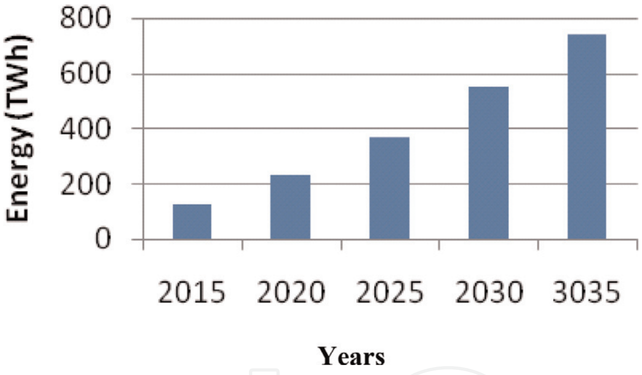

Figure 9.
Global energy generation from PV systems [19].

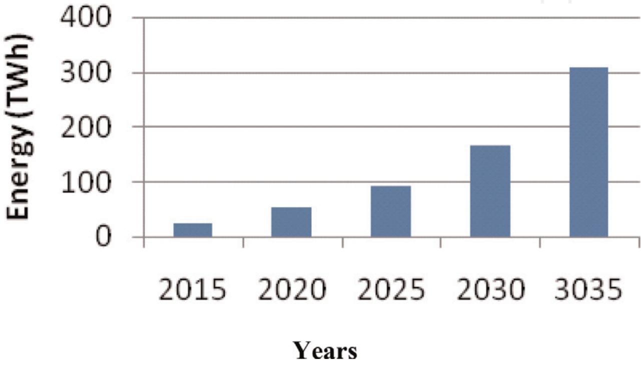

Figure 10.
Global energy generation from CSP plants [19].

3. Grid connection codes of solar power plants in Egypt

Two codes have been issued in Egypt for connecting solar power plants to electricity networks:

- The first one is ssPV code which stipulates the special requirements for the connecting small-scale photovoltaic systems (with rating < 500 kW) to low-voltage distribution networks [10].

- The second is the Solar Energy Grid Connection Code (SEGCC) which stipulates the technical requirements for connecting medium-scale (with capacity 500 kW to less than 20 MW) and large-scale (with capacity greater than or equal to 20 MW) solar power plants to the medium-voltage distribution networks or to the transmission grid.

The Grid Code (GC) in Egypt [9] defines the extra-high voltage (EHV) levels to be above 132 kV, the high voltage (HV) from 33 kV up to 132 kV, and medium voltage (MV) from 11 kV up to 22 kV. The solar plant grid connection codes are related to the following codes:

i. The Electricity Distribution Code (EDC) [8] which sets out the rules and procedures to regulate the relationship between the distribution utilities and users of the electricity distribution networks.

ii. The Egyptian Transmission System Code, commonly known as the “Grid Code” [9]. It sets out technical and legal relationships between the transmission system operator and the users of the transmission grid. The users are electricity production companies, distribution system companies, and bulk customers who are directly supplied from the transmission grid, etc.

In addition to the above codes, there is the “Wind Farm Grid Connection Code” [20] which concerns with the rules and procedures for connecting wind energy conversion systems to the transmission grid. The above five codes are shown in **Figure 11**. For instance, the wind grid farm connection code and the Grid Code are two complementary codes that should be fulfilled for connecting a wind farm to the transmission system.

The solar energy code and the Grid Code are two complementary technical documents that should be satisfied for connecting a solar power plant to the grid. The aim of the solar energy grid connection code is to stipulate the technical

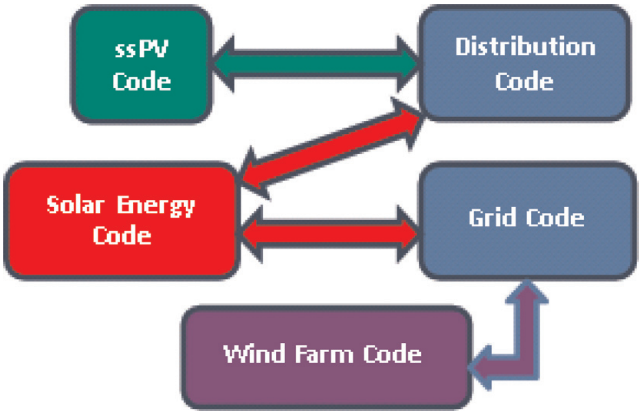

Figure 11.
Association of various codes in Egypt.

requirements for connecting solar energy resources either new or modified to the grid, so that security and quality of the grid are guaranteed.

The solar energy grid connection code specifies the special requirements for connecting solar energy plants to the MV distribution networks or HV/EHV transmission network. The technical requirements include permitted limits of voltage and frequency variations in addition to power quality limits such as of phase unbalance limits, harmonic distortion limits, and flicker severity limits. The code specifies also the operational limits of solar power plants to be integrated into the grid, plant capability requirements, active and reactive power control systems, safety measures, protection settings, synchronization, etc. The solar energy connection code shall apply to all medium-scale and large-scale solar power plants (either PV parks or solar thermal power plants) to be connected to the transmission grid. For connecting small-scale PV systems with capacity <500 kW to the LV distribution networks, we refer the reader to the small-scale PV (ssPV) code [10].

4. Solar energy grid connection requirements

4.1 Point of common coupling

The "point of common coupling (PCC)" is a point at which solar power plant is connected to the grid. It is sometimes called the "grid connection point (GCP)." The PCC is usually the connection point at the high-voltage terminals of the generator step-up transformer; it is generally located at the grid side of the isolating switch between the solar power plant and the grid. Normally, the solar energy grid connection code specifies the following technical requirements at the PCC.

