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Review of Electricity Distribution Codes and PV Connection Codes

Review Article

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Abstract: Electricity is the key driver of the global economy. It is the prime energy resource for supplying customers (industry, irrigation, commerce, service, residence, etc.). This paper discusses technical requirements for Electricity Distribution Codes in various countries. The major similarities and differences between Electricity Distribution codes are clarified. Then, a detailed comparison of photovoltaic systems grid connection codes is presented. The comparison includes voltage and frequency deviations, active and reactive power control, power factor control and fault ride through.

Keywords: PV integration; PV code; Electricity distribution code

Introduction

Government programs in most of countries, are driving markets, creating opportunities for small businesses and delivering sustainable energy services. To achieve that, the network should be capable to ensure safe, secure and reliable operation. Distribution networks are the most confrontational to bidirectional flow challenge as most of businesses are small and medium scale renewable plants, which are connected directly to distribution networks. Therefore, Electricity Distribution code (EDC) and renewable codes should be updated to cope with these emerging challenges.

Detailed review of Egyptian Small-Scale Photovoltaic Code (SSPVC) and case study for a 200 kW photovoltaic (PV) plant was presented in [1]. An overview of various international standards for Low Voltage (LV) PV systems grid integration was presented in [2], showing the discrepancies between them. In addition, a comparison between Germany, France and Spain codes for Medium Voltage (MV) PV integration was presented. The current Vietnamese technical and administrative framework for connecting PV plants to the LV and Medium Voltage (MV) grids was examined in [3] including a comparison with the relevant Italian technical and administrative framework. European grid-code requirements for PV power plant installations to LV and MV is described in [4]. PV power integration related grid codes are collected and compared in [5] for different countries (China, Europe, North America). Detailed technical requirements for connecting solar power plants to electricity networks were presented in [6]. It included a brief comparison of solar power plants connection codes of Egypt, UK, Germany, and USA.

The structure of this paper is as follow: Requirements for electricity distribution codes in different countries are discussed in Section II. A detailed comparison of photovoltaic (PV) code in different countries is presented in Section III. Small scale PV Code is discussed in Section IV. Finally, main conclusions are summarized in Section V.

Electricity Distribution Codes

EDC regulates distributing and connecting electricity to customers. It also covers embedded generating units and transferring electricity between distribution systems. In this section, different EDCs are discussed including the British Distribution Code (BDC) [7], Saudi Arabian Distribution Code (SADC) [8], Egyptian Electricity Distribution Code (EEDC) [9], and Germany Medium Voltage Code (GMVC) [10].

A. Voltage range

The Distribution Network Operator (DNO) preserves the limits of the contracted nominal voltage change at supply point. Table 1 presents the operation voltage range in codes.

All codes defined operation voltage range with in ± 5 % for low voltage and medium voltage in EEDC; it is ± 10 % for aerial networks due to longer distances.

B. Frequency range

The DNO takes the necessary measures to preserve the network frequency, while taking into consideration the changes allowed within the grid code. Table 2 presents the operation frequency range in various codes.

The BDC and GMVC define the operation frequency range, but EEDC did not define the range, however it should follow the instruction of the National Control Centre.

C. Fault level consideration

The short circuit rating of user's equipment at the connection point should be not less than the design fault level of the distribution network operator's distribution system to which it is connected. Table 3 shows the necessity of not exced the short circuit level at the connection point.

All codes clarify the limits of short circuit level at the connection point, which shall not exceed certain limits by the user's equipment, and these limits are different according to the different construction of the networks.

D. Voltage phase unbalance

Voltage phase unbalance is defined as the ratio between the rms values of the negative sequence component and the positive sequence components of the voltage. Table 4 shows the limits of voltage phase balance in each code.

The BDC and GMVC define the allowed percentage of voltage phase unbalance. EEDC defines the allowed percentage of current phase unbalance.

E. Power factor

The ratio of active power to apparent power is the power factor. Table 5 defined the power factor of the user.

Table 1: Limits of operating voltage.

