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Technical Requirements for Connecting Medium and Large Solar Power Plants to Electricity Networks in Egypt

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TECHNICAL REQUIREMENTS FOR CONNECTING MEDIUM AND LARGE SOLAR POWER PLANTS TO ELECTRICITY NETWORKS IN EGYPT

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ABSTRACT

This paper discusses basics of the technical design specifications, criteria, technical terms and equipment parameters required to connect Medium Scale Solar Plants (MSSPs) and Large Scale Solar Plants (LSSPs) to the electricity networks in Egypt. The MSSPs range from 500 kW up to less than 20 MW can be connected either to Medium Voltage (MV) distribution networks or to High Voltage (HV) transmission network. Successful connection of an MSSP should satisfy requirements of both the Solar Energy Grid Connection Code (SEGCC) and the Electricity Distribution Code (EDC), if connected to the distribution network, or the Grid Code (GC) if connected to the transmission network. Also, connection of a LSSP to the transmission network should satisfy the requirements of both SEGCC and the GC.

The SEGCC specifies the special requirements for the connection of MSSPs and LSSPs to the appropriate networks in Egypt. The EDC sets out the rules and procedures to regulate technical and legal relationship between distribution utilities and users of the distribution networks. The GC sets out the rules and procedures to regulate technical and legal relationship between the transmission utility and users of the transmission network. The aim is to maintain optimal operation, safety and reliability of the power system. The technical specifications including permitted voltage and frequency variations in addition to power quality measures such as limits of harmonic distortion, phase unbalance, and flickers. MSSP and LSSP operational limits, capability requirements, etc. will be explained and discussed.

1- INTRODUCTION

There has been a continuous increase in the share of renewable resources for generating the required electricity to cope with increasing demand. Future electricity generation plans of countries around the world expect more contribution of renewable energies in the electricity generation mix. Some utilities set a target of 20% renewable energy of total required energy by 2020. Others expect 50% by 2050. Among various renewable energies, wind and solar are the most promising resources and proved to be efficient in real applications at decreasing competitive kWh costs. The increasing ratio of renewable energy sources to be connected to electric power systems has resulted in technical issues related to power quality, capacity, safety, protection, synchronization, etc.

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Electricity utilities and regulators have issued regulation roles for connecting renewable energy sources to power grids at distribution level and transmission level. An overview of recent grid codes for Photovoltaic (PV) power integration is presented in [1]. It provides a survey of grid codes, regulations and requirements for connecting PV systems to LV and MV networks, including power quality concerns and anti-islanding issues. A guide to PV interconnection issues [2] has been developed by the Interstate Renewable Energy Council, North Carolina Solar Center, USA. Interconnection issues cover all steps for connecting a small scale renewable energy system to the utility network, including technical, contractual, and rates and metering issues. German codes for connecting PV systems to medium voltage power grid are described in [3]. A comparison of Germany's and California's interconnection processes for PV systems is discussed in [4]. The Institution of Engineering and Technology (IET) has developed the standards: “Code of Practice for Grid Connected Solar Photovoltaic Systems [5]. The National Energy Regulator of South Africa has approved the “Grid Connection Code for Renewable Power Plants Connected to the Electricity Transmission System or the Distribution System” [6]. In general, utilities either modify their codes to include regulations for connecting renewable energy resources or issuing complementary codes for these resources.

This paper concerns with technical design specifications and criteria, technical terms and equipment parameters required to connect Medium Scale Solar Plants (MSSPs) and Large Scale Solar Plants (LSSPs) to the electricity networks in Egypt. The objective is to provide basic information on the technical design specifications, criteria, technical terms and equipment parameters required to connect solar plants to the electrical networks in Egypt. Successful connection of a solar plant should satisfy the requirements of the Solar Energy Grid Connection Code (SEGCC) [7] and in the meantime the provider should comply with the requirements of the Electricity Distribution Code (EDC) [7] / Grid Code (GC) [8].

The SEGCC specifies the special requirements for the connection of MSSPs and LSSPs to distribution networks or to the transmission network. The capacity MSSPs range is 500 kW to < 20 MW, while LSSP range is ≥ 20 MW. MSSPs can be connected either to MV distribution networks or to the HV transmission network, whilst LSSPs are normally connected to the HV/EHV transmission network. Successful connection of MSSPs should satisfy requirements of both the SEGCC and the EDC, if connected to the distribution network (or the GC if connected to the transmission network). Similarly, connection of a LSSP to the transmission network should satisfy the requirements of both the SEGCC and the GC. Technical terms of these codes should be clearly understandable to correctly implement the rules and procedures of theses codes.

It is worth noting that the technical requirements for connecting small-scale photovoltaic (ssPV) systems to the Low Voltage (LV) distribution networks in Egypt are stipulated in the ssPV Code [7]. Although the ssPV Code is all complementary documents that entail obligatory provisions for customers seeking ssPV installations, the customer should also satisfy the requirements of the EDC. Technical background of connecting ssPV system to distribution networks in Egypt are described in [9].

