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Identification of Linearized RMS–Voltage Dip Patterns Based on Clustering in Renewable Plants

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Abstract

Generation units connected to the grid are currently required to meet low-voltage ride-through (LVRT) requirements. In most developed countries, these requirements also apply to renewable sources, mainly wind power plants and photovoltaic installations connected to the grid. This paper proposes an alternative characterization solution to classify and visualize a large number of collected events in light of current limits and requirements. Our approach is based on linearized root-mean-square- (RMS-) voltage trajectories, taking into account LRVT requirements, and a clustering process to identify the most likely pattern trajectories. The proposed solution gives extensive information on an event's severity by providing a simple but complete visualization of the linearized RMS-voltage patterns. In addition, these patterns are compared to current LVRT requirements to determine similarities or discrepancies. A large number of collected events can then be automatically classified and visualized for comparative purposes. Real disturbances collected from renewable sources in Spain are used to assess the proposed solution. Extensive results and discussions are also included in the paper.

Index Terms

Clustering, Voltage measurement, pattern recognition

I. Introduction

Traditionally, primary sources of energy generation have been based on fossil fuels, such as petroleum, natural gas, or coal supplied to the electric grid through conventional power plants [1]. During the last several decades, most developed countries have promoted policies and incentives to change this paradigm, turning a scenario of efficient and renewable energy into reality. Yet, despite the significant growth in low-carbon sources of energy —such as the shift from oil and coal to natural gas and renewable sources— fossil fuels remain dominant in the global energy mix [2]. In the context of reducing dependence on fossil fuels and foreign energy sources, electricity emerges as a sector where renewable energy policies and energy-efficient initiatives are most likely to be implemented because electricity can be generated from a variety of fuels. Approximately 75% of residential/commercial energy consumption and approximately 35% of industrial energy consumption is in the form of electricity [3]. Consequently, displacing fossil-fueled generation with renewable generation presents many desirable outcomes within the electric power sector, including reducing pollution and carbon dioxide (CO_2) emissions. Significant goals can also be achieved through these actions —for example, the reliable delivery of electric power of acceptable quality nearly 100% of the time [4].

Concerns about global climate change, finite fossil-fueled resources, and the decreasing costs of renewables have been major contributors to justify the promotion of renewable energy sources (RES) and energy-efficiency policies in a significant number of countries [5]. Indeed, some authors affirm that the combination of these factors is driving more renewable energy integration [6], [7] In the case of Europe, a new directive was adopted in 2001 to promote investments in renewable energy sources (RES). The directive gave each member state of the European Union an indicative target according to its existing level of renewable electricity penetration, and member states approved the target of generating 20% of energy consumption from renewable sources by 2020. Member states have different individual goals to meet this overall objective, and they must provide detailed pathways describing how they will achieve these goals [8]. Concerns about RES integration into power systems is a topic of interest for European countries. Additional recent climate policy agreements in Europe require a reduction of at least 80% of all CO_2 emissions by 2050, eventually leading to the full decarbonization of the power sector [10]. Further, price volatility and competition in global energy markets are creating remarkable incentives for national governments to develop available RES [9]. Today, RES is an indispensable part of the global energy mix. RES integration into power systems has been partially created by the continued growth of hydropower as well as the rapid expansion of wind power and photovoltaic (PV) integration. These are underpinned by falling technology costs and rising fossil fuel prices and carbon pricing, but also and mainly by continued subsidies, which will increase from $88 billion globally in 2011 to nearly $240 billion in 2035. In 2015, RES became the world's second largest source of generation (approximately half that of coal), and it is approaching coal as the primary source of global electricity. By 2035, RES will account for almost one-third of global electricity output. Nevertheless, to avoid excessive burdens on governments and consumers, subsidies to support new renewable energy projects need to be adjusted over time as capacity increases and the costs of renewable technologies fall [11].

As RES technologies achieve significant penetration levels of integration, there is growing interest in analyzing the potential impacts of RES on the electric distribution grid and the possibilities for these renewable resources to offer ancillary services [12]. With these matters in mind, some countries have developed specific grid codes for the connection of wind and PV to ensure the continuity and security of their electricity supply [13]. For example, some European countries that have a high capacity for renewable generation, such as Germany and Spain, have developed new requirements to ensure the continuity of electricity supply during disturbances, especially voltage dips. These requirements have mainly focused on wind and PV installations because no other technology has or will be mature enough to challenge PV, wind, or gas in the next five years [14]. The installed capacity of other renewable technologiessuch as hydropower, biomass, waste, concentrating solar power, geothermal, and ocean energieshas increased during the past decade, but it has been to a lesser extent than wind and PV.