Code	Requirements in the Code
BDC	Low Voltage: In relation to alternating current, a voltage exceeding 50 volts but not exceeding 1 kV.
	Medium Voltage: voltage exceeding 1 kV.
	Voltage Operation Range:
	For Low Voltage = ± 5 %
	For Medium Voltage = ± 5 %
SADC	Low Voltage: voltage used for the supply of electricity, the upper limit of nominal RMS value of which does not exceed 1 kV.
	Medium Voltage: voltage used for the supply of electricity, the nominal value of which is between 11 kV and 36 kV.
	Voltage Operation Range
	For Low Voltage = ± 5 %.
	For Medium Voltage = ± 5 %.
EEDC	Low nominal voltages: voltages up to 0.4 kV.
	Medium nominal voltages: voltages higher than 0.4 kV and up till less than 33 kV.
	Voltage Operation Range
	For Low Voltage = ± 5 %
	For Medium Voltage
	For underground cables = ± 5 %.
	For aerial networks = ± 10 %.
	In the Egyptian Electricity law [10], voltage level is defined as follows:
	'Low Voltage: voltages up to 1 kV.
	Medium voltage: voltages higher than 1 kV and up till less than 33 kV.'

Table 2: Limits of frequency operation.

Code	Requirements in the Code
BDC	Normal Operation Frequency = 50 Hz.
	Frequency Operation Range shall normally be controlled within the limits of 49.5 - 50.5 Hz.
GMVC	Normal Operation Frequency = 50 Hz.
	Frequency Range 49.5-50.25Hz.
EEDC	Normal Operation Frequency = 50 Hz.
	Frequency Operation Range
	The licensed distributor is obliged to follow the instructions given to him from the National Control Centre.

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Table 3: Short circuit rating of user's equipment.

Code	Requirements in the code
BDC	The short circuit rating of User's Equipment at the Connection Point should be not less than the design Fault Level of the DNO's Distribution System to which it is connected. The DNO in the design of its System will take into account the contribution to Fault Level of the User's connected System and Apparatus.
GMVC	Electric installations must be designed, constructed and erected in such a way that they reliably withstand mechanical and thermal effects of a short-circuit current. The connection owner shall furnish proof of the short-circuit current capability for the entire transfer station.
EEDC	When designing and operating the scattered production unit it should be taken into consideration short circuit level shall not exceed limits in the code.

Table 4: Voltage phase unbalance.

Code	Requirements in the code
BDC	The voltage unbalance should not exceed 1.3 % for systems with a nominal voltage below 33 kV.
GMVC	The customer facility must not exceed a resultant degree of unbalance $K_{U,i}$ = 0.7% with averaging over 10 minutes.
EEDC	Load Balance: The subscriber is to verify the balance of his loads so that the current of each phase does not deviate from the average of the measured three-phase - whatever the applied calculation method is or the measuring device. At normal case, LV unbalance= 2% and MV unbalance = 5%. At emergency less than 2 minutes, LV unbalance= 10% and MV unbalance = 4%.

Table 5: User's power factor.

Code	Requirements in the code
GMVC	The displacement factor cos φ of the customer facility must be between 0.9 inductive and 0.9 capacitive. The network operator may determine closer limits for its network.
EEDC	The subscriber of 10 kW power and more is obliged to keep the average power factor at 0.90. In case the factor increases above 0.92, the subscriber then deserves a reduction of the invoice value according to the electrical current supply contracts that have been approved by the Authority.
	In tariff calculation by the Egyptian Electricity regulator [11], The tariff is calculated to loads with 0.92 power factor.

The GMVC allows the customer facility to be between 0.9 inductive and 0.9 capacitive. While EEDC obliged the customer to keep the average power factor at 0.90 but the exact billing is at average power factor 0.92 every three months [12].

Medium Scale Photovoltaic Codes

Medium Scale Photovoltaic Code (MSPVC) stipulates the technical requirements and specifications of integrating Medium Scale PV (MSPV) power plants to the medium voltage distribution networks. It should include technical requirements and limits of system performances such as frequency and active power control, voltage and reactive power control, and fault ride through. This section presents a comparison between British generating plant connection (BMSPVC) [13], Germany grid code for connecting PV systems to the medium voltage power grid (GMSPVC) [14], Grid connection code for renewable power plant connected to the electricity transmission system or the distribution system in South Africa (SAMSPVC) [15], Egyptian Solar Energy Plants Grid Connection Code (EMSPVC) [16] and California Requirements for Large Generator (CMSPVC) [17].

The Frequency and Active Power Control

The main reason for the active power control is to ensure frequency within range. Table 6 shows how the renewable station can help in controlling the active power.

Reactive power control

Consumption and generating of reactive power must be matched in order to maintain a stable system voltage. Table 7 shows the contribution of reactive power to overcome voltage decrease.

The GMSPVC mentioned that the facility must be capable of feeding required reactive power within 20 ms while the EMSPVC requires 250 ms of reactive current injection.