The EDC is a document containing a set of rules and procedures to regulate technical and legal relationship between a Distribution System Operator (DSO) and users of the distribution network. The GC sets out the rules and procedures to regulate technical and legal relationship between the Transmission System Operator (TSO) and users of the transmission network. The objective is to establish the obligations and responsibilities of each party; i.e. the DSO, TSO and all network users; namely, subscribers, bulk customers, electricity production, etc. This will lead to maintain optimal operation, safety and reliability of the power system.

The technical specifications of integrating MSSPs and LSSPs to the distribution networks or to the transmission network include permitted voltage and frequency variations in addition to power quality measures such as limits of harmonic distortion, phase unbalance, and flickers. Solar plants operational limits, capability requirements, etc. will be explained and discussed.

The rest of the paper is organized as follows: Section II presents a brief introduction to solar energy. Section III describes the solar energy grid connection codes in Egypt. Section IV explains the technical requirements and criteria for connecting MSSPs and LSSPs to MV distribution networks or the HV/EHV transmission grid in Egypt. A brief review of power quality terms and criteria referred to in the SEGCC is presented. Section V summarizes the main conclusions and recommendations. The Appendix at the end of the paper concerns with the main components of the solar power plants and the required IEC technical specification standards.

II- INTRODUCTION TO SOLAR ENERGY

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 radiated electromagnetic energy rate is 3.8 x 10^{20} MW. Table (I) shows yearly Renewable Energy (RE) resources and human consumption. Figure (1) shows the world annual solar insolation [10].

Table I- Yearly RE Resources & Human Use of Energy

Yearly RE Resources & Human Use of Energy[1]	
Solar	**3,850,000**
Wind	**2,250**
Biomass potential	**~200**
Primary energy use[2]	**~557**
Electricity generation[2]	**~89**
[1] Energy given in Exajoule (EJ) = 10^{18} J = 278 TWh	
[2] In Year 2016	

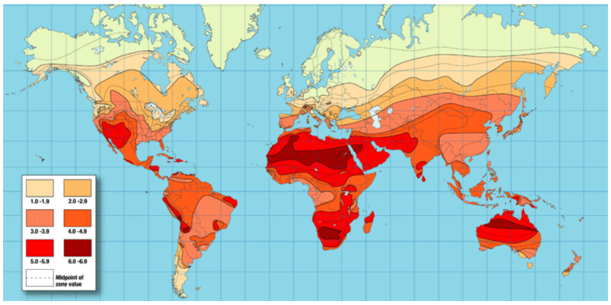

Fig. 1- Worldwide Annual Insolation [10]

Egypt is one of the countries that having the highest solar insolation in the world. Figure (2) shows the annual average of direct solar radiation in Egypt [11]. The south regions have higher solar radiation than northern coastal regions. The region shown in yellow has the highest solar radiation (> 9.0 kWh/m^2/day).

Egypt Annual Average of Direct Solar Radiation

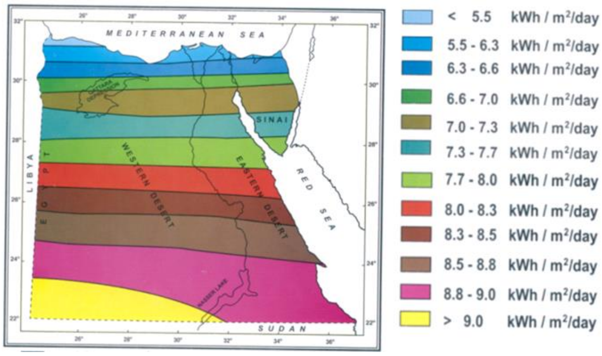

Fig. 2-Solar Atlas of Egypt [11]

Figure (3) shows the existing world's largest PV power plant of 1500 MW located at Tengger Desert solar park in China. Currently, Egypt is constructing a 2000 MW PV solar power plant in Benban near Aswan [11]. It consists of 40 PV power stations with 50 MW each. Figure (4) shows the location of Benban PV solar power plant [12]. After completion, it will be the largest PV power plant in the world.

Fig. 3-1500 MW Tengger Desert Solar Park in China

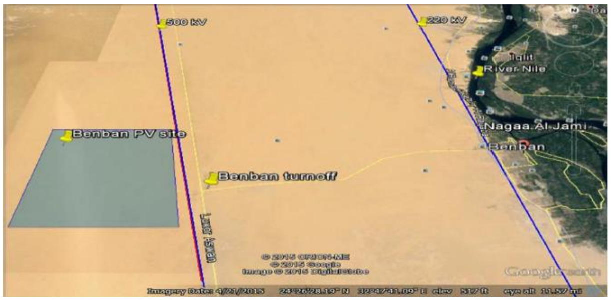

Fig. 4-2000 MW Benban PV Plant in Egypt [12]

Recently, IBM and Air light Energy Solutions are developing a high concentration PV system using a parabolic dish to concentrate sunlight up to 2000 times onto triple junction solar PVs. Each 1 by 1 cm chip can convert 50 W with 80% efficiency, using liquid cooling. A tracking system is used to follow the sun. Figure (5) shows the concept of this new technology.