4.2 Range of voltage

The grid-connected solar power plant shall be able to deliver its actual active power when the voltage at the point of common coupling remains within the ranges shown in **Table 2**. If required by the transmission system operator, the solar plant shall be also capable of automatically disconnecting from the grid at specified voltages.

4.3 Frequency range

In the case of a deviation of the grid frequency from its permissible value, the solar power plant shall perform as follows:

a. If the frequency is <50 Hz, the solar plant shall continue injecting active power until the frequency reduces below 47.5 Hz.

b. For over-frequency between 50 and 50.2 Hz, the solar power plant shall maintain the 100% of active power.

Range of voltage (pu)	Time of operation
0.85–1.10	Unlimited
1.10–1.15	30 min

Table 2.
Range of voltage at the PCC.

c. If the frequency is >50.2 Hz, the solar power plant shall inject active power up to 51.5 Hz.

4.4 Starting up solar power plants

The solar power plant shall only be connected to the power grid if the frequency and the voltage at the PCC are within the limits given in **Table 3** or as otherwise stated in the Connection Agreement (CA) between the transmission system operator and the owner of solar power plant.

During the start-up of a solar power plant, the active power increasing rate shall not exceed 10% (of the rated active power of the plant) per minute.

4.5 Power quality requirements

The solar plants connected to the power grid shall endeavor to maintain the quality of the voltage waveform at the PCC. The solar power plants shall comply with the requirements specified in Section 5.3 of the Performance Code of the Grid Code and/or the related part in the Electricity Distribution Code.

4.6 Harmonic distortion

The maximum harmonic distortion levels at the PCC which are attributable to the solar power plant shall obey the stipulations in the IEEE Standard 519-1992 as specified in Section 5.3.7 of Performance Code and/or the applicable section in the Electricity Distribution Code.

It is well known that a linear load, such as incandescent lamps or heaters, draws electric current from the source proportional to the applied voltage, while a nonlinear load such as an adjustable-speed drive draws currents apart from the voltage wave. The current of the nonlinear load comprises odd harmonics (third, fifth, seventh, etc.). The distortion effect of the third harmonic component is shown in **Figure 12**. Components of harmonic currents will interact with source currents, thus causing voltage harmonics. The voltage harmonic components are superimposed on the fundamental voltage component leading to a distorted voltage waveform. It may be mathematically described by the Fourier form Eq. (1):

$$f(t) = \alpha_o + \sum_{n=1}^{\infty} \alpha_n \cos(n\omega_o t) + \sum_{n=1}^{\infty} b_n \sin(n\omega_o t) \tag{1}$$

where

$$\alpha_0 = \frac{1}{T}\int_0^T f(t)dt + DC\ component \tag{2}$$

$$\alpha_n = \frac{2}{T}\int_0^T f(t)\cos(n\omega_o t)\,dt \tag{3}$$

Frequency	48.0 Hz ≤ f ≤ 51.0 Hz
Voltage	0.90 u ≤ U ≤ 1.10 pu

Table 3.
Limits of voltage and frequency during the start-up of a solar plant.

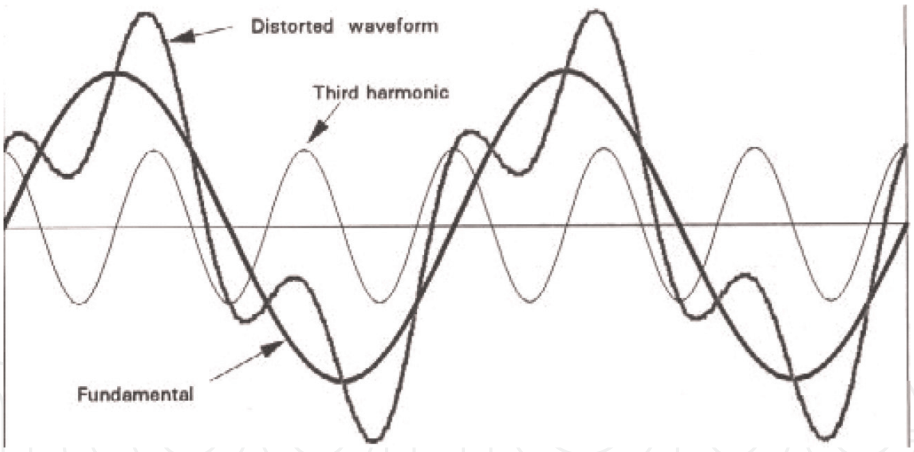

Figure 12.
Effect of the third harmonic.

$$b_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega_o)t\,dt \tag{4}$$

The total harmonic distortion in voltage (THDv) and current (THDi) are defined as follows:

$$THD\nu = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots}}{V_1} \tag{5}$$

$$THDi = \frac{\sqrt{i_2^2 + i_3^2 + i_4^2 + i_5^2 + \dots}}{I_1} \tag{6}$$

The flow of harmonic currents in electrical equipment can cause problems such as heating of equipment, overloading neutral line, wrong tripping of circuit breakers, increasing skin effect, etc. Hence, electricity codes specify appropriate limitations on the total and individual harmonics in the grids. The solar energy grid connection code defines the limits of the individual and total harmonic distortion of voltage and current waveforms at the PCC as listed in **Tables 4**–7 in accordance with the IEEE Standard 519-1992. The updated version of this standard (IEEE Standard 519-2014) has introduced new two rows as given in **Tables 4** and 7. We recommend using the updated version of the standard.