The range of reactive power within 0.95 leading to 0.95 lagging power factor at rated active power in medium voltage codes except for SAMSPVC.

Fault ride through

Fault Ride Through ability means that the grid-connected photovoltaic power station could remain online when the point of common coupling voltage is higher than the prescribed critical low voltage curve and lower than the critical high voltage curve during various faults and their clearance. Fault ride through is illustrated in Table 8, Figure 1.

Time of withstanding fault is different in the codes for either 150 ms or 250 ms but the operation area is totally different.

Small scale photovoltaic code

Small Scale Photovoltaic Code (SSPVC) specifies the technical requirement for integrating small scale PV (SSPV) plant to the low voltage distribution network. In this section, the comparison includes the British small scale embedded generator connection PV (BSSPVC) [18], Germany Technical Conditions for the Connection to the low voltage network (GSSPVC) [19] and Egyptian Technical Requirements for Connecting Small Scale PV Systems to Low Voltage Distribution Networks (ESSPVC) [20].

A. Voltage Range

PV integration may increase the system voltage so it is so important to limit the maximum voltage. Table 9 presents the range of the voltage.

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Table 6: Control of active power for frequency regulations.

Code	Requirements in the code
BMSPVC	Be able to control the active power for frequency regulations (Installed capacity 50MW).
GMSPVC	Be capable of operation at reduced power output (if PCC rated voltage 10kV).
	All generating units have to reduce their power output above a system frequency of 50.2 Hz.
	The power has to reduce with a gradient of 40%/ Hz of the instantaneously available power.
	The output power is only allowed to increase again as soon as the frequency becomes below 50.05 Hz.
SAMSPVC	When the *frequency* on the network exceeds 50.5 Hz, the renewable power plant shall reduce the active power as a function of the change in frequency. Once the frequency exceed 51.5 Hz for longer than 4 seconds the renewable power plant shall be tripped.
EMSPVC	For grid frequencies in the range from 50.2 Hz to 51.5 Hz the solar plant has to reduce active power (Installed capacity from 500 kW to 50MW).
	The output power must be reduced by:
	$\Delta P = 0.4 \times PM \times (\Delta f/Hz)$
	The output power is allowed to increase again as soon as the frequency becomes below 50.2 Hz.
CMSPVC	The plant is set to operate at a curtailed power level that is 10% lower than the available estimated peak power. The upper limit of the droop curve is the available plant power, and the lower limit is at a level that is 20% below the then-available peak power. The implemented droop curve also had a ±36 mHz frequency dead band.

Table 7: Reactive power contribution.

Code	Requirements in the code
GMSPVC	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 required reactive power within 20 ms.
EMSPVC	For 3-phase faults, the solar plant must inject reactive current for the time period 250ms 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.
	The solar plant must be able to control reactive power at the grid connection point in a range of 0.95 lagging to 0.95 leading at maximum active power to 20% of active power.
SAMSPVC	The reactive power capability of renewable power plant shall be available within the parameters:
	Voltage (p.u): 0.20-0.80, power factor: -0.95:0.95.
	Voltage (p.u): 0.80-1.10, power factor: -0.975:0.975.
CMSPVC	For the asynchronous generating facility, provide reactive power at 0.95 lagging power factor when voltage levels are between 0.95–1 p.u. Likewise, it should be able to absorb reactive power at 0.95 leading power factor when voltage levels are between 1–1.05 p.u.

Table 8: Fault ride through.

Code	Requirements in the code
BDC	Any generation set or power station connected to the DNO's distribution system, where it has been agreed between the DNO and the generator that the generator's power station will contribute to the DNO's distribution system security, may be required to withstand, without tripping, the effects of a close up three phase fault and the phase (voltage) unbalance imposed during the clearance of a close-up phase-to-phase fault, in both cases cleared by the DNO's main protection.
GMSPVC	Figure 1 shows the limiting curve of plants during faults. They must not disconnect during voltage drop down to 0%Uc with duration of ≤ 150 ms. Underneath the blue line; there are no requirements to remain grid connection.
EMSPVC	The Solar Plant shall trip if all phase-to-phase voltages are below the curve in Figure 1.
SAMSPVC	Fig. 1 for SAMSPVC shows the combinations of voltage and time that renewable power plant shall be able to endure. 'Must Remain Connected Area' is between upper and lower bounds.
CMSPVC	The plant should withstand zero voltage up to 150 msec and according to Figure 1.

B. Frequency Range

PV that operates in parallel with utility system shall operate within the frequency limits. If the system frequency exceeds these limits, the PV system should disconnect until the system returns to normal frequency operation range. Table 10 presents the frequency limits.

