Aalborg Universitet

Overview of Grid Codes for Photovoltaic Integration

Zheng, Qianwei; Li, Jiaming; Ai, Xiaomeng; Wen, Jinyu; Fang, Jiakun

Published in:
Proceedings of 1st IEEE Conference on Energy Internet and Energy system Integration (EI² 2017)

DOI (link to publication from Publisher):
10.1109/EI2.2017.8245501

Publication date:
2017

Document Version
Accepted author manuscript, peer reviewed version

Overivew of Grid Codes for Photovoltaic Integration

Qianwei Zheng, Jiaming Li, Xiaomeng Ai, Jinyu Wen
Huazhong University of Science and Technology
Wuhan, China
qianwei_zheng@hust.edu.cn

Rong Cai, Hailian Xie
ABB (China) Ltd., Corporate Research Centre
Beijing, China

Jiakun Fang
Department of Energy Technology
Aalborg University
Aalborg, Denmark

***Abstract*—The increasing grid-connected photovoltaic (PV) power stations might threaten the safety and stability of power system. Therefore, the grid code is developed for PV power stations to ensure the security of PV integrated power systems. In this paper, requirements for PV power integration in different grid codes are first investigated. On this basis, the future advocacy is concluded. Finally, several evaluation indices are proposed to quantify the grid code compliance so that the system operators can validate all these requirements by simulation.**

Keywords—photovoltaic integration, grid code, frequency regulation, voltage regulation, renewable energy

I. INTRODUCTION

Driven by the policy incentives and public awareness, renewable energy including Photovoltaic(PV) power has been rapidly developed in recent years. The global installed PV capacity has reached 177GW [1] by the end of 2014 and shows obvious growth in most of countries, as indicated in Fig. 1. Increasing penetration of PV generation might threaten the security and stability of power system with fast and violent power fluctuation as well as incapability of frequency support. Therefore, different grid codes have been proposed in order to confine both the steady-state and dynamic behaviors of PV power stations (or all the inverter-based sources). Some of these requirements can be easily met, while some need case-specific design due to different system parameters, geographical locations, etc. Nowadays photovoltaic grid code is announced generally in the form of national standards or by transmission / distribution system operators [2]-[8]. However, due to the lower penetration level of PV power compared to other power sources, the current grid codes related to grid-connected PV power stations are inadequate. In order to further pinpoint the essential problems in PV generation, this paper investigates and analyzes the requirements of existing grid codes of PV power stations.

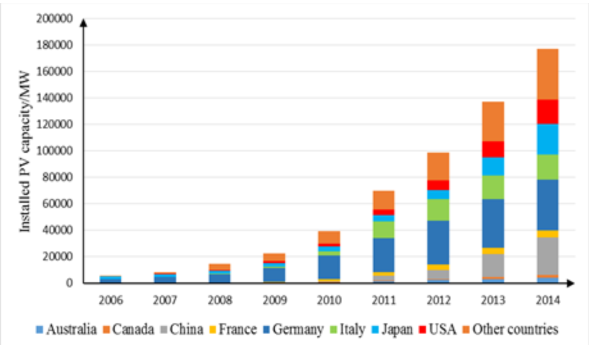

Fig. 1 Cumulative installed PV capacity from 2006 to 2014

The structure of this paper is organized as follow. The PV power integration related grid codes in different countries/regions are summarized in section 2 and section 3, the requirements are given for the performance under steady state (time resolution from minutes to hours) and transient (time resolution from milliseconds to seconds) in these two sections, respectively. The future advocacy concerning the improvements in the PV grid codes are proposed in section 4. Some evaluation indices are introduced in section 5 to describe the Grid Code conformity and conclusion is given in section 6.

II. THE STEADY-STATE REQUIREMENTS IN GRID CODE

In general, the grid code requirements for PV power stations can be categorized into steady-state and transient requirements. The steady-state grid codes are shown in this section while the transient part will be introduced later in Section 3.

In steady-state operation, grid codes mainly requires for the PV plants on active power regulation, and reactive power support, which can be listed as follows.