It should be noted that the harmonic distortion level may exceed the levels listed in the above tables for a period no longer than 30 s provided that such increases in harmonic distortion level do not compromise service to the users or cause damage to any equipment in the grid as determined by the TSO.

Level of voltage	**Harmonic voltage distortion level (%)**	
	Odd harmonic limits	**Total harmonic limits**
V ≤ 1 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
V > 161 kV	1.0	1.5

The first row for (V ≤ 1 kV) has been introduced in the IEEE Standard 519-2014.

Table 4.
Limits of harmonic voltage distortion.

Short circuit ratio	**Maximum integer harmonic current distortion as percentage of I_L**					
	Odd harmonic distortion**					**TDD**
I_{SC}/I_L	**<11**	**≥11 to <17**	**≥17 to <23**	**≥23 to <35**	**≥35**	
<20*	4.0	2.0	1.5	0.6	0.3	5
20 < 50	7.0	3.0	2.5	1.0	0.5	8
50 < 100	10.0	4.5	4.0	1.5	0.7	12
100 < 1000	12.0	5.5	5.0	2.0	1.0	15
>1000	15.0	7.0	6.0	2.5	1.4	20

where I_{SC} = the maximum short-circuit current at the PCC; I_L = the maximum demand load current (fundamental frequency component) at the PCC.
**All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.*
***The limits of even harmonics are 25% of the corresponding limits of odd harmonics listed in the table.*

Table 5.
Harmonic current distortion for transmission voltage level 69 kV and below.

Short circuit ratio	**Maximum integer harmonic current distortion as percentage of I_L**					
	Odd harmonic distortion**					**TDD**
I_{SC}/I_L	**<11**	**≥11 to <17**	**≥17 to <23**	**≥23 to <35**	**≥35**	
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4
50 < 100	5.0	2.25	2.0	0.75	0.35	6
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10

where, I_{SC} = the maximum short-circuit current at the PCC; I_L = the maximum demand load current (fundamental frequency component) at the PCC.
**All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.*
***The limits of even harmonics are 25% of the corresponding limits of odd harmonics listed in the table.*

Table 6.
Harmonic current distortion for transmission voltage level above 69 kV up to 161 kV.

Short circuit ratio	**Maximum integer harmonic current distortion as percentage of I_L**					
	Odd harmonic distortion**					**TDD**
I_{SC}/I_L	**<11**	**≥11 to <17**	**≥17 to <23**	**≥23 to <35**	**≥35**	
<25*	1.0	0.5	0.38	0.15	0.1	1.5
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75
The first row for (<25*) has been added in IEEE Standard 519-2014						

where, I_{SC} = the maximum short-circuit current at the PCC; I_L = the maximum demand load current (fundamental frequency component) at the PCC.
**All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.*
***The limits of even harmonics are 25% of the corresponding limits of odd harmonics listed in the table.*

Table 7.
Harmonic current distortion for transmission voltage level above 161 kV.

It should be also noted that the updated version IEEE Standard 519-2014 specifies the width of the window for measuring the harmonics to be 10 cycles in the 50 Hz systems, i.e., 200 ms window, as follows:

- For *very-short time* harmonic measurements, use the following equation:

$$F_{n,\nu s} = \sqrt{\frac{1}{15}\sum\nolimits_{i=1}^{15} F_{n,i}^2} \tag{7}$$

- For *short time* harmonic measurements, use the following equation:

$$F_{n,sh} = \sqrt{\frac{1}{200}\sum\nolimits_{i=1}^{200} F_{(n,\nu s),i}^2} \tag{8}$$

The system owner/operator should limit the line-to-neutral voltage harmonics at the PCC as follows:

- The values of the daily 99th percentile very-short time (which is 3 s in the 50 Hz systems) should be <1.5 times the values given in the tables.

- The values of the weekly 95th percentile short time (10 min) should be less than the values given in the tables.

For the current harmonic distortion **Tables 5–7**, the following points are applicable:

- The daily 99th percentile very-short time harmonic currents should be <2 times the values listed in the tables.

- The weekly 99th percentile short time harmonic currents should be <1.5 times the values given in the tables.

- The weekly 95th percentile short time harmonic currents should be less than the values given in the tables.

4.7 Limits of flicker severity

Table 8 shows the limits of the flicker severity produced by a solar energy power plant at the PCC as per recommendations of the IEC 61000-3-7.

Voltage flicker at the PCC is produced by voltage variations caused by a load such as an arc furnace when spectral characteristics of the voltage variations is in the range of a fraction of a cycle per second to about one third of the system frequency. It is a characteristic where a high-frequency (ω_o) sinusoid is modulated by a low-frequency sinusoid (ω_f).

In mathematical form

$$v(t) = \left\lfloor 1 + V_f \cos\left(\omega_f t\right)\right\rfloor V_m \cos\left(\omega_0 t\right) \tag{9}$$

Short-term (10 min)	$P_{st} \leq 0.35$
Long-term (2 h)	$P_{lt} \leq 0.25$

Table 8.
Levels of flicker severity at the PCC.

Intensity of flicker is given by

$$F = \frac{V_f}{V_m} = \frac{S_{scf}}{S_{sc}} \tag{10}$$

where S_{scf} is the short-circuit power (in MVA) at the electrode tip; S_{SC} is the short-circuit power (in MVA) at the PCC.

