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Comparison of Voltage Dip Characterization under Grid-Code Requirements: Application to PV Power Plants

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Abstract. The present paper describes and compares different voltage dip representations aiming to characterize the voltage dip severity in terms of duration, depth and time interval around the residual rms-voltage. With this objective, a set of real disturbances collected in Spanish PV power plants along different field-measurement campaigns have been selected and characterized by means of different approaches: (i) rms-voltage values, (ii) scatter-plot distribution and (iii) dq0 transformation. Results and examples regarding the collected disturbances are also included in the paper, as well as a comparison with current Grid-Code requirements for renewable energy resources connected to the grid under the presence of disturbances.

Key words

Voltage dip characterization, Grid-Code requirements.

1. Introduction

During the last decades, most developed countries have promoted relevant initiatives focused on the integration of renewable energy resources into power systems. The reduction of fossil fuel dependence and foreign energy sources, as well as a sort of climate policy agreements, can be considered major arguments to justify the promotion of these renewable energy sources and their integration as supply-side solutions. Consequently, these installations cannot be currently neglected in terms of power capacity, moving from 3.6 GW in 2000 and representing 22.4% of new power capacity installations, to 47.4 GW in 2013 and accounting for more than 72% of new installations. Within these renewable sources, Wind and Photovoltaic power plants have been widely developed and implemented into power systems, with more than 115.4 and 80 GW installed respectively. During the last three years, PV power plants have been the largest generation source in terms of installed capacity in Europe. Indeed, the amount of PV power plants installed in 2013 was over 11 GW (31% of total capacity), just behind by wind farms with around 11.2 GW (31%) and gas with 10.5 GW (23%) [2]. The rest of resources, as renewable as conventional installations, are far from these values.

In parallel with this high penetration of renewable technologies in power systems, new Grid-Code requirements have been issued for the grid connected renewable energy sources to maintain the continuity of supply. Consequently, and according to the potential impacts of these resources on the reliability of both current electrical distribution and transmission system, renewable energy sources (mainly wind farms and PV power plants) must meet specific operational conditions required by the system operators under the presence of disturbances. With regard to European countries, most of them present specific criteria for PV power plant connection and performance under disturbances. Indeed, it can be found a sort of different criteria and requirements in terms of connection to the grid and behaviour under the presence of disturbances. In an attempt to compare these different requirements, a sort of European Grid-Codes is selected, comparing their rms-voltage limitations at the grid connection point for PV power plants. Both magnitude and duration of the voltage dips according to the different rules and specifications are depicted, characterizing the severity of their requirements and emphasizing their differences. From this framework, the present paper describes and compares different voltage dip representations aiming to characterize the voltage dip severity in terms of duration, depth and time interval around the residual rms-voltage. With this objective, a set of real disturbances collected in Spanish PV power plants along different field-measurement campaigns have been selected and characterized by means of different approaches.
The rest of the paper is structured as follows: Section 2 briefly discusses current European examples of requirements for renewable installations as well as the last draft issued by ENTSO in an attempt to provide general rules for the European grids; Section 3 analyses the current Spanish Grid-Code in terms of requirements for renewable energy resources connected to the grid;

Section 4 discussed different approaches to characterize voltage dips in terms of rms-voltage estimations, scatter-plot distributions and Park transformation, preliminary results have been included in this section; finally, Section 5 gives the conclusion of the paper.

2. European Examples of Requirements for Renewable Installations Connected to the Grid

Before the last decade, and due to the penetration level of renewables was extremely small compared to the conventional generation systems, most national grid codes did not include any regulations for these upcoming resources. However, the situation has radically changed during the last years in most European countries, with a remarkable increase of the capacity of renewable installations integrated into the grid. This shift from conventional to renewable resources has raised serious concerns due to the impacts of these sources as an intermittent and/or fluctuate power generation. Furthermore, the additional loss of power generation as a result of disconnections from the supply-side can cause a greater generation/consumption imbalance and thus drop in the system frequency in a wider region. To minimize possible stability problems and avoid other drawbacks, Transmission and System Operators have recently promoted strict technical requirements for renewable installations, mainly focused on wind power plants. Indeed, the requirements vary between countries and their severity usually depends on the wind power penetration level as well as on the robustness of the national or regional power network. Only a few countries have provided specific technical requirements for PV power plants. In Europe, examples of these initiatives can be found in the Spanish, German and Italian grid code requirements, whit specific rules for the disconnection of PV plants connected to the grid under the presence of disturbances, mainly voltage dips.