A. Active Power/Frequency Regulation

a) The active power control

In most cases, grid codes requires that the PV power plants to be able to control the active power according to the reference signals sent from the power system operators.

TABLE 1 Requirements of the active power controllability in different grid codes

Grid codes	Requirements in the grid codes
National standard and SGCC enterprise Grid Code (China)	Be able to control the active power according to the commands issued by dispatch center (if PCC rated voltage ⩾ 10kV)
National Grid (UK)	Be able to control the active power for frequency regulations (Installed capacity ⩾ 50MW)
Germany	Be capable of operation at reduced power output (if PCC rated voltage ⩾ 10kV)
ENTSO-E (Europe)	Be able to control the active power for frequency regulations (Installed capacity ⩾ 0.8kW or decided by local TSO)
Others	N/A

TABLE 1 lists the active power control requirements in different regions. In China, PV power station are required to have their own active power control system, which should be able to continuously and smoothly adjust the output power.

Furthermore, this active power control system should be able to receive and automatically execute the control commands on the active power output as well as the output ramp rate issued by the power grid dispatch center[2][3].However, any violation to the dispatch commands due to the sudden decrease of solar radiation intensity is neglected. In Germany, PV power stations are required to decrease the output if necessary according to the command of dispatch center [4]. As for the United Kingdom [5] and ENTSO-E [6] grid codes, the PV power stations should keep its active power output within a certain range specified by the local TSO during severe frequency disturbance.

b) The active power ramp rate control

In order to alleviate the influence of the power fluctuation of the PV output. The active power ramp rate requirements in grid codes limits the speed of active power changes of grid-connected photovoltaic power station.

TABLE 2 Requirements of the active power ramp rate in different grid codes

Grid Codes		Requirements		
China	National standard	The max ramp range of PV power station should be less than 10% installed capacity per minutes.		
	SGCC enterprise Grid Code	PCC rated voltage	10min max ramp range (MW)	1min max ramp range (MW)
		380V	Installed capacity	0.2
		10kV~35kV	Installed capacity	Installed capacity/5
		⩾ 66kV	Installed capacity/3	Installed capacity/10
Germany		Increases the active power after the plant has been reconnected (after faults) with a gradient of maximally 10% of the rated power per minute (If the installed capacity > 1 MVA)		
ENTSO-E (Europe)		The ramp rate limit should be specified by regional Transmission System Operator if necessary		
Others		N/A		

It is clearly stated in Chinese [2][3], German [4] and European [6] grid codes that the ramp rate should be limited in a certain range. The range is determined by regional TSO in European ENTSO-E Grid Code [7], while specified to be 10% in Chinese national standard [2] and German Grid Code [4]. But the excessive negative ramp rate caused by the sudden decrease of solar radiation intensity is neglected in Chinese national standard. The grid code announced by State Grid Q-GDW 517-2011 [3] also limits the ramp rate of PV power stations by different rated voltage levels. As for other regional grid codes, there are not any clear restrictions on photovoltaic power output ramp rate at present. However, various countries have requirements that the active power and its ramp rate should be controllable for wind power and the ramp rate limits are commonly set as 10%-15% of the rated power/min, which can be regarded as a reference for PV power stations.

c) Frequency deviation response

Grid-connected photovoltaic power station is required to respond to the frequency deviation in several grid codes. Different output response requirements are generally specified to three frequency ranges separated by the solid black lines in Fig. 2. It consists of 3 segments.

First, in the range of ± 0.2~0.5 Hz maximum deviation from the base frequency a dead band is set. The system frequency within this range needs no response of the photovoltaic power station output.

Secondly, the over-frequency range corresponds to the positive frequency deviations out of the dead band. Usually the grid-connected photovoltaic power station is required to reduce its output as shown in Fig. 2. Several droop coefficients in different grid codes are shown in the following TABLE 3.

Finally, in the low-frequency range, corresponding to the negative frequency deviation out of the dead band, it's required that the PV power output should not be lower than a certain percentage (usually 90%~100%) of the maximum possible value.