A flicker meter has been developed by the IEC to measure flicker severity in terms of fluctuating voltage magnitude and its corresponding frequency of fluctuations. The meter employs a software technique to convert measured voltage fluctuations to the following statistical quantities:

- Short-term flicker severity (P_{ST})
- Long-term flicker severity (P_{LT})

The flicker meter takes measurements automatically at 10-min intervals. The P_{ST} is calculated every 10 min. The flicker severity indicator P_{ST} which has a value of 1 is the level of visual flicker severity at which 50% of people would perceive flicker in a 60 W incandescent lamb. The long-term flicker severity P_{LT} is a combination of 12 P_{ST} measurement values of 10 min each.

4.8 Limits of voltage unbalance

The voltage unbalance in the three-phase system is defined as the difference between the highest and lowest line voltage divided by the average line voltage of the system. Solar power plants shall be able to withstand voltage unbalance not exceeding 2% for at least 30 s as stipulated in part 5.3.5 of Section 5 (Performance Code) of the Grid Code and/or the relevant section in the Distribution Code.

A three-phase system is balanced if the three-phase voltages have the same amplitude and are phase-shifted by 120° with respect to each other. Otherwise, the three-phase system is unbalanced. **Figure 13** shows the voltage waveforms of an unbalanced three-phase system.

The mathematical relationships between the symmetrical components of system voltages ($V_0 - V_1 - V_2$) and the phase components ($V_A - A_B - V_C$) are given in Eqs. (11) and (12):

$$\begin{bmatrix} V_0 \\ V1 \\ V2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{11}$$

$$a = e^{j120} \tag{12}$$

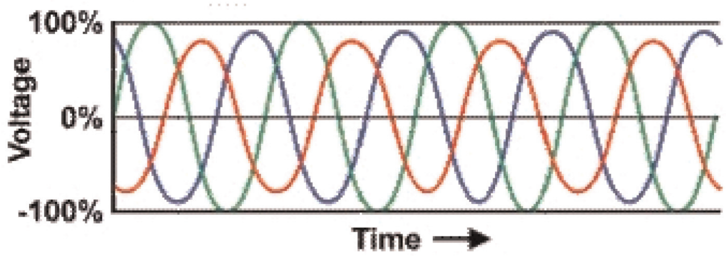

Figure 13.
Voltage waveforms of unbalanced three-phase system.

V_0 = zero-sequence component; V_1 = positive-sequence component; V_2 = negative-sequence component.

According to the EN-50160 and IEC-61000-3-x Standards, the voltage unbalance (V_{2U}) is defined as

$$V_{2U}\% = \frac{V_2}{V_1} \times 100 \tag{13}$$

The above standards define the following limits of voltage unbalance:

$$V_{2U} < 1\% \text{ for HV} \tag{14}$$

$$V_{2U} < 2\% \text{ for MV\&LV} \tag{15}$$

The voltage unbalance is measured as 10-min average value with an instantaneous maximum of 4%. Voltage unbalance may also be defined [21]:

IEEE definition of voltage unbalance

$$\%P_{vu} = \frac{\text{Maximum deviation from average } V_{ph}}{\text{Average } V_{ph}} \tag{16}$$

In Eq. (16) only magnitudes are considered.

NEMA defines the same formula but considers line voltages.

Approximate formula

$$\%VU = \frac{82 \times \sqrt{V^2abe + V^2bce + V^2cae}}{Average\, V_{line}} \times 100 \tag{17}$$

Subscript e means deviation from average. The causes of unbalance include generators; transformers; unbalanced impedances of long, non-transposed low-voltage lines; unbalanced load currents; single-phase loads on three-phase systems; etc. Unbalance can adversely affect motors and transformers by increasing heat and reducing their efficiencies.

4.9 Limits of voltage fluctuations

Voltage fluctuations, at the PCC of a solar power plant, can occur due to switching operations inside the solar plant elements such as transformers, capacitor banks, connection circuit, etc., resulting from inrush currents. These voltage fluctuations shall be up to 3% of nominal voltage provided that the fluctuations do not compose any risk to the grid or other connected users in the view of the TSO.

4.10 Control of active power

Figure 14 shows the ranges of voltage, frequency, and time periods within which the solar power plant shall continue delivering actual active power to the grid at the PCC. For grid frequencies in the range from 50.2 to 51.5 Hz, the solar power plant should reduce its active output power consistent with Eq. (18) and **Figure 15** providing that the voltage is within the range 0.9–1.1 pu:

$$\Delta P = 0.4 \times PM \times \Delta F \text{ perHZ} \tag{18}$$

where *PM* is the actual output power before the frequency of the grid exceeds 50.2 Hz; ΔF is the actual frequency minus 50.2 Hz.

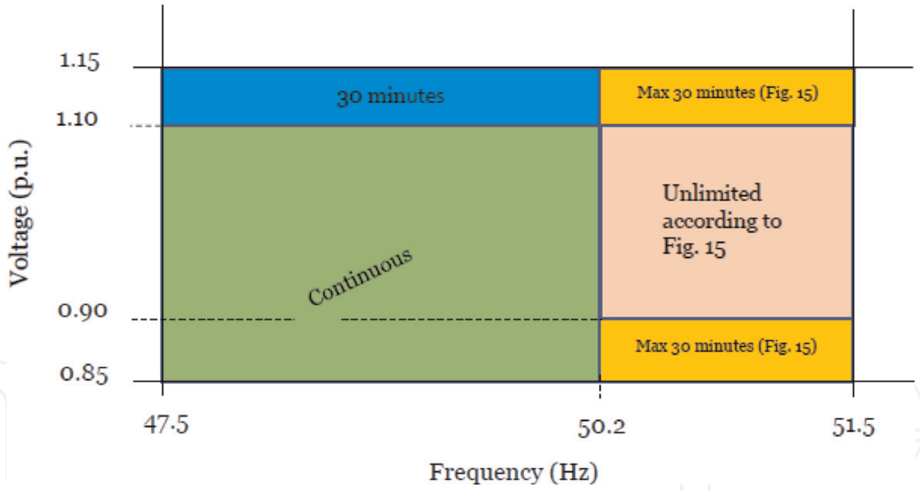

Figure 14.
Voltage, frequency, and time ranges of solar plant operation.