In Germany, the first Grid Code for wind turbines was introduced in 2003. However, and due to the experiences acquired in the recent years, it became necessary to update the Grid Code. These new grid connection requirements have been developed by *bdew* (energie. Wasser. Leben). In 2008, *bdew* published the "*Technical Guideline Generating Plants Connected to the Medium-Voltage Network Guideline for generating plants connection to and parallel operation with the medium-voltage network*". The German grid code then introduced a distinction between type-1 and type-2 generating plants with regard to their behavior in the event of network disturbances: A type-1 is for generating plants in which a synchronous generator is directly (only through the generator transformer) connected to the network. All other plants are type-2 generating units.

The general rules for connecting to the transmission system in Italy are given by different reports and rules. The main technical standards for the connection of electrical generators to the Italian grid are the CEI 0-16: reference technical rules for the connection of active and passive consumers to the high-voltage (HV) and medium-voltage (MV) electrical networks of distribution companies; the CEI 11-20: electrical energy production system and uninterruptable power systems connected to low-voltage (LV) and MV networks; and the CEI 11-32: electrical energy production system connected to HV network. In this country, technical requirement for the PV plant connection is detailed in CEI 0-21.

To compare the different grid codes, the different limiting curves of voltage at the grid connection point for PV are overlapped as shown in Figure 1. After a preliminary comparison of the grid requirements, it can be affirmed that the German Grid-Codes involve more demanding technical requirements in comparison with the current Spanish limitations. In fact, German and Italian grid codes impose more severe conditions, since PV power installations must support voltage dips involving zero-voltage values without disconnecting from the grid.

In terms of grid code rules for renewables, an important diversity of rules can be found in different European countries. Moreover, there is also a lack of requirements in some European countries for renewable installations connected to the grid. Both differences and lack of rules for these installations is high- lighted by some authors as an important obstacle toward the deployment of distributed energy renewable sources, such as PV installations. Under this scenario, the last draft of Network Code on Requirements for Generators (provided by ENTSO-E) offers guidance for the national implementation of processes for all generators wishing to connect below 110 kV within the European Union [3]. These requirements are focused on avoiding power generating modules connected to networks from disconnection after a secured fault on the higher transmission level. The objective is to limit the potential losses of generation after a fault on the distribution or transmission system at voltage levels of 110 kV or above.

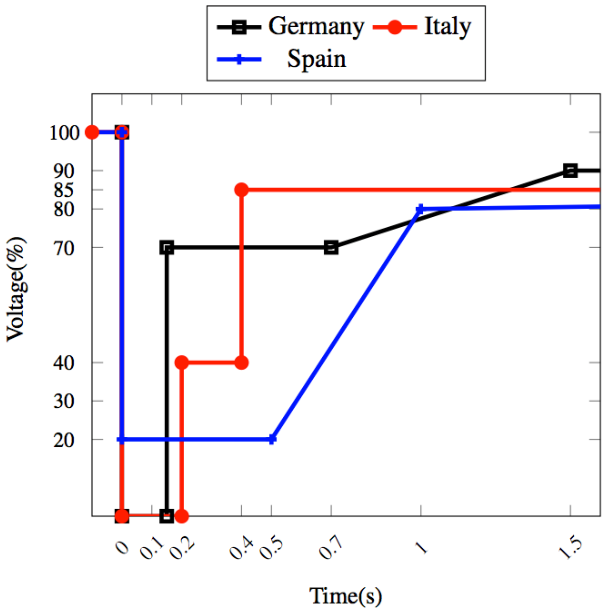

Fig. 1. PV power plant grid code requirements for voltage dips

Table I. – Guideline for grid code requirements: parameters for time intervals and rms-voltage provided by ENTSO (Draft)