Fig. 5- High Concentration PV System [13]
Image: www.airlightenergy.com/

Figure (6) shows the existing world's largest CSP located in Ivanpah, CA, (in the desert right by

Nevada) USA. The installed capacity is 392 MW. It was commissioned in 2014 [14]. Other larger CSP plants are under development. Morocco's Ouarzazate solar power plant will provide about 580 MW of power once it is completed in 2020 [15]. Dubai approved concentrated solar power project that will generate 1,000 MW by 2020 and 5000 MW by 2030.

Fig. 6- World's Largest CSP Located, Ivanpah, CA [14]

The existing world's largest parabolic trough CSP is the solar energy generating systems located in Mojave Desert in California. It has a capacity of 354 MW and covers 1600 acres. This solar power plant was built in stages from 1984 to 1990; its average capacity factor is about 21%. Figure (7) shows the plant.

Fig. 7- Parabolic Trough CSP SYSTEM

Figure (8) shows the concept of the solar updraft tower power plant (or solar chimney) [16]. It consists of four main parts: air collector, tall tower, wind turbines and electric generator. The collector is suspended 2 to 20 m above the ground surrounding the tower. The air beneath the collector is warmed by the sun and becomes hotter than the air outside. The warm air is drawn up through the tower and when passing through the wind turbine, installed at the bottom of the tower base, rotates the turbine and hence the generator.

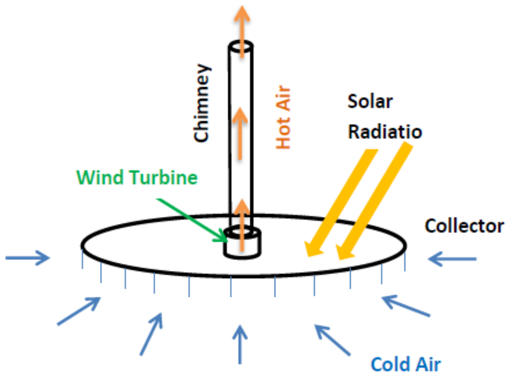

Fig. 8- Solar Chimney

The main advantage of the solar chimney over PV systems is that it can operate 24 hours a day even after sunset, thus overcoming the intermittency of solar power; the available warm air can continue operating the turbine and generator at night.

Figure (9) and Figure (10) show the development of world energy generation from PV and CSP systems, respectively up to 2035 [17].

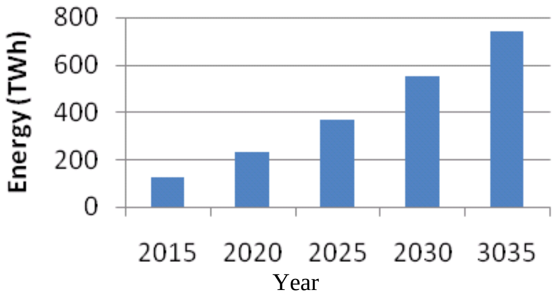

Fig. 9 - Global PV Energy Generation [17]

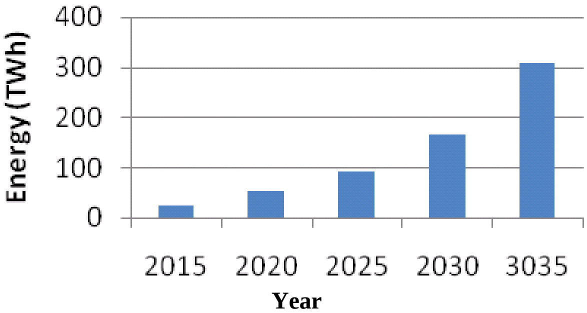

Fig. 10- Global CSP Energy Generation [17]

III - Solar Energy Grid Connection Codes in Egypt

There are two codes for connecting solar energy generation systems to the electricity grids in Egypt:
* The *ssPV Code* [7] which specifies the special requirements for the connection of small-scale PV systems (< 500 kW) to LV distribution networks.

* The *Solar Energy Grid Connection Code* [7] which specifies the requirements for connection of the Medium-Scale (500 kW to < 20 MW) and the Large-Scale (≥ 20 MW) solar plants to the MV distribution networks or to the HV/EHV transmission network.

As defined in the Grid Code (GC) in Egypt [8], Extra High Voltage (EHV) are voltage levels above 132 kV, the High Voltage (HV) are 33 kV up to 132 kV, and Medium Voltage (MV) are 11 kV up to 22 kV. The solar connection codes are associated to the following main codes:
1- The *Electricity Distribution Code* [7] which sets out the rules and procedures to regulate technical and legal relationship between distribution utilities and users of the distribution networks. The aim is to maintain optimal operation, safety and reliability of the power system.

2- The Egyptian Transmission System Code, known as *Grid Code* [8], sets out the relationship between the transmission system operator and users of the grid which includes: generation companies, distribution companies and bulk customers directly connected to the transmission grid.