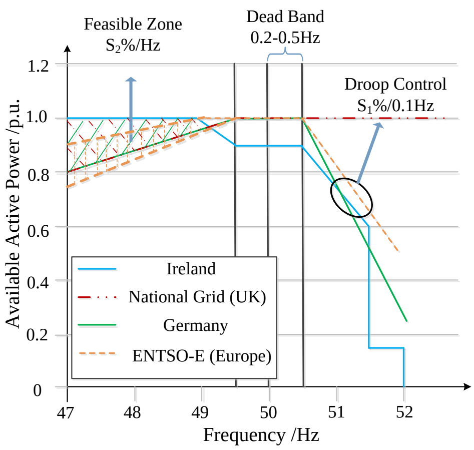

Fig. 2 Frequency response requirements in different grid codes

TABLE 3 Droop coefficient S_1 and S_2 in different grid codes

	S_1 (%)	**S_2 (%)**
Ireland	3~7	\
National Grid (UK)	0	case by case
Germany	3~7	case by case
ENTSO-E	2~12	10

It should also be noticed that since the dead band in Fig. 2 is usually wider than the normal frequency variation range of the local power system, these frequency response requirements of PV power station are not designed for primary frequency response but for emergency frequency support only.

No detailed frequency response requirement is found in the Chinese PV power related Grid Code [2][3]. However, the national standard stipulates that the photovoltaic power station should be able to participate in the power system frequency regulation and peak shaving if necessary. Moreover, it's stated that when the power system frequency is higher than 50.2Hz, PV power station should be ready to reduce its active power according to the commands of dispatch center.

B. *Reactive Power/Voltage Regulation*

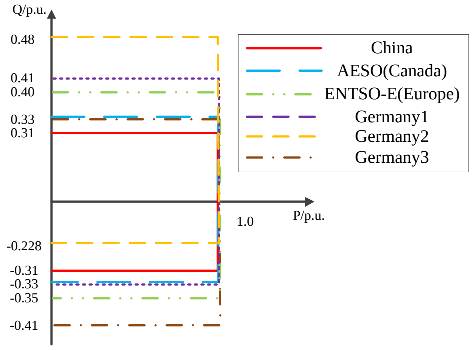

Fig. 3 Reactive power generation capability required in different grid codes

The steady-state reactive power requirements are presented in almost all the regional grid codes, which is used to ask the PV power plants to help with voltage regulation of the power systems. Different requirements on reactive power capacity of PV power stations in several regional grid codes are shown in Fig. 3. Term 6.1 in the Chinese national standard GB/T 19964-2012 [2] clearly prescribes that: "The grid-connected inverters installed in photovoltaic power station should meet the requirement that their power factors could be dynamically adjusted within the range of 0.95 leading ~ 0.95 lagging at the rated active power output."

The European Network of Transmission System Operators for Electricity (ENTSO-E) standard [6] and the German Transmission Code 2007 [4] also elaborate the requirements on the adjustable range of reactive power generated by photovoltaic power station under different PCC voltages level, as shown in Fig. 4. There are again three optional ranges in the German Grid Code for TSOs.

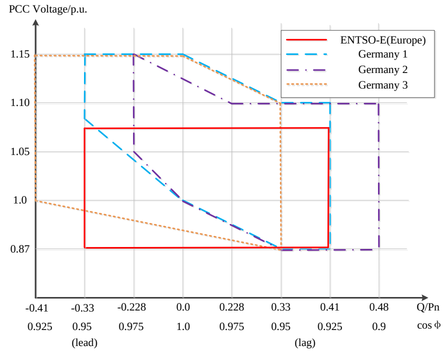

Fig. 4 Required reactive power generation capability under different PCC voltage level

Grid-connected photovoltaic power station (with necessary reactive power compensators) is supposed to have the ability to control the voltage of grid connection point and keep it within a certain range. The specific range differs in different grid codes as shown in the following table.