Synchronous Power Generating Modules				**Power Park Modules**			
Voltage parameters (pu)		Time parameters (sec)		Voltage parameters (pu)		Time parameters (sec)	
U_{ret}	0.05 – 0.3	t_{clear}	0.14 – 0.25	U_{ret}	0.05 – 0.15	t_{clear}	0.14 – 0.25
U_{clear}	0.7 – 0.9	t_{rec1}	t_{clear}	U_{clear}	U_{ret} – 0.15	t_{rec1}	t_{clear}
U_{rec1}	U_{clear}	t_{rec2}	t_{rec1} – 0.7	U_{rec1}	U_{clear}	t_{rec2}	t_{rec1}
U_{rec2}	0.85 – 0.9 and U_{clear}	t_{rec3}	t_{rec2} – 1.5	U_{rec2}	0.85	t_{rec3}	1.5 – 3.0

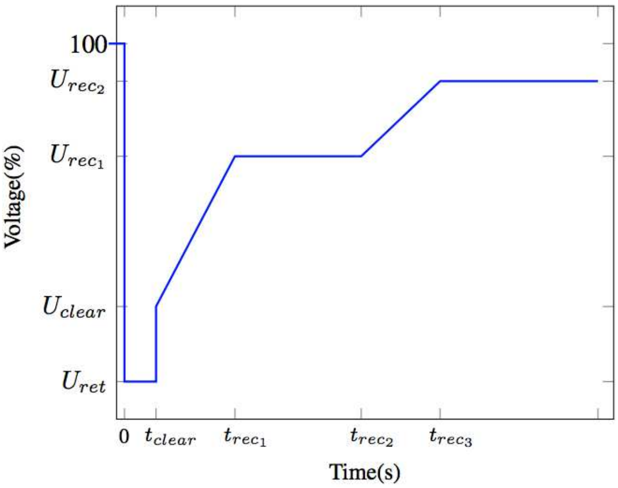

Fig. 2. General ENTSO guideline for grid code requirements: voltage-limiting curves for generating units.

Figure 2 and Table I summarize the general requirements currently under consideration and provided by ENTSO [4]. With this new general limitations, it is expected to avoid more severe situations, i.e. frequency collapse in a synchronous area causing demand tripping and unexpected power flows resulting in overloads both on internal transmission lines and tie lines with neighboring systems possibly leading to cascading tripping, system splitting, load shedding, major faults, brown outs and even black outs [5].

3. Spanish Grid Connection Requirements for Renewable Energy Sources

Along the last decade, Spanish governments have promoted a sort of legal frameworks regarding grid connection and technical requirements. In this way, the 54/97 Law and the Royal Decree (RD) 1955/2000 firstly defined the Spanish legal framework for grid connection. Later, in 2004, the Spanish government published the RD 436/2004, which were mainly focused on renewable energy sources [6]. This RD allowed the operator system to send power curtailments and operational set-points to the wind farms. In some cases, the addition of suitable technical equipment to maintain the continuity of supply under the presence of voltage dips has been necessary to fulfill the current Spanish grid-code requirements. The Spanish TSO (REE), as system operator of the national grid, developed the Operation Procedure "*Requirements for response to voltage dips of production facilities under the special regime*" (P.O.12.3) [7].

These requirements were approved and issued in October 2006. In this case, only wind farms were called to fulfill the specific requisites under the presence of such disturbances. Recently, in November 2010, the RD 1565/2010 was proposed and issued, [8], supposing an extension towards PV power plants of the previous continuity requirements in response to voltage dips, see Fig. 3.