In addition, the *Wind Farm Grid Connection Code* [7] concerns with the roles of connecting wind energy conversion systems to the power grid. Figure (11) depicts the relationships among the five codes. For example, the wind farm code and the grid code are two complementary codes that should be satisfied when connecting a wind farm to the transmission grid.

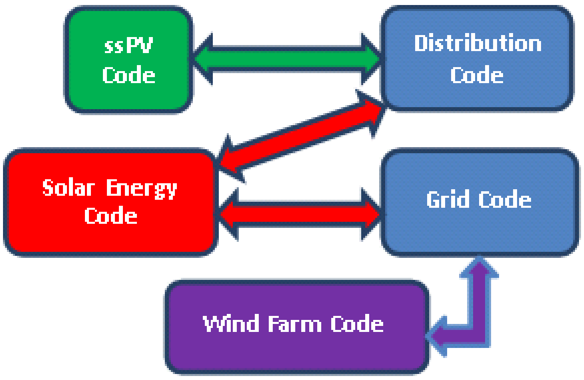

Fig. 11- Relationships Between Codes

The codes; solar energy grid connection code and the grid code (or the distribution code) are two complementary documents. The objective of the solar energy grid connection code is to determine the requirements for new or modified solar energy plants, so that it ensures security and quality of the grid.

The solar energy grid connection code specifies the special requirements for the connection of solar energy plants to the MV, HV, and EHV distribution and transmission grids. The required technical specifications include permitted voltage and frequency variations in addition to power quality measures such as limits of harmonic distortion, phase unbalance, and flickers. Operational limits of the solar systems to be connected to the grid, capability requirements, active & reactive power control, safety, protection, synchronization**, e**tc. are also specified in the code. The code shall apply to all MSSP and LSSP solar power plants (PV and thermal) to be connected to the grid. For the photovoltaic plants with generation capacity of less than 500 kW, refer to small scale PV (ssPV) Code [7].

IV-SOLAR ENERGY GRID CONNECTION REQUIREMENTS

A- Grid Connection Point (or the Point of Common Coupling

The point at which solar power plant is connected to the grid is called the "Grid Connection Point (GCP) or more widely the "Point of Common Coupling (PCC)". It is the connection point at the high voltage terminals of the generator transformer; normally located at the grid side of the isolating switch between the grid and the solar power plant. The following technical requirements are specified at the GCP (or PCC).

B-Voltage Range

In case of a deviation of the voltage at the PCC from its permissible voltage range, the solar plant shall be able to deliver actual active power when the voltage at this PCC remains within the ranges specified by the Table (II). The solar plant shall be also capable of automatic disconnection from the grid at specified voltages, if required by the TSO.

Table II- Voltage Range at the PCC.

Voltage range(PU)	Time period for Operation
0.85 – 1.10	Unlimited
1.10 – 1.15	30 minutes

C- Frequency Range

In 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 below 50Hz, the solar power plant shall continue injecting active energy until the frequency reduces below 47.5Hz.

b) In case of over frequency between 50 Hz to 50.2Hz the solar plant shall maintain the 100% of active power.

c) If the frequency is above 50.2Hz, the solar plant shall inject active energy up to 51.5Hz.

D- Start-up of the Solar Power Plant

The solar plant shall only be connected to the grid if the frequency and the voltage at the PCC are within the limits shown in Table (III), or as otherwise stated in the connection agreement between the TSO and the solar plant owner.

Table III- Limits of Voltage & Frequency During Start-up the Solar Plant

Frequency	**48 Hz ≤ f ≤ 51 Hz**
Voltage	**0.90 per unit ≤ U ≤ 1.10 per unit**

During the start-up of the solar plant the increase of the active power shall not exceed 10% if the rated power of the plant per minute.

E- Power Quality

All the solar power plants connected to the grid shall endeavor to maintain the voltage wave-form quality at the PCC. The solar plants shall comply with the requirements of Section 5.3 of the Performance Code in the Grid Code [8] and/or the relevant section in the Distribution Code [7].

F- Harmonics

The maximum levels of harmonic distortion at the PCC which are attributable to the solar plant shall follow the provisions in IEEE 519-1992 standard as set out in chapter 5.3.7 in Performance Code in the Grid Code and/or the relevant section in the Distribution Code.