TABLE 4 Voltage regulation range in different grid codes

		Connected voltage level	Voltage range (p.u.)
China		110 kV and 66 kV	0.97~1.07
		220kV and above	1.0~1.10
ENTSO	Continental Europe	All	0.90~1.118
	Nordic	All	0.90~1.05
	UK	All	0.90~1.10
	Ireland	All	0.90~1.118
	Baltic	All	0.90~1.12
National Grid (United Kingdom)		132kV	0.90~1.10
		275kV	0.90~1.10
		400kV	0.95~1.05
AESO (Canada)		115kV	0.98~1.10

III. The Transient Requirements in Grid Code

The transient requirements for PV power can be summarized to three aspects. Grid codes on fault ride through prevents the PV power plants from disconnecting from the grid during system fault. For dynamic reactive current injection, system operators utilize the PV plants to help with the voltage recovery. And low/high frequency ride through capabilities require PV plants remain grid-connected during frequency deviation conditions.

A. *Fault Ride Through*

Fault ride through ability means that the grid-connected photovoltaic power station could remain online when the PCC voltage is higher than the prescribed critical low voltage curve and lower than the critical high voltage curve during various faults and their clearance.

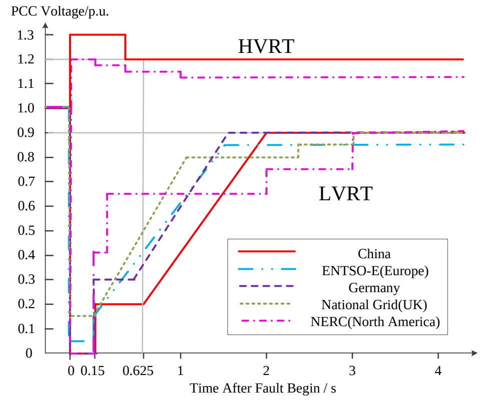

Fig. 5 LVRT and HVRT requirements in different grid codes

The fault ride through ability required by different countries and regions differs from one to another, as shown in Fig. 5 [2], [3]-[6]. Requirements of China and Natural Environment Research Council (NERC) are the strictest ones since the zero voltage ride through for 150ms is required. High voltage ride through ability is also required in China and NERC for PV power station to withstand the overvoltage.

B. *Dynamic Reactive Current Injection*

To get faster grid voltage recovery, the grid-connected photovoltaic power station is required to increase its reactive current output when the voltage dip occurs at PCC. Apart from that, the Spanish [8] and German [4] grid codes stipulate that the photovoltaic power station should be able to withdraw reactive current when the overvoltage occurs, as shown in Fig. 6.

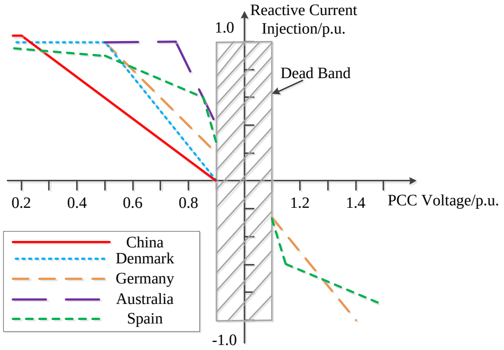

Fig. 6 Dynamic reactive current injection required in different grid codes

In these grid codes, a dead zone is set up where the PCC voltage is between 0.9~1.1 p.u. When the voltage falls below 0.9 p.u., grid-connected photovoltaic power station is required to inject reactive current to the grid proportional to the voltage deviation. For example, the Chinese national standard [2] stipulates that the injected reactive current I_T should follow the following formulas: (U_T is the PCC voltage magnitude in per unit value, I_N is the rated output current of the PV power station)

$$\begin{cases} I_T \geq 1.5(0.9 - U_T) I_N & (0.2 \leq U_T \leq 0.9) \\ I_T \geq 1.05 I_N & (U_T \leq 0.2) \\ I_T = 0 & (U_T \geq 0.9) \end{cases} \tag{1}$$

Apart from the value of injected reactive current, there're possible requirements on the response time to achieve the reactive current target in some of the grid codes. Chinese national standard [2] requires that the response time of dynamic reactive current should not be longer than 30ms. German grid code [4] is even stricter with the required response time less than 20ms. As comparison, the response time required for wind power to provide dynamic RCI is 75ms in China [9] and 100ms in Denmark [10] respectively.