Most European utilities have put forward the low-voltage ride-through (LVRT) requirement in their grid codes to ensure dynamic voltage recovery during grid faults. LVRT is described as a characteristic of voltage against time, denoting the minimum required immunity of the generating units to dips in the system voltage [15]. LVRT criteria for different countries have been recently defined by [16], [17]. Control system strategies to ensure efficient and reliable electricity generation from both PV and wind turbine systems have been also proposed [18]. However, few significant works in the literature allow us to characterize large groups of voltage dips collected in field-measurement campaigns. Practical comparisons between root-mean-square (RMS) voltage profiles and the voltage requirements imposed by the norms are lacking, despite the fact that LVRT is considered the most important requirement regarding wind power plant operation that has been recently introduced in the grid codes [19]. Under this scenario, and considering the lack of contributions to automatically characterize and compare real disturbances to grid code requirements, this paper focuses on describing and assessing a new solution based on a linearized RMS-voltage process and an estimation of averaged RMS-voltage dip patterns through a clustering process.

The identification of RMS-voltage patterns during disturbances allows us to estimate the severity of these faults and to compare them to current grid code requirements —not only in terms of time and minimum RMS-voltage but also based on an alternative, linearized RMS-evolution during the disturbance. The estimations of averaged RMS-voltage patterns are classified by their probability of occurring, providing additional information that can be used to test power electronics and the control system. In line with [20], a finite set of conceivable fault voltage waveforms are selected to test power electronics and control systems experimentally and/or via computer simulation. Therefore, and according to a set of field-test campaigns, the proposed solution gives the most expected RMS-voltage trajectories for a specific location. These linearized RMS-voltage patterns can then be used to test power electronics and control systems because the goal to protect against all other fault waveforms might lead to overengineered solutions, potentially increasing their cost. To evaluate the advantages of this novel methodology, disturbances collected in different PV installations and wind power plants in Spain during a series of data collection field campaigns (20082013) were first linearized to determined the RMS-voltage trajectories during the fault. Second, the most representative RMS-voltage patterns were estimated and compared to the Spains current voltage dip requirements to provide an extensive and complete characterization of the severity of the events in accordance with the current requirements.

The rest of the paper is structured as follows: Section II describes the RMS-voltage linearization process according to current LVRT requirements. The pattern estimation methodology based on K-means clustering analysis is proposed in Section III. The results and discussion are presented in Section IV and Section V offers the paper's conclusion.

II. Voltage Dip Linearization based on LVRT Requirements. Proposed Solution

A. Preliminaries

Due to the remarkable penetration of RES into power systems, in recent years national grid codes have radically changed to promote severe technical requirements for RES installations to avoid widespread supply-side disconnections during disturbances, especially voltage dips. Renewable generation units that are connected to the grid are called on to maintain specific ranges of active and reactive power when they are exposed to voltage dips. These LVRT requirements were initially applied to wind

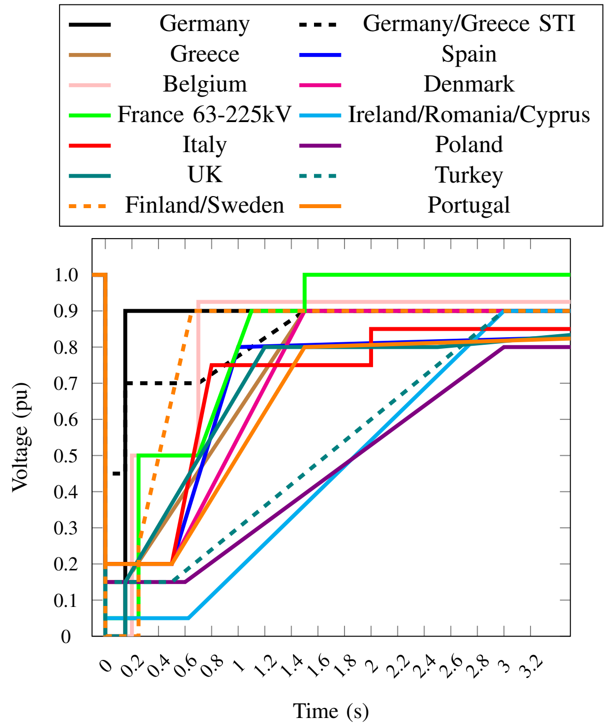

Fig. 1: Low Voltage Ride Through (LVRT) requirements: comparison of rms-voltage limits at the common coupling point [30]

power plants [21] and later to PV plants. Policies in some European countries —such as Spain, Italy, Germany, and Denmark— are clear examples of these norms and their evolution and extension from wind power plants to PV installations. As an example, wind power plants in Spain were initially required to stay connected to the grid in response to narrow and short-term voltage dips. A Royal Decree (RD-565/2010) was issued in November 2010 [22] extending these requirements to PV installations. Since February 2016, after Spains Secretary of State for Energy imposed a new regulatory framework, wind power plants in Spain have participated in providing some ancillary services managed by the Spanish transmission system operator, Red Electrica de España.