Linear loads such as incandescent lighting and heating draw currents proportional to applied voltages, whilst non-linear loads such as adjustable speed drives draw currents during a part of the voltage cycle. The currents of nonlinear loads contains odd harmonics (3^{rd}, 5^{th}, 7^{th}, etc.). Figure (12) shows the distortion effect of the third harmonic component. Harmonic currents interact with source currents, leading to voltage harmonics. These harmonic components are superimposed on the fundamental voltage component resulting in a distorted voltage wave, which has the following Fourier form:

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

Where

$$\alpha_O = \frac{1}{T}\int_O^T f(t)dt + DC\ component \ldots\ldots\ldots\ldots (2)$$

$$\alpha_n = \frac{2}{T}\int_O^T f(t)\cos(n\omega_O t)\, dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$b_n = \frac{2}{T}\int_O^T f(t)\sin(n\omega_O)t\ \ dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

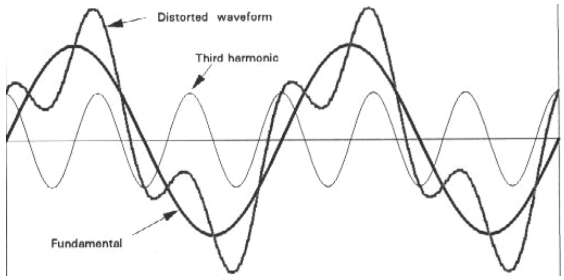

Fig. 12- Effect of Third Harmonic

The Total Harmonic Distortion in voltage (*THDv*) and current (*THDi*) are defined as follows:

$$THD\,v = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \ldots.}}{V_1}$$

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

Harmonic currents can cause problems such as equipment heating, false tripping of circuit breakers, neutral line overloading, increased skin effect, etc. Therefore, electricity codes stipulate limitations on *THD* and also individual harmonics in the networks. The SEGCC sets out the limits of the individual and total harmonic distortion of voltage and current at the PCC as shown in Tables (IV) to (VII) according to the IEEE 519-1992 Standard. New rows have been added in the updated version “IEEE 519-2014 Standard” as shown in Table (IV) and Table (VII). It is advisable to use the updated version in the Egyptian codes.

Table IV- Harmonic Voltage Distortion

Voltage Level (kV)	**Level of Harmonic Voltage Distortion (%)**	
	Odd Harmonics	**Total Harmonics**
V ≤ 1 kV	**5.0**	**8.0**
1 kV < V ≤ 69	**3.0**	**5.0**
69 kV < V ≤ 161	**1.5**	**2.5**
V> 161	**1.0**	**1.5**
The first row for (V ≤ 1 kV) has been added in IEEE 519-2014		

Table V- Harmonic Current Distortion Transmission Voltage Level 69 kV and Below

Short Circuit Ratio	Maximum Integer Harmonic Current Distortion as Percentage of IL					
	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

Table VI- Harmonic Current Distortion 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	
<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

Table VII- Harmonic Current Distortion Transmission Voltage Level above 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 519-2014						

Notes on the Tables

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.

** Even harmonics are limited to 25% of the odd harmonic limits in the Tables.

Where:

I_{SC}: maximum short circuit current at PCC.

I_L: maximum demand load current (fundamental frequency component) at PCC.

The harmonic distortion may exceed the above levels for a period not exceeding 30 seconds provided that such increases in harmonic distortion do not compromise service to users or cause damage to any grid equipment as determined by the TSO.

Harmonic measurements according to the updated IEEE 519-2014 Standard specify the measurement window width to be 10 cycles in 50Hz systems:

* Very short time harmonic measurements

$$F_{n,vs} = \sqrt{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^{2}} \quad \text{..............................(5)}$$

* Short time harmonic measurements

$$F_{n,sh} = \sqrt{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^{2}} \quad \text{.........................(6)}$$

At the PCC, the system owner or operator should limit line-to-neutral voltage harmonics as follows:

* Daily 99th percentile very short time (3s) values should be less than 1.5 times the values given in the tables.

* Weekly 95th percentile short time (10min) values should be less than the values given in the tables.

Daily 99th percentile very short time (3s) harmonic currents should be less than 2 times the values given in the tables. Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in the tables. Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in the tables.

G- Flicker

The flicker, caused by a solar power plant at the PCC, must be within the limits shown in Table VIII, as per the IEC 61000-3-7.

Table VIII- Flicker Severity Levels

Short term (10 minutes)	$P_{st} \leq 0.35$
Long term (2 hours)	$P_{lt} \leq 0.25$

If a load such as an arc furnace causes voltage variations at the PCC with spectral characteristics in the range of a fraction of a cycle/s and about one third of the system frequency, this effect is known as voltage flicker. It is a characteristic where a high frequency (ω_o) sinusoid is modulated by a low frequency sinusoid (ω_f).

* In mathematical form

$$v(t) = \lfloor 1 + V_f \cos(\omega_f t) \rfloor V_m \cos(\omega_O t) \text{ ....(7)}$$

* Intensity of flicker is given by,

$$F = \frac{V_f}{V_m} = \frac{S_{scf}}{S_{sc}} \text{ ....(8)}$$

$\mathbf{S_{scf}}$ = short-circuit MVA at the electrode tip
$\mathbf{S_{SC}}$= short-circuit MVA at the PCC

The IEC has developed a flickermeter which measures flickers in terms of fluctuating voltage magnitude and its corresponding frequency of fluctuations. It uses a software technique to convert flicker voltage fluctuations into the following two statistical quantities:

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

The flicker meter takes measurements automatically at ten minutes intervals. The short term flicker severity is calculated every 10 minutes. The indicator P_{ST} having a value of 1 represents the level of visual severity at which 50% of people would perceive flicker in a 60 W incandescent bulb. The long-term flicker severity P_{LT} is a combination of 12 P_{ST} values.