C. Low/High Frequency Ride Through

Frequency ride through refers to that when the system frequency deviates from the nominal frequency in a certain range, grid-connected photovoltaic power station must remain online for a prescribed time period. The requirements on the low/high frequency ride through, defined in different countries/regions [2], [4]-[7] are presented in Fig. 7 by drawing both the critical high and low frequency curve.

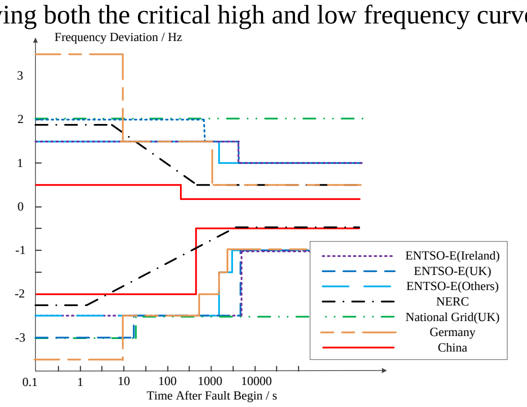

Fig. 7 Frequency ride through ability required in different grid codes

When the operation point falls between the high and low frequency curves in Fig. 7, the PV power station should keep on operation. Otherwise, the PV power station may disconnect from the power system. The detailed requirement is listed in the following table.

TABLE 5 Frequency ride through requirements in Chinese National Standard

Frequency Range	Requirement
< 48Hz	Whether the PV power station should operate or not is based on the minimum possible operation frequency of it
48Hz ⩽ f < 49.5Hz	PV power stations should keep on operation for at least 10 min
49.5Hz ⩽ f ⩽ 50.2Hz	Normal operation range
50.2Hz < f ⩽ 50.5Hz	PV power station should keep on operation for at least 2 min and reduce the output power according to the dispatch commands The offline PV power stations should not connect to the grid
> 50.5Hz	PV power stations should stop power generation immediately

IV. Future Advocacy of Grid Code

Although the installed capacity of PV power is rapidly increasing, the current penetration levels of photovoltaic power generation in most countries are not high comparing to other power sources. Therefore, the grid code requirements on the grid-connected photovoltaic power station in many countries/regions are not very strict or even absent in a lot of countries/regions. On the other hand, in those countries that already have large shares of PV power, a complete set of standards for grid-connected photovoltaic power is established.

It can be predicted that the influence of the intermittent characteristics of the PV power on grid will become more and more serious when the penetration level of the photovoltaic power is further increased. It will definitely promote the proposal of PV power grid code in those countries which still neglect it. Moreover, according to the researches, the existing PV power grid codes might be improved especially in the following aspects:

(1) The limits of the maximum ramp rate of PV power station might become stricter. It can be seen those power grids with high penetration of PV power (eg.30%) and mainly rely on thermal power units as conventional generation may not be able to compensate the PV output power fluctuation even when it obeys the GRID CODE, for the current limit of the PV ramp rate is higher than that of traditional thermal generator.

(2) Requirements on the primary frequency regulation might be added. Nowadays, some countries/regions already required the wind farms to provide the primary frequency regulation, which is favorable and necessary for the recovery of grid frequency after disturbances since the conventional generators are replaced. The photovoltaic power station can also achieve the similar function by special design of the control strategy.

(3) Requirements on the virtual inertia control might be added. It's commonly noticed that holding enough inertia is essential for power grid stability after various disturbances [11]. Since the grid-connected PV power station is connected to the grid by power electronic devices with control strategy that is too fast to participate in the electro-mechanical dynamics to help stabilizing the moving states of other

traditional synchronous generators, it's said that the grid-connected PV power station has no contribution of inertia to the grid. As more and more synchronous generators are replaced by PV power stations in the future, the total inertia of the power system will be sharply decreased, which will severely affect the stability of the entire power system. Therefore, PV power GRID CODE will certainly put forward some requirements on the special control strategy to compensate the missing inertia of the grid, which is called the 'virtual inertia control'.