In accordance with the evolution of the Spanish Grid Code requirements and the increasing presence of wind farms and PV power plants in the power grid, the Spanish TSO (REE) published in 2008 a draft of the P.O.12.2 under the title "Technical requirements for wind power and photovoltaic installations and any generating facilities whose technology does not consist on a synchronous generator directly connected to the grid" [6]. The main difference of this draft in comparison with previous characteristics is focused on the voltage-time curve profile, which presents different proposals depending on the nature of the fault. In this way, an alternative voltage–time curve characteristic limiting the magnitude and duration of the voltage dips for single-phase, two-phase-to-ground and three-phase faults. In the particular case of a two-phase to ground fault, the P.O.12.2 gives another voltage–time curve to characterize the magnitude and duration of the allowed voltage dips.

This current Operation Procedure also provide characteristics related to reactive and active power capabilities. Indeed, it is not allowed the demand of active and/or reactive power during periods of system failure and recovery. The global time interval ranges from the occurrence of the failure (and the voltage drops below 0.85 pu) until the voltage on the grid is within the limits of operation. During the fault and later, including the voltage recovery period after the clearance of the fault, wind farms and PV power plants at the grid connection point, must provide the maximum generation of current.

Both wind farms and PV power plants must supply reactive current with voltage levels under 0.85 pu, and they must not demand reactive power between 0.85 pu and the minimum allowed voltage level for the normal operation of the grid. With these premises, it is then desirable to maintain an active power generation similar to the pre-fault conditions.

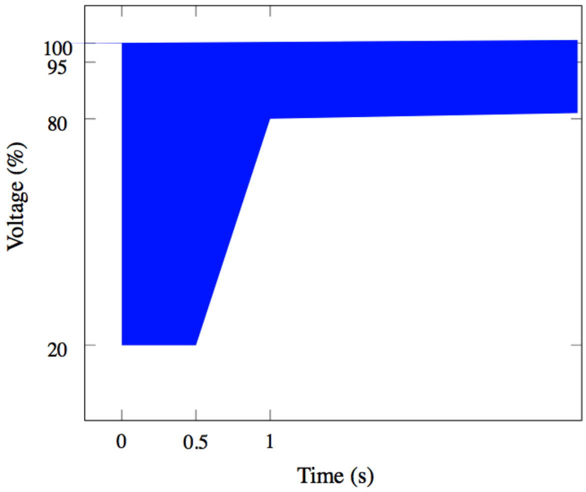

Fig. 3. Spanish Grid-Code requirements for voltage dips

4. Characterization of Voltage Dips: Methodologies and Preliminary Results

A set of real disturbances collected in Spanish PV power plants along the last years have been selected and characterized by means of the following approaches, in an attempt to offer a proper comparison of different methodologies to represent this kind of disturbances.

A. RMS-voltage evolution along the disturbance

The selection of the rms-voltage considering the voltage-phase more affected by the disturbance is usually suggested by current Grid-Code requirements as an estimation of the severity of the events, as well as limitations to be fulfilled by the generation connected to the grid. Consequently, matching with the rms-voltage profiles proposed by the different European Grid-Code requirements are needed to evaluate the severity and the expected performance of the supply-side units. For this proposal, instantaneous rms-voltage values are estimated from the collected voltage data. Based on the sample values, over a specified period, rms-voltage values are then determined according to the following expression [1],

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} v_i^2} \,,$$

where N is the number of samples per cycle and v_i the collected (sampled) instantaneous voltage waveform.

Examples of the collected data can be seen in Fig. 4, where both the instantaneous three-phase voltage values directly collected by the power quality recorder, estimated rms-voltage values are depicted. In a similar way to the previous example, Fig. 5 shows a disturbance where an overvoltage was collected during a voltage dip.

Actually, these situations should be included in the specific rules for renewable energy sources connected to the grid under the presence of events, analysing the specific requirements to be supported for these supply-side units not only as a consequence of residual rms-voltage values and decreasing of the voltages, but also due to over-voltages along the events.