C. Power Factor

According to power factor, the PV will inject or absorb reactive power to the network, which affects the voltage of the network. Table 11 presents the required power factor.

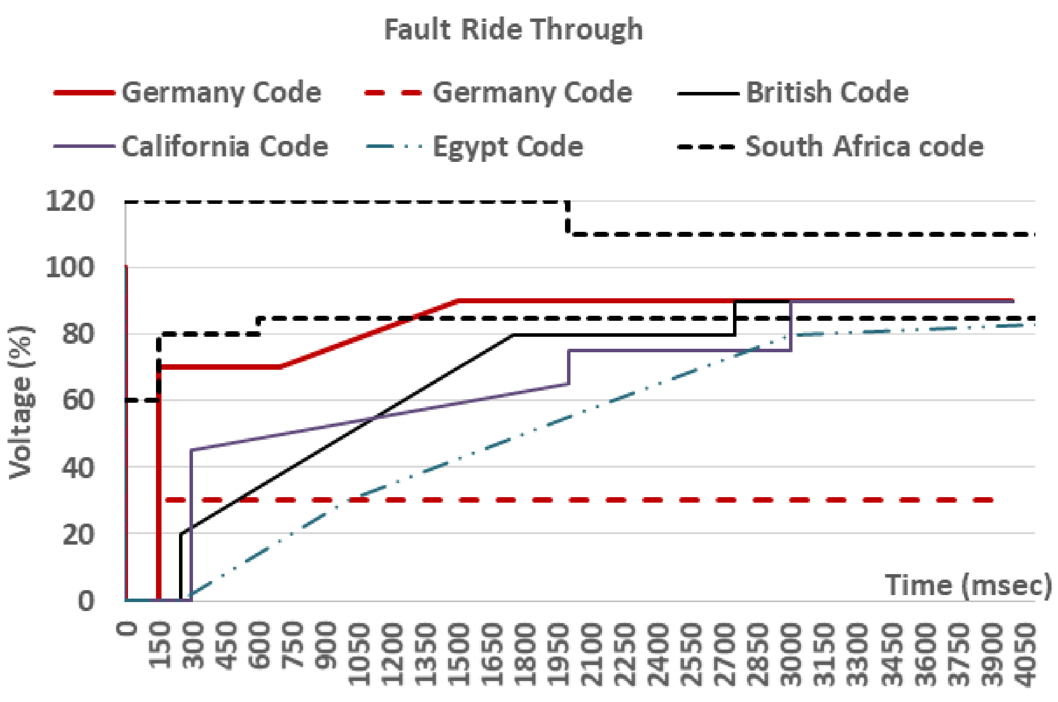

Figure 1: Fault Ride Through for Germany, British, California, Egyptian and South Africa codes.

Table 10: Frequency range.

Code	Requirements in the Code
BSSPVC	SSPV shall operate within the frequency trip limits (47.5-51.5 Hz)
GSSPVC	Disconnection at over-frequency: Inverter manufacturers have to implement threshold values between 50.3 Hz and 51.5 Hz (uniformly distributed)
ESSPVC	An SSPV that operates in parallel with the utility system shall operate within the frequency trip limits in accordance to the Distribution Code 4-1-3 (48.5Hz -51 Hz).

Table 9: Voltage range.

Code	Requirements in the Code
BSSPVC	Voltage limits (119% to 87%) of nominal voltage
GSSPVC	Voltage limits (110% to 80%) of nominal voltage
ESSPVC	In accordance to Distribution Code 4-1-1 “Quality of electrical supply voltage”, the DNO shall maintain the limits of the voltage variation in the range of +/- 10% of the nominal voltage.

Table 11: Power factor.

Code	Requirements in the code
BSSPVC	SSPV shall operate at a power factor within the range 0.95 lagging to 0.95 leading relative to the voltage waveform unless agreed with the distribution network operator
GSSPVC	For SSPV < 13.8 kVA, power factor 0.95 lead or lag.
	For SSPV > 13.8 kVA, power factor 0.90 lead or lag.
ESSPVC	“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.

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Conclusion

Different codes from different countries have been reviewed. The requirements from each grid code are compared with each other and comments on major similarities and differences between them were given. Connection conditions for renewable power plants have been analysed and summarized for each grid code. Steady state or normal operations conditions such as voltage and frequency deviations, active and reactive power control, voltage control, and power factor control requirements were studied. Furthermore, fault ride through requirement during grid disturbance were covered.

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