V. Indices to Validate the Grid Code Compliance

After the clarification of the PV power related grid codes requirements, corresponding control schemes should be designed. In order to verify whether the GRID CODE requirements could be met by these control schemes and quantitatively describe how severe violations to the requirements will be if they are not be fulfilled, four indices used in the evaluation (by simulation) are proposed as follows:

A. The Violation Probability of the Power Ramp Rate

It is assumed that a series of field measured or simulated PV output power are available (The sampling rate should be at least 1 time per minute. In our simulations, the sampling rate of 1 time per minute is used). The violation probability of output ramp rate is defined as:

$$\text{Prob}_{RRV} \triangleq \frac{n_{RRV}}{N_{rec}} \tag{2}$$

n_{RRV} is the number of output power records that do not meet the ramp rate requirement, and N_{rec} is the total number of the records obtained from the field measurement or simulations. n_{RRV} is counted by the following procedure:

(1) Set the initial index of PV output power record $i = 1$, and initiate the ramp rate violation count $n_{RRV} = 0$.

(2) Suppose $P(i)$ is the i^{th} PV power data. For each PV power data $P(j)$ sampled within the past 1 min of the sampling time instant of $P(i)$, check if the inequation (3) holds. If any $P(j)$ violates inequation (3), let $n_{RRV} = n_{RRV} + 1$. When all $P(j)$ are checked, go to step (3); (The 1min ramp range requirement of the PV power is R_1)

$$|P(i) - P(j)| \le R_1 \tag{3}$$

(3) For each PV power data $P(j)$ sampled within the past 10 min of the sampling time instant of $P(i)$, check if the inequation (4) holds. If any $P(j)$ violates inequation (4), let $n_{RRV} = n_{RRV} + 1$. When all $P(j)$ are checked, let $i = i + 1$ then go to step (2); (The 10min ramp range requirement of the PV power is R_{10}

$$|P(i) - P(j)| \le R_{10} \tag{4}$$

The procedure ends until index i reaches the last record of the PV output power series.

B. The Violation Probability of the Voltage Range

It is assumed that a series of field measured or simulated PV active and reactive power output records (The sampling rate should be at least 1 time per minute. In our simulations, the sampling rate of 1 time per minute is used) as well as the power flow model of the grid are available. The violation probability of the voltage range is defined as:

$$\text{Prob}_{VV} \triangleq \frac{n_{VV}}{N_{rec}} \tag{5}$$

n_{VV} is the number of records that do not meet the voltage range requirement, and N_{rec} is the total number of records of the field measured or simulated PV output power series. n_{VV} is counted by the following procedure:

(1) Set the initial index of PV output power record $i = 1$ and initiate the voltage range violation count $n_{VV} = 0$.

(2) Substitute the active power record $P(i)$ and reactive power record $Q(i)$ into the power flow model, then calculate the RMS voltage $V_m(i)$ at PCC.

(3) Check if the inequation (6) holds. If it does not hold, let $n_V = n_V + 1$ then go to step (4). If it holds, then directly go to step (4). (The required maximum and minimum PCC voltage are V_{max} and V_{min} in RMS values)

$$V_{\max} \ge V_m(i) \ge V_{\min} \tag{6}$$

(4) Let $i = i + 1$ then go to step (2) until index i reaches the last record of the output power series.

C. The Low Voltage Ride Through Capability

This index is used to indicate whether the PV power station is capable of low voltage ride through (LVRT). It's actually a testing procedure of LVRT used in the simulation.

In LVRT simulation, the following steps are taken:

(1) Set the solar radiation of all PV arrays to the maximum possible value (We used 1000W/m^2 in the simulations)

(2) Connect the PV power station directly to an ideal voltage source with zero impedance.