H- Voltage Unbalance

Voltage unbalance is defined as the deviation between the highest and lowest line voltage divided by the average line voltage of three phases. Solar plants shall be able to withstand voltage unbalance not exceeding 2% for at least 30 seconds as per the provisions in the chapter 5.3.5 of the Section 5 (Performance Code) in the Grid Code and/or /or the relevant section in the Distribution Code.

A three-phase power system is called balanced if the three phase voltages (and also currents) have the same amplitude, and are phase shifted by 120^o with respect to each other. If either or both of these two conditions are not met, the system is called unbalanced as shown in Figure 13.

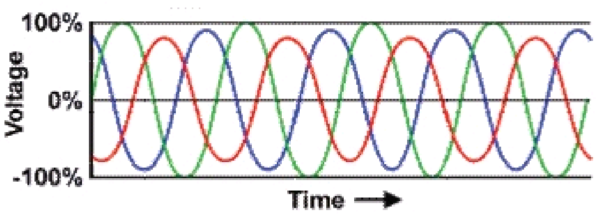

Fig. 13- Unbalanced Three-phase Voltages

The relations between the symmetrical components (V_0- V_1- V_2) and the phase components (V_A - A_B - V_C) are given in (9) and (10):

$$\begin{bmatrix} V_O \\ V1 \\ V2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \text{ ....(9)}$$

$$a = e^{j120} \text{ ....(10)}$$

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,

$$V_{2U}\% = \frac{V_2}{V_1} \times 100 \text{ ....(11)}$$

The above standards stipulate the following voltage unbalance limits:

V_{2U} <1% for HF ....(12)
V_{2U} < 2 for MV & LV ....(13)

These values are measured as 10-minute average value with an instantaneous maximum of 4%. Other definitions [18] of voltage unbalance are:

<u>IEEE</u>

$$\%Phvu = \frac{Max\,Deviation\ from\ AverageVph}{AverageV_{ph}} \times 100 \text{ ..14)}$$

Only magnitudes are considered.

<u>NEMA:</u> Same formula but line voltages are used.

<u>APPROXIMATE</u>

$$\%VU = \frac{82 \times \sqrt{V^2abe + V^2bce + V^2cae}}{AverageV_{line}} \times 100 \text{ ....(15)}$$

Subscript e means deviation from average. Causes of unbalance include: generators, transformers, unbalanced impedances of long, non-transposed low voltage lines, unbalanced load currents, single-phase loads on 3-phase systems, etc. Unbalance can adversely affect equipment such as motors and transformers by increase heating and reduce efficiency.

I- Voltage Fluctuations

Voltage fluctuations at the PCC of a solar plant can occur because of switching operations within the Solar Plant facilities (i.e. capacitor banks, collection circuit transformers) due to inrush currents. Voltage fluctuation at the PCC shall be up to 3% of nominal voltage provided that this not constitutes a risk to the Grid or other user in the TSO's view.

J- Active power control

The solar power plant shall continue injecting actual active power within the frequency range of 47.5Hz up to 50.2 Hz and grid voltage range, at the PCC, for the time periods given in Table II .For grid frequencies in the range from 50.2 Hz to 51.5 Hz the solar plant has to reduce active output power according to (16) provided that the voltage is within 0.9 pu to 1.1 pu:

$\Delta P = 0.4 \times PM \times \Delta f$ per Hz ………………… (16)

PM: actual output power before the grid frequency exceeds 50.2 Hz

Δf: actual grid frequency minus 50.2 Hz

Also, in this range of frequency (50.2 Hz to 51.5 Hz) and the voltage is in the ranges (0.85 pu to 0.9 pu) or (1.1 pu to 1.15 pu), the operation with reduced active power should be limited to 30 minutes. The reduction or increase ramp will be given as percentage of the maximum power, in steps of a 10% each.

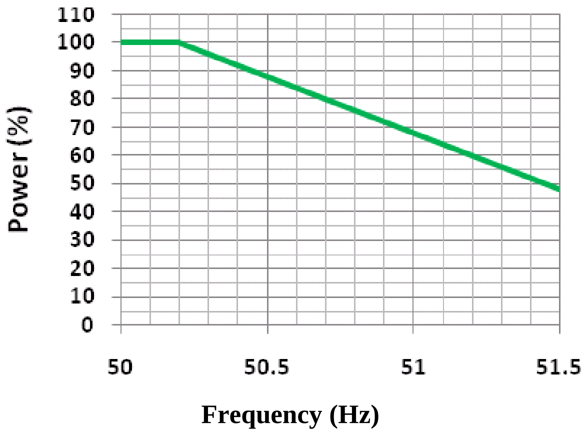

Fig. 14- Active Power Reduction Due To Over Frequency

K- Reactive Power Control

The solar plant must be able to control reactive power at the PCC in a range of 0.95 lagging to 0.95 leading at maximum active power and according to Figure 15 for MSSPs and Figure 16 for LSSPs. The solar plant must be able to control reactive power as follows:

- Set-point control of reactive power Q.
- Set-point control of power factor (cos φ).
- Fixed power factor (cos φ).
- Characteristic: power factor as a function of active power output of the Solar Plant, cosφ(P).
- Characteristic: reactive power as a function of voltage, Q(U).