LVRT requirements have traditionally been developed in terms of RMS-voltage limits for generating units connected to the grid. As shown in Figure 1, current norms significantly different among countries, even within the European Union, which is an important barrier to efficiently integrating RES [24]. Some reports suggest that the large diversity of requirements and norms is one of the major obstacles toward the deployment of distributed RES [25]. Moreover, the authors of [26] affirm that the variety of RMS-voltage limits have proven to be a major barrier for the PV industry because the control strategies applied to inverters must be upgraded to fulfill the different requirements imposed in different countries. The performance criteria for disturbances are usually determined by protection tripping times [27]. A suggested fault-ride-through profile for PV and wind power plants can be found in [28]; according to the authors, it could be used to harmonize the requirements. The values of the profile can be adjusted according the grid immunity and protection requirements, giving the transmission system operator the flexibility of choice. Similarly, the latest draft of the Network Code on Requirements for Generators (provided by the European Network of Transmission System Operators for Electricity), which governs connections to the grid that are less than 110 kV and within the European Union [29], has been issued in terms of RMS-voltage limits. It considers only the RMS-voltage of the phase most affected by the disturbance as an estimation of the severity of the fault.

B. Linearized RMS-Voltage Trajectories

According to Figure 1, most current LVRT requirements are based on RMS-voltage linearized trajectories. Indeed, all profiles consist of linear plots that take into account not only minimum RMS-voltage and duration but also their evolution along the transient. In this way, two types of existing profiles in LVRT can be observed: (i) rectangular profiles based on steps of system protection tripping and (ii) profiles with a recovery ramp, representing the most severe profiles obtained by statistical analysis of network failures. Under this scenario, the linearized RMS-voltage transient characterization can be considered a conventional method for characterizing events. Consequently, a suitable methodology to compare requirements and real disturbances should be based on matching linearized RMS-voltage trajectories and LVRT limits. However, this approach becomes initially ineffective and impractical when a large number of disturbances are considered and then each linearized event needs to be compared to the corresponding LVRT requirement. For this reason, and according to the specific literature, most previous contributions have

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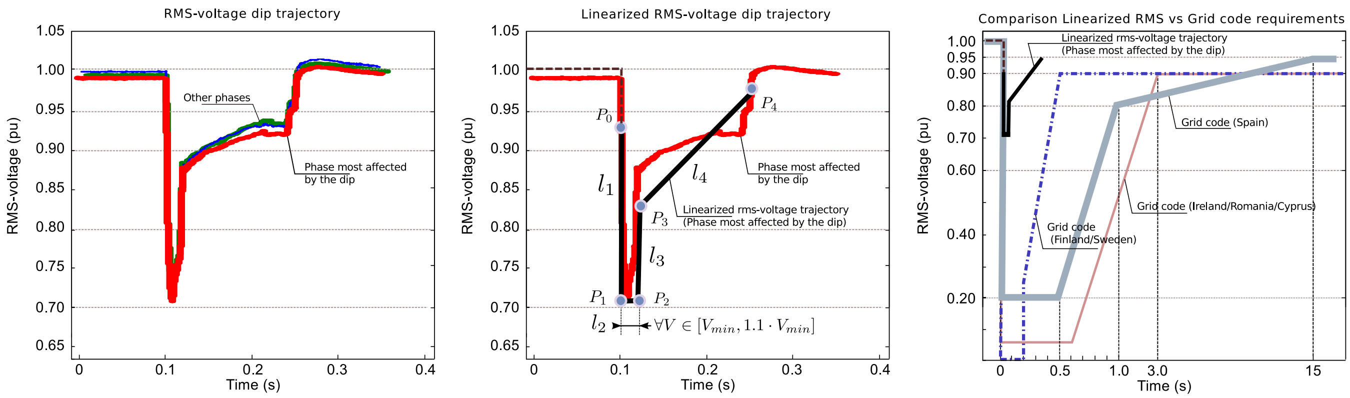