(3) Use this voltage source to simulate the voltage drop exactly same as the critical LVRT voltage curve given by the grid code, measure the voltage at the DC bus of PV inverters $V_{DC}(t)$ and the output current of the inverters $I_{inv}(t)$.

(4) Compare $V_{DC}(t)$ and $I_{inv}(t)$ with the maximum available DC bus voltage V_{DCmax} and inverter current I_{invmax}. (Pre-defined according to the capacity of inverter) If at any time $V_{DC}(t)$ or $I_{inv}(t)$ is larger than the maximum values, the LVRT test is failure. Otherwise, the LVRT capability of PV inverter is guaranteed.

D. Response Time and Error of Dynamic Reactive Current Injection

According to the grid codes in China and Germany, PV power stations should provide reactive current injection (RCI) to the power system according to equation (1) within the specified response time. Direct evaluations of the Grid Code compliance can be defined as follows:

a) Response Time

During the LVRT test, measure the time T_r for reactive current injection to rise up to 90% of the reference value.

If the response time is less than the requirement (30ms in Chinese Grid Code), the response time of dynamic RCI is satisfied. Otherwise, more flexible reactive power sources should be added or the reactive power control strategy of the PV power station should be improved.

b) Response error

Assuming the RCI reference is $I_T(t)$, the response error of RCI E_{RCI} can be defined as:

$$E_{RCI} = \sum_{i=0}^{N} e(i)\Delta t$$
$$e(i) \triangleq \begin{cases} \left|I_T(t_0 + i\Delta t) - i_R(t_0 + i\Delta t)\right| & i_R(t_0 + i\Delta t) < I_T(t_0 + i\Delta t) \\ 0 & i_R(t_0 + i\Delta t) \geq I_T(t_0 + i\Delta t) \end{cases} \tag{7}$$

t_0 is the time instant that the fault starts, Δt is the sampling time step and $t_0 + N\Delta t$ should be set long enough for the system to get recovery and be stabilized after the fault is cleared.

VI. Conclusion

With the rapid development of PV power, the PV power integration related rules in grid codes are supposed to be stressed and perfected to avoid the stability problems in power system. In this paper, first the PV power integration related grid codes are collected and compared in different countries/regions like China, Europe, North America. Base on the researches, several aspects are predicted to be improved in the existing PV power grid codes. Furthermore, several evaluation indices are proposed to quantitatively confirm the Grid Code compliance by simulation, which can be regarded as references for the researchers and practioners concerned.

Acknowledgment

References

[1]. PVPS IEA. PVPS report-trends 2015 in photovoltaic application execute summary[R]. Report IEA-PVPS T1-27, 2015.

[2]. Standardization Administration of the People's Republic of China. GB/T 19964-2012 Technical requirements for connecting photovoltaic power station to power system [S]. 2012

[3]. State Grid Corporation of China. Q-GDW 617-2011. Technical requirements for connecting photovoltaic power station to power system [S]. 2011

[4]. German VDN e.V. beim VDEW. Transmission Code 2007 Network and System Rules of the German Transmission System Operators[S]. Berlin: 2007.

[5]. National Grid. The Grid Code[S]. 2015

[6]. European Network of Transmission System Operators for Electricity. Implementation Guideline for Network Code - Requirements for Grid Connection Applicable to all Generators[S]. 2013

[7]. NERC. Standard PRC-024-1 Generator Frequency and Voltage Protective Relay Settings[S]. Under Development.

[8]. Crăciun B I, Kerekes T, Séra D, et al. Overview of recent grid codes for PV power integration[C]. 13th IEEE International Conference on Optimization of Electrical and Electronic Equipment, 2012: 959-965.

[9]. Standardization Administration of the People's Republic of China. GB/T 19963-2011 Technical rule for connecting wind farm to power system[S]. 2011

[10]. Energinet.DK. Technical Regulation 3.2.5 for Wind Power Plants with a Power Output Greater than 11kW[S]. 2010

[11]. A Ulbig, T S. Borsche, G Andersson. Impact of Low Rotational Inertia on Power System Stability and Operation[C] Proceedings of the 19th IFAC World Congress. 2014: 7290–7297.