The solar plant must have an input signal for a set-point value at the PCC, to control the reactive power or cos φ of the solar plant. The solar plant shall be able to receive the set-point with an accuracy of 1 kVAr. The TSO will provide the set-point signal through verbal communication or SCADA, whichever is present. The solar plant must follow the set- point signal of the TSO within one minute. When operating at an active power output below the rated capacity of the solar plant (P < Pmax), the solar plant shall be able to be operated in every possible operating point in the P-Q diagram for solar plant sizes MSSP (Figure 15) and LSSP (Figure 16). For LSSP, even at zero active power output (e.g. during the night), reactive power injection at the PCC shall fully correspond to the P-Q diagram taking the auxiliary service power, the losses of the transformers and the solar plant cabling into account.

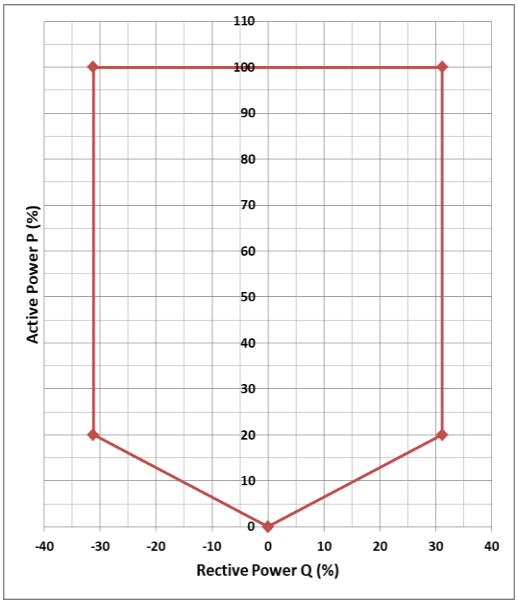

Fig. 15- P-Q Diagram for MSSPs

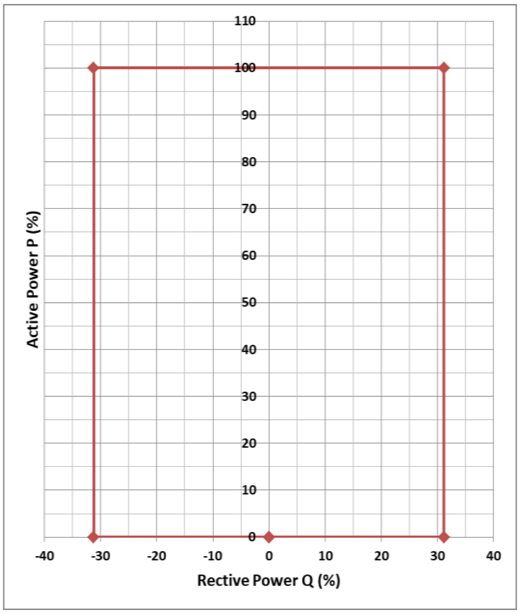

Fig. 16- P-Q Diagram for LSSPs

The maximum Q capacitive and the maximum Q inductive in Figure 15 and Figure 16 are calculated from the nominal generation capacity of the solar plant and the power factor of 0.95. The use of capacitor and/or reactor banks to meet this P-Q requirement at the PCC is acceptable.

L- Fault Ride Through

For temporary voltage drops, when positive sequence voltage is above the curve in Figure 17, solar plants have to ride-through the grid fault without disconnection from the grid. The solar plant shall trip if all phase-to-phase voltages are below the curve in Figure 17.

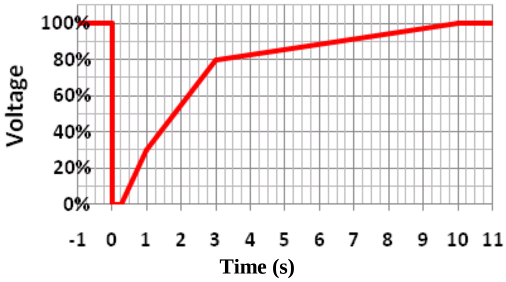

Fig. 17: Fault Ride- Through of Solar Power Plants

During the temporary voltage drop the solar plant must fulfill the following requirements concerning reactive power or reactive current. For 3-phase faults the solar plant must inject reactive current according to Figure 18 and equations (17) and (18) for the time period of 250 ms after the beginning of the fault until fault clearance.