B. Scatter-plot distribution proportional to the time interval around the residual voltage

This characterization of the disturbances provides a summarized representation of the events collected during the field-measurement campaigns. This information regarding the duration of the disturbances and the residual voltage values is used as parameters to determine the severity of the events. For this purpose, 2D color map is proposed and depicted in Fig. 6, where the color-scale is proportional to the number of events for a specific range of residual voltage and duration. As can be seen, the collected disturbances present a significant short duration and high voltage residual values, which means low depth voltage dips. In fact, most events have residual voltage values between 0.8 and 0.9 pu, with durations even less than 100 ms.

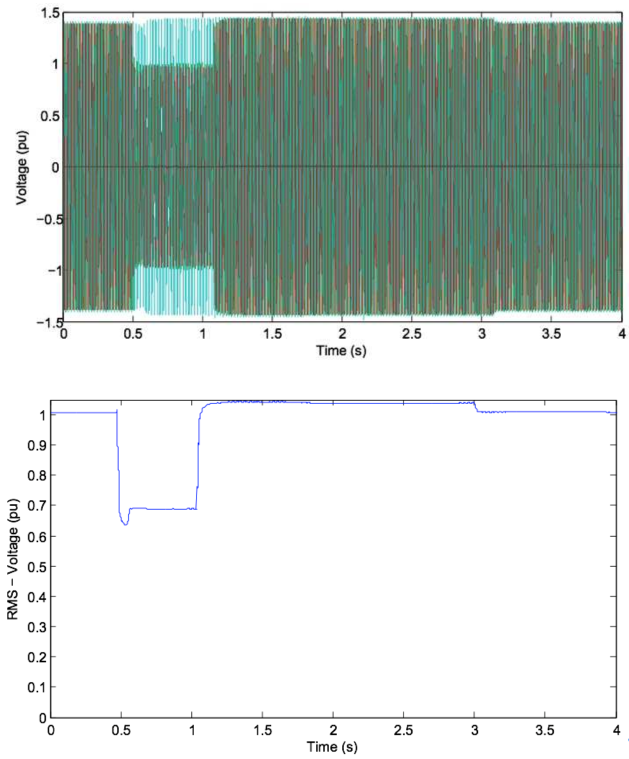

Fig. 4. Example of collected voltage dip: rms-voltage characterization

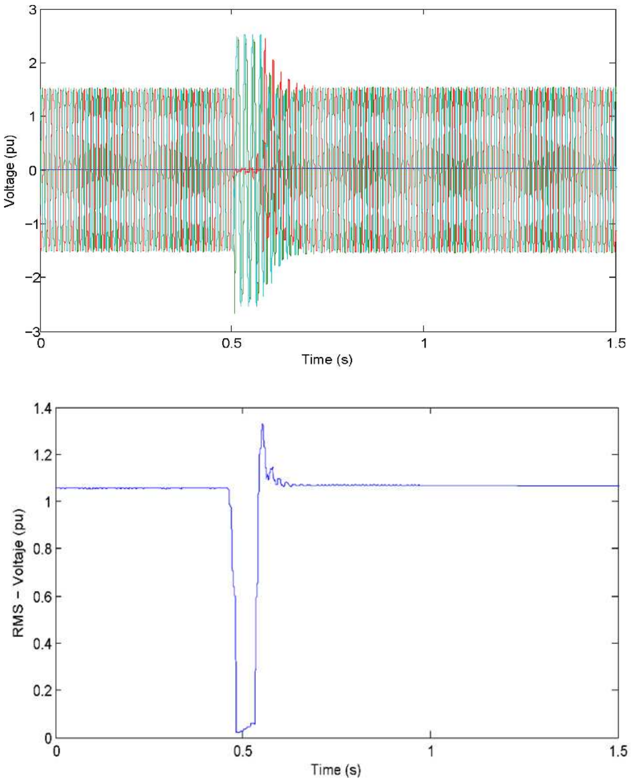

Fig. 5. Example of collected voltage dip: rms-voltage characterization

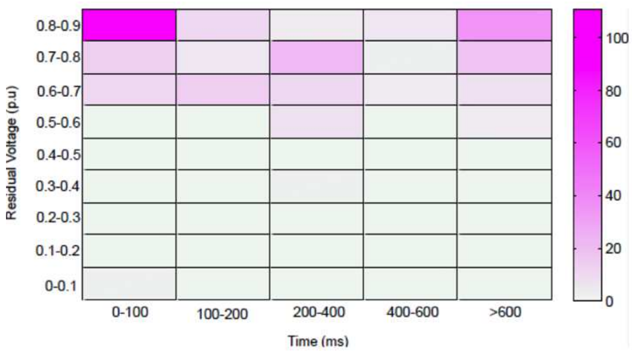

Fig. 6. Scatter-plot distribution of events

C. Park-Transformation: dq0 representation

From the collected instantaneous voltage values, dq0 components are estimated offering a global characterization of the disturbances. Indeed, and due to most collected voltage dips are unbalance, this approach gives a suitable methodology to represent this kind of disturbances by using all voltage values collected