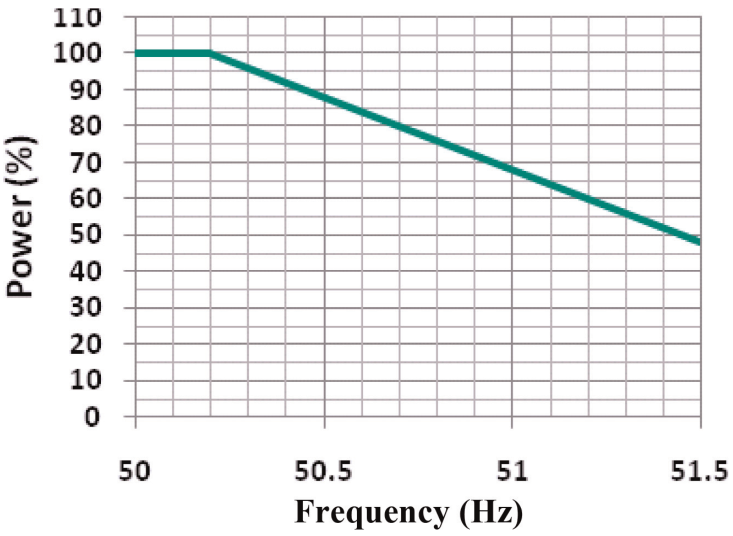

Figure 15.
Reduction in active power due to over-frequency.

Also, in this frequency range (i.e., 50.2–51.5 Hz) and the voltage ranges (0.85–0.9 pu) or (1.1–1.15 pu), the operation with reduced active power shall be limited to 30 min. The increasing or decreasing ramp of power will be performed in steps of a 10% (each) of the maximum power.

4.11 Control of reactive power

The solar power plant must be able to control reactive power at the PCC in a range of 0.95 lagging power factor to 0.95 leading power at the maximum active power of the plant and in consistent with **Figure 16** for the MSSPs and **Figure 17** for the LSSPs. The solar power plant must be able to perform reactive power control as follows:

- Set-point control of reactive power (Q)
- Set-point control of power factor
- Fixed power factor

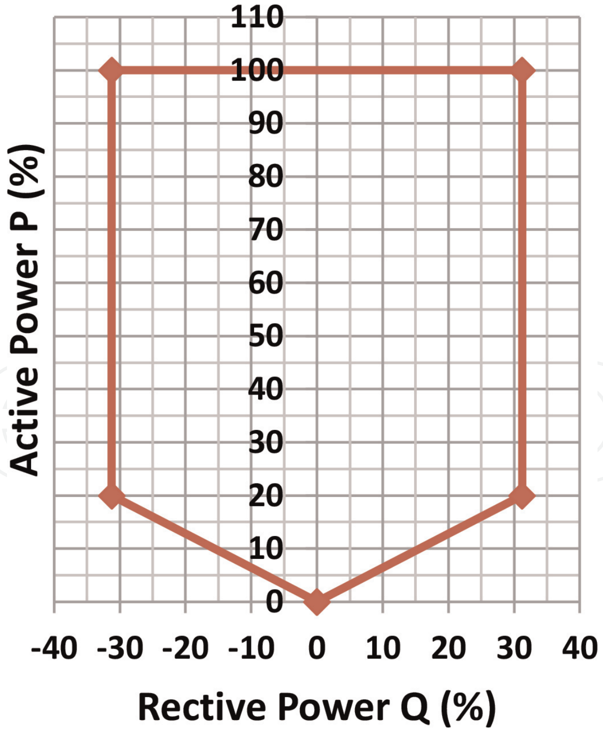

Figure 16.
P-Q capability chart for MSSPs.

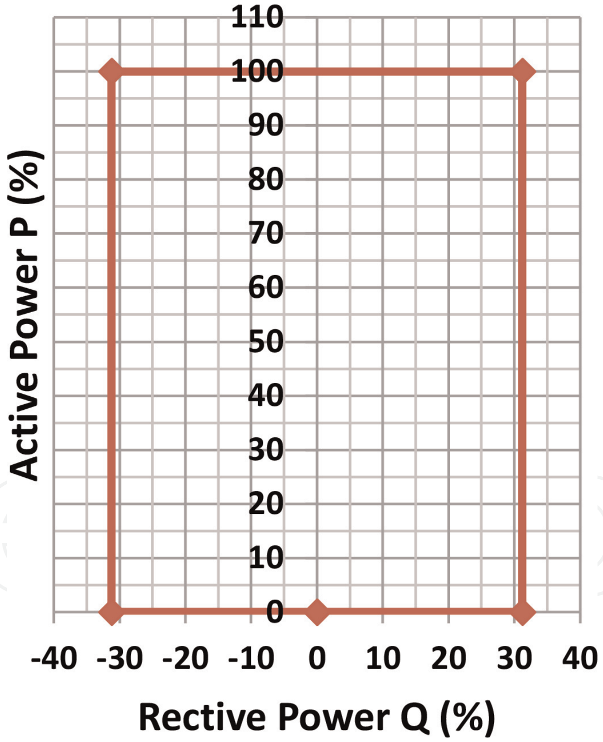

Figure 17.
P-Q capability chart for LSSPs.