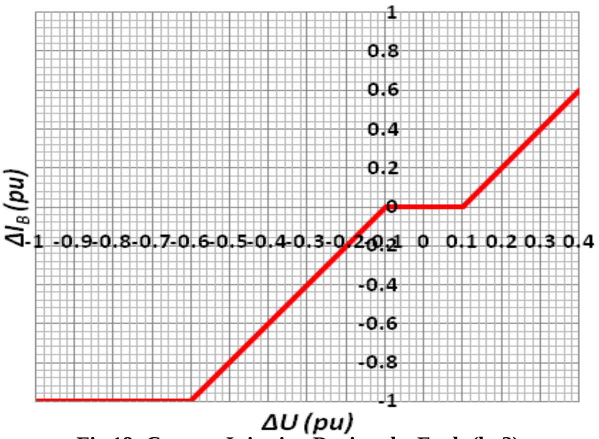

Fig.18: Current Injection During the Fault (k=2)

Figure 18 depicts the required minimum reactive current, expressed by the ratio of the reactive current and the nominal reactive current (in per unit), against the voltage drop, expressed by the ratio of the actual voltage value and its nominal value (in per unit) at the grid connection point.

Current injection during the fault

$$\frac{\Delta I_B}{I_N} = k \times \frac{\Delta U_r}{U_N} \quad \text{.................................(17)}$$

$$\Delta U = U - U_O \quad \text{.. (18)}$$

If $\Delta U \geq 0.1$, then $\Delta U_r = \Delta U - 0.1$

If $- 0.1 < \Delta U < 0.1$, then $\Delta U_r = 0$

If $\Delta U \leq - 0.1$, then $\Delta U_r = \Delta U + 0.1$

If $\Delta U \leq - 0.6$, then $\Delta I_B = -1$pu

where

U_N: rated voltage

I_N: rated current

U: voltage during fault

ΔI_B: required reactive current change during fault

U_0: pre-fault voltage

ΔU_r: relevant voltage change during the fault

The factor k in (17) shall be adjustable in the range from 0 to 4. 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 that 110% nominal voltage in non-faulty phases at the PCC. After fault clearance the active power output of the solar plant must reach the same level as before the fault within a time period of 10 s after fault clearance and the consumption of reactive power of the solar plant must be equal or below the consumption of reactive power before the fault.

V- CONCLUSIONS

The paper has presented the technical design specifications, criteria, technical terms and equipment parameters required to connect Medium-Scale and Large-Scale Solar Plants (MSSP & LSSP) to the electricity networks in Egypt. The specifications, terms and parameters are extracted from the MSSP & LSSP Code, Grid Code and Distribution Code and explained in more details. The presented technical specifications and criteria are useful for researchers, design engineers, and installations engineers working in the field of connecting MSSP & LSSP systems into the HV/EHV transmission grid or the MV distribution networks. For successful connection of these solar power systems to the networks, it is recommended to read the full versions of the concerned codes. Academic researchers should take into consideration the requirements of utility codes in performing research works. Engineers in the field of designing, installing, testing, commissioning and operation of solar power plants need to clearly acquire detailed technical background of the codes.

APPENDIX

Solar Plant Components Standards

Design, manufacturing and installation of all components employed in solar power plants shall be certified according to the relevant international standards. Table IX lists the IEC Standards used. All components shall meet the grid connection ranges and the operational requirements specified in the MSSP and LSSP solar plant connection code. The plant should be equipped with a synchronization unit with a phase-locked loop to keep the inverter synchronized with the grid to provide the right amount of power within permitted operational voltage and frequency changes. The switchgear rating and short circuit duties shall comply with the GC requirements. Efficiency of the power transformer shall be ≥ 96%.

Table IX- Technical Specification Standards for Solar Power Plant Components

Component	Standard
Inverter	IEC 62109-2 IEC 62116
AC Switchgear	IEC 62271
Power Transformer	IEC 60076 IEC 60085 for electrical insulation and IEC 60214 for tap changer
Site Implementation	IEC 60364 series
Cabling and Accessories in the Site	IEC 60227 series for LV (below 1kV) IEC 60502 series for HV installations
All Relevant Components	IEC 60068-2 series for Basic Environmental Tests, at least for IEC 60068-2 /1 cold, /2 dry, /14 Change of Temperature, and /30 Damp Heat

The solar power plant shall be equipped with monitoring and security systems with a communications medium having remote access to facilitate visibility and control of the plant. The telecommunication, remote monitoring and controlling equipment and the communication links shall comply with the requirements of the GC and the EDC as relevant case. Details of real-time data, measuring, monitoring and control equipment can be found in the SEGCC. The measurements include powers (kW, kVAr), energies (kWh, kVArh), voltages, currents, frequency, solar irradiance, temperature, and harmonics (THDv, THDi). Status signals from the solar power plant shall be provided. These include status of transformer tap position, circuit breakers, disconnectors and earthing switches, alarms of the telecommunication system, protection signals at the grid side, inverter, etc. Set-point values, such as those of the active power, reactive power or power factor shall be indicated.

Details of technology solutions which shall be implemented in measuring, monitoring and control of the solar plant are given in the SEGCC. The settings of the grid protection devices in the solar power plant must conform to those shown in the SEGCC, unless agreed otherwise with the TSO. The grid protections for the PCC shall comply with the Protection Code of the Grid Code [8].

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