by the different phase-to-phase. As an example of comparison between real collected voltage dips and Spanish Grid-Code requirements, Fig. 7 shows the evolution of the dq0 components for both characterizations. This representation takes into account the evolution of three-phase voltages, offering a complete comparison between the disturbance and the Grid-Code limitations.

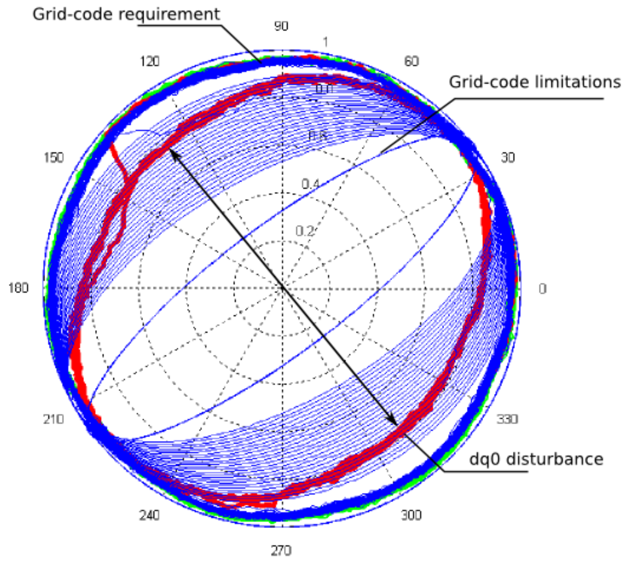

Fig. 7. Park Transformation: comparison between collected data and Spanish Grid-Code requirements

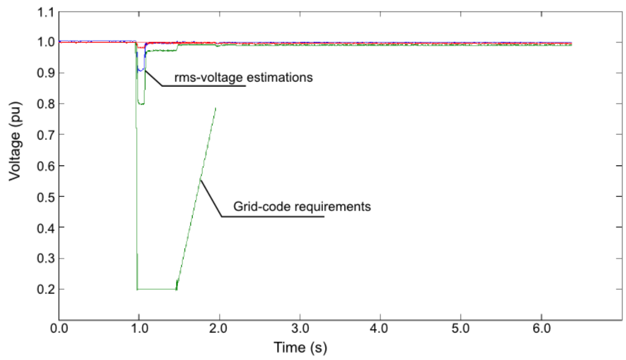

Fig. 8. Comparison between collected data and Spanish Grid-Code requirements: rms-voltage estimations

The representation depicted in Fig. 7 can also be compared with rms-voltage estimations. Actually, and as it can be seen in Fig. 8, rms-voltage limitations and rms-voltage estimations are plotted in an attempt to compare the severity of the faults in terms of time duration, residual rms-voltage and time around the minimum rms-voltage value.

5. Conclusion

Different methodologies to represent voltage dips are discussed with the aim of characterizing real disturbances collected from Spanish PV power plants. These data are also used to compare a selection of Grid-Code European requirements for PV power plants submitted to voltage dips. Both results and characterization are included in the paper, as well as a complementary analysis of the current requisites in comparison with real events.

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