- Characteristic: power factor as a function of active power output of the solar power plant, i.e., $\cos\varphi\ (P)$
- Characteristic: reactive power as a function of voltage, i.e., Q (V)

The solar power plant must possess an input signal for a set-point value at the PCC in order to control the reactive power or power factor of the plant. It is able to receive the set point within reactive power accuracy of 1 kVAr. The set-point signal will be provided by the TSO through verbal communication or SCADA, whichever is available. The solar power plant must follow the set-point signal of the TSO within 1 min. When the solar power plant operates at an active power output below its rated capacity, it shall be able to be operated in every possible operating point in the P-Q capability chart for plant size MSSP as shown in **Figure 16** and LSSP as shown in **Figure 17**. It should be noted that for LSSPs, even at zero active power output, reactive power injection at the PCC shall fully correspond to the P-Q capability chart taking into account the power requirements of auxiliary services, transformers' losses, and solar plant cabling.

The maximum values of the capacitive and inductive reactive power in **Figures 16** and **17** are calculated from the nominal generation capacity of the solar power plant and the power factor limit of 0.95 leading and lagging. Using capacitors and/or reactors to meet the requirements of the P-Q chart at the PCC is acceptable.

4.12 Low fault ride through (LVRT)

The SEGCC stipulates that, in case of a grid fault, the grid-connected solar power plant has to remain connected to the grid when the positive-sequence voltage at the PCC is above the curve shown in **Figure 18**. This defines the ability of the solar power plant to ride through the grid fault without disconnection from the grid. If all line-to-line voltages are below the curve shown in **Figure 18**, the solar power plant shall disconnect from the grid.

During this temporary voltage sag, the solar power plant must satisfy the following reactive power (or reactive current) requirement: in the case of a three-phase fault, the solar power plant must be able to inject reactive current in accordance with the curve shown in **Figure 19**, and satisfying Eqs. (19) and (20) for the time period of 250 ms started at the beginning of the fault and continue until clearing the fault.

Figure 19 shows the minimum reactive current required for the solar power plant during the fault. It is represented as the ratio of the reactive current to the nominal plant reactive current against the voltage drop which is represented as the ratio of the actual voltage to the nominal voltage at the PCC. All currents and voltages are in pu.

The following Eqs. (19) and (20) describe the required injected current during the fault:

$$\frac{\Delta I_B}{I_N} = k \times \frac{\Delta U_r}{U_N} \tag{19}$$

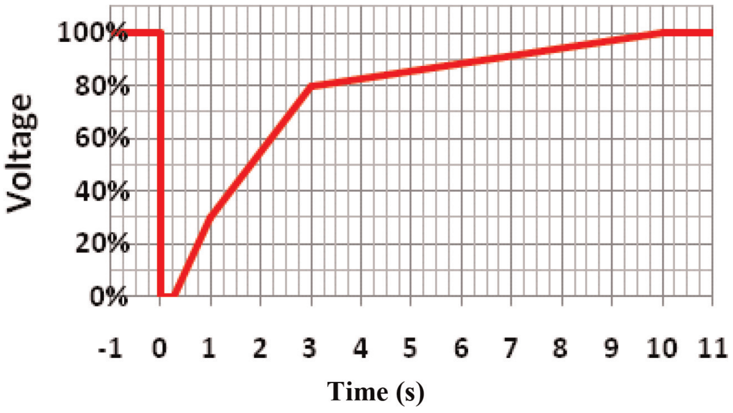

Figure 18.
Low voltage ride-through curve of solar plants.

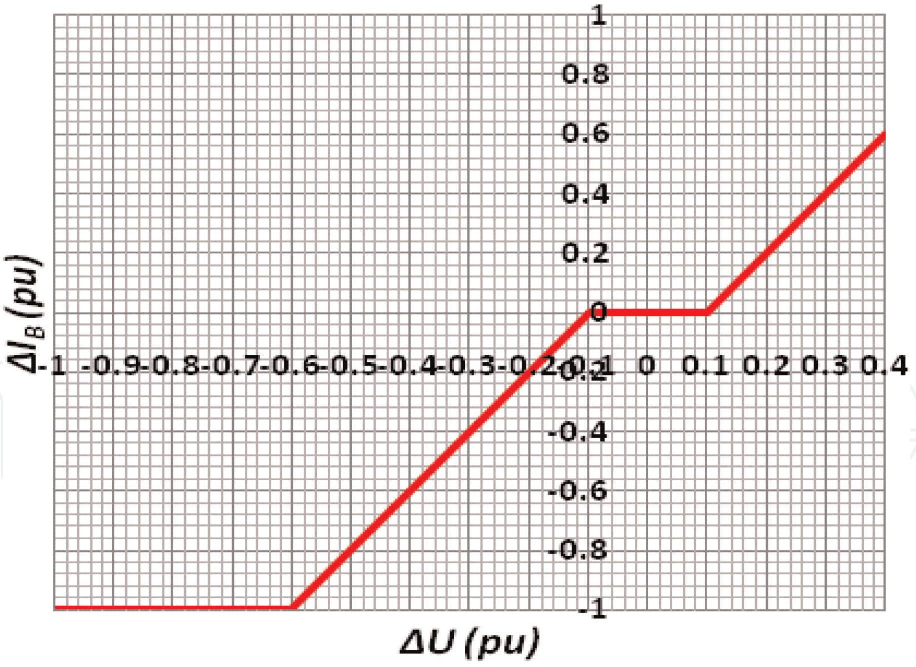

Figure 19.
Requirement of reactive current injection during the fault (k = 2).

$$\Delta U = U - U_O \tag{20}$$

If $\varDelta U \geq 0.1$, then $\varDelta U_r = \varDelta U - 0.1$
If $-0.1 < \varDelta U < 0.1$, then $\varDelta U_r = 0$
If $\varDelta U \leq -0.1$, then $\varDelta U_r = \varDelta U + 0.1$
If $\varDelta U \leq -0.6$, then $\varDelta I_B = -1$ pu

where U_N = the rated voltage; I_N = the rated current; U = the voltage during the fault; ΔI_B = the required reactive current change during the fault; U_0 = the voltage pre the fault; ΔU_r = the related change in the voltage during the fault.

In Eq. (19), the factor k shall be adjustable within the range of 0–4. In the case of unsymmetrical faults, it is not permitted to feed reactive currents to the grid during a fault which will cause rise to voltages higher than 110% of the nominal voltage at the PCC in the non-faulty phases. After fault clearance, the active power output from the solar power plant must reach the same value as that of pre-fault value within a period of 10 s after clearing the fault, and the reactive power consumption of the solar power plant must be less than or equal to the reactive power consumption before occurrence of the fault.

5. Comparison of solar energy grid connection codes

Solar energy grid connection codes may be issued as national standards in various countries or by transmission and distribution system operators [22]. These solar energy grid connection codes may be included in the relevant codes or issued separately as a complementary part. For example, the German Association of Energy and Water Industries issued new grid codes for integration of generating power plants to medium-voltage networks. Directives have been released in Germany for connecting electric generation power plants to medium-voltage and low-voltage grids [3]. The directives were based on the results of developing the German Grid Code for integrating renewable power plants into the high-voltage electricity grid [23]. The scope of the directives includes wind power plants, hydroelectric plants, PV solar generating systems, and combined heat and power plants.

In the UK, the Operations Directorate of Energy Networks Association has issued the Engineering Recommendation G83 [24] titled "Recommendations for connecting small-scale type tested embedded generators (up to 16 A/phase, i.e., 11.04 kW three-phase) in parallel with LV distribution systems." The Engineering Recommendation G59 [25] deals with generating plants greater than 11.04 kW up to 50 kW (three-phase). The rules of these engineering recommendations are applicable to all generation power plants irrespective of the type of electric generator and equipment employed for converting energy source into electricity.

The technical and design criteria required for connecting all types of distributed generation power plant are generally set out in the "Distribution Planning and Connection Code" of the UK distribution code [26] and in the "Connection Conditions Code" of the UK Grid Code [27].

In the USA, code standards, guides, and rules for PV systems are available [28–32]. The IEEE has issued a number of standards for integration of distributed energy resources (DERs) into power grids. The IEEE-1547 Standard series concerns with connecting DERs, including PV systems, among others, to electric power systems. The IEEE-2030 series of standards is issued to help implement communications and information technologies to enhance integration of DER with the grid. The National Electrical Code (NEC) Article 690 addresses safety standards for installing PV systems. Other NEC articles may also be applicable to PV installations. The Underwriters Laboratories (UL) Standard-1741 concerns with DER equipment including inverters, converters, and controllers. Standards and technical requirements for solar equipment, installation, etc. are available as guides for states

Code	Requirements in the code
UK Distribution Code	Be able to control the active power for frequency regulations (installed capacity 50 MW)
Germany grid codes for connecting PV systems to the medium-voltage power grid	Be capable of operation at reduced power output (if PCC rated voltage 10 kV) In above system frequency of 50.2 Hz, all generators have to reduce their output power with a gradient of 40%/Hz of the instantaneous available power The output power of the generator is only allowed to increase again as soon as the frequency reduces below 50.05 Hz
CAISO, USA	It is required that the solar plant be capable of providing a frequency response with 5 and 3% droop settings through its governor-like control loop. The definition of the PV plant droop control is the same as that of conventional generating units: $\frac{1}{\text{Droop}} = \frac{\Delta P/\mathrm{P}_{\text{rated}}}{\Delta F/60\text{Hz}}$ The dead band of the droop curve is ±36 mHz
Egyptian Solar Energy Plants Grid Connection Code	For grid frequencies in the range from 50.2 to 51.5 Hz, the solar plant has to reduce active power (installed capacity from 500 to 50 MW) The output power must be reduced by $\Delta P = 0.4 \times PM \times (\Delta f/\text{Hz})$ The output power is allowed to increase again as soon as the frequency is below 50.2 Hz

Table 9.
Comparison of active power and frequency control.

and municipalities [28]. A joint report produced by the North American Electric Reliability Corporation (NERC) and the California Independent System Operator (CAISO) provides information to maintain power system reliability while integrating variable energy resources, mainly wind and PV systems [29]. Large PV power plants are normally connected to the transmission grid [30]. Recently in 2019, the National Renewable Energy Laboratory (NREL) published two useful guide books for DER interconnection including current practices and emerging solutions [31] and permitting guide book for small solar systems [32].

As discussed in detail in previous sections of this book chapter, electricity authorities in Egypt have issued complementary documents to the Grid Code and distribution code for connecting solar systems to grids.

Comparisons of some rules in PV grid connection codes of Germany [1, 3, 22], the UK [1, 22], [24–27], the USA [28–32], and Egypt [7–11], [33] are presented here. The comparisons include power and frequency control rules and reactive power control rules. Detailed comparisons are available in [1, 3, 22].

Code	Requirements in the code
Germany grid codes for connecting PV systems to the medium-voltage power grid	In the event of voltage drop of more than 10% the reactive current contribution of at least 2% of the rated current per percent of the voltage drop, the facility must be capable of feeding the required reactive power within 20 ms
USA: requirements for reactive power control of PV power plants	FERC Order 661-A may be applied to PV power plants, and the required power factor range is ±0.95 measured at the Point of Interconnection (POI). It is also required that the PV power plant be capable of providing sufficient dynamic voltage support to guarantee reliability and safety of the system CAISO reactive power requirement stipulates a voltage operation window for PV power plants to provide reactive power at 0.95 pf lagging when voltage level at the POI is within 0.95–1 pu. Also, the PV plant should be able to absorb reactive power at 0.95 pf leading when voltage level at the POI is within the range of 1–1.05 pu
Egyptian Solar Energy Plants Grid Connection Code	For three-phase faults, the solar power plant must inject reactive current for a time period of 250 ms after the beginning of the fault until fault clearance For unsymmetrical faults, it is not permissible that during the duration of the fault, reactive currents be fed into the grid which will give rise to voltages higher than 110% nominal voltage in non-faulty phases at the grid connection point Reactive power of the solar power plant must be equal to or below the consumption of reactive power before the fault
Egyptian Technical Requirements for Connecting Small-Scale PV (ssPV) Systems to Low-Voltage Distribution Networks	“Power factor: The ssPV shall not inject reactive power into the utility network, while the drain of reactive power shall be limited to a power factor of 0.9. This limit applies unless otherwise agreed upon with the utility.” The ssPV consumes reactive power

Table 10.
Comparison of reactive power control.

5.1 Active power and frequency control

The main reason for the active power control is to ensure a stable frequency. **Table 9** summarizes the comparison between active power and frequency control rules in the relevant PV grid connection codes of the four countries, the UK, Germany, the USA, and Egypt.

5.2 Reactive power control

Consumption and generation of reactive power must be matched in order to maintain a stable system voltage. **Table 10** presents comparison of reactive power control requirements in PV grid connection codes.

6. Conclusions and recommendations

This chapter has explored technical design specifications, criteria, technical terms, and equipment parameters required to connect Medium-Scale and Large-Scale Solar Plants (MSSP and LSSP) to the electricity networks. The specifications, terms, and parameters have been extracted from the connection code of the MSSP and LSSP, Electricity Distribution Code, and Grid Code. Technical background of these specifications has been discussed in detail. Comparisons of some important rules in the PV grid connection codes of the UK, Germany, the USA, and Egypt have been described. The technical specifications and design criteria presented here are of great importance for planning, design, installations, testing, commissioning and operation, and engineers working in the field of connecting MSSP and LSSP systems to the transmission or distribution grids.

It is recommended to refer to the full versions of the concerned codes to comply with detailed grid connection requirements and successful operation of the solar power systems. Academic researchers are advised to follow the requirements of utility codes in performing research works related to integrating solar power plants into grids.

Appendix: standards of solar plant components

In the stages of designing, manufacturing, and installation of the solar power plant components, relevant international standards must be satisfied. As an example in Egypt, various IEC standards used for these purposes are listed in **Table 11**. All components shall meet the ranges and the operational requirements stipulated in the MSSP and LSSP solar plant connection codes. The solar power plant should be equipped with a synchronizing unit with a proper phase-locked loop to keep the inverter synchronized with the grid to deliver the right amount of power within permissible operational frequency and voltage variations. The rating and short-circuit duties of the switchgear shall comply with the Grid Code requirements. The power transformer efficiency shall be greater than or equal to 96%.

To enable visibility and control, the solar power plant shall be equipped with monitoring and security facilities having remote access communications means. The remote monitoring and controlling, telecommunications equipment, and the communication links shall comply with the requirements of the Grid Code and the distribution code as requirements of relevant case. The SEGCC contains details of specifications of real-time data, measuring, monitoring, and control equipment. The measurements include active power (kW), reactive power (kVAr), active

Solar plant components	IEC standards
Power transformer	IEC Standard 60076 IEC Standard 60085 for electrical insulation and IEC Standard 60214 for tap changer
AC switchgear	IEC Standard 62271
Inverter	IEC Standard 62109-2 IEC Standard 62116
Cabling and accessories in the site	IEC Standard 60227 series for LV (below 1 kV) IEC Standard 60502 series for HV installations
All relevant components	IEC Standard 60068-2 series for basic environmental tests, at least for IEC Standard 60068-2/1 cold, /2 dry, /14 change of temperature, and /30 damp heat
Site implementation	IEC Standard 60,364 series

Table 11.
IEC standards for components of solar power plants in Egypt.

energy (kWh), reactive energy (kVArh), voltages, currents, frequency, solar irradiance, temperature, and voltage and current harmonic distortions (THDv and THDi). The solar power plant shall provide all status signals, including transformer tap position, circuit breakers, disconnectors and earth switches, telecommunication alarms, protection signals at the grid side, inverter, etc. Also, set points of active power, reactive power, or power factor shall be indicated.

Technology solutions which shall be implemented in measuring, monitoring, and control of the solar power plants are described in detail in the SEGCC. The grid protection settings in the solar plants must comply with the requirements stipulated in the SEGCC, unless otherwise agreed with the transmission system operator. At the PCC, the grid protections shall be in compliance with the protection code of the Grid Code [9].

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