Fig. 2: Example of RMS-voltage linearization: voltage dip (wind power plant in Spain)

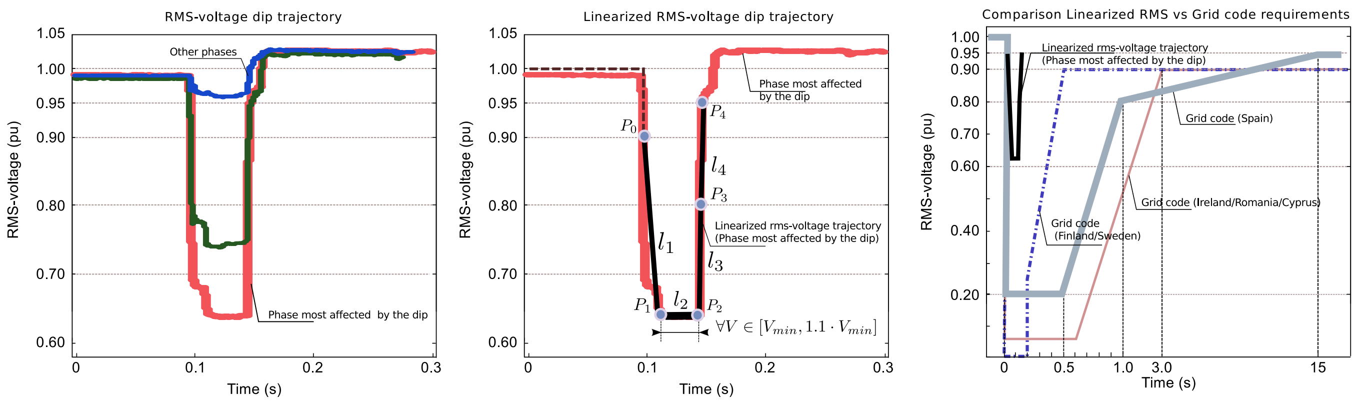

Fig. 3: Example of RMS-voltage linearization: voltage dip (PV installations in Spain)

considered a reduced number of parameters to characterize voltage dips. A general solution consists of identifying voltage dips by two main parameters: magnitude and duration [31]. Voltage dips are then commonly characterized by the lowest voltage and longest duration measured across all channels. The authors of [32] define a voltage dip as a reduction in the magnitude of RMS-voltage during a certain time interval. The voltage dip duration is defined as the time interval during which the RMS-voltage values remain lower than a specific threshold. Both parameters —minimum RMS-voltage value and time duration— can then be represented by using a set of well-known techniques: density tables [33], [34], color maps [35], [36] or scatter plots [37]. A more detailed representation of groups of disturbances was proposed in [37], wherein the size of the marker is proportional to the area generated as a consequence of the disturbance, determined in volt-seconds. The disturbance area is described as a measure of the power loss during the event. A more recent analysis of voltage dips is also based on a typical scatter plot in the duration-residual voltage plane, and an additional statistical analysis focused on global duration distributions for these events [38]. In our opinion, these previous contributions do not provide a suitable solution for comparing collected disturbances and RMS-voltage limits given by current norms in terms of severity and the fulfillment of requirements. Moreover, there is a lack of advances in extensive tools to analyze a large amount of events under RMS-voltage requirements. To overcome these drawbacks, an alternative method to characterize and represent voltage dips based on a linearized process of the RMS-voltage trajectories and a subsequent clustering process is proposed by the authors and initially discussed in [39]. The segments to be considered for the linearized process are defined according to the LVRT requirement. Therefore, the number of segments, their lengths, and slopes are in line with the specific rules provided by the corresponding transmission system operator. For example, and in the case of Spain, a set of four segment lengths (l_1 to l_4) related with partial time intervals and RMS-voltage trajectories are defined. The visualization of the four lengths l1 to l4 for two real disturbances collected in a wind power plant and a PV installation in Spain is shown in Figure 2 and Figure 3. In addition, the linearized RMS-voltage trajectories are compared to different grid code requirements, including Spanish criteria, to give a general overview about the severity of the fault facing current rules. It is thus a complete characterization of the disturbance that considers not only a reduced number of parameters —such as minimum RMS-voltage and duration— but also the minimum linearized RMS-voltage trajectory during the fault. Moreover, this characterization allows us to establish a direct relationship between the required RMS-voltage limits and the disturbances after determining each corresponding segment and length to characterize both the severity and maximum slopes allowed by the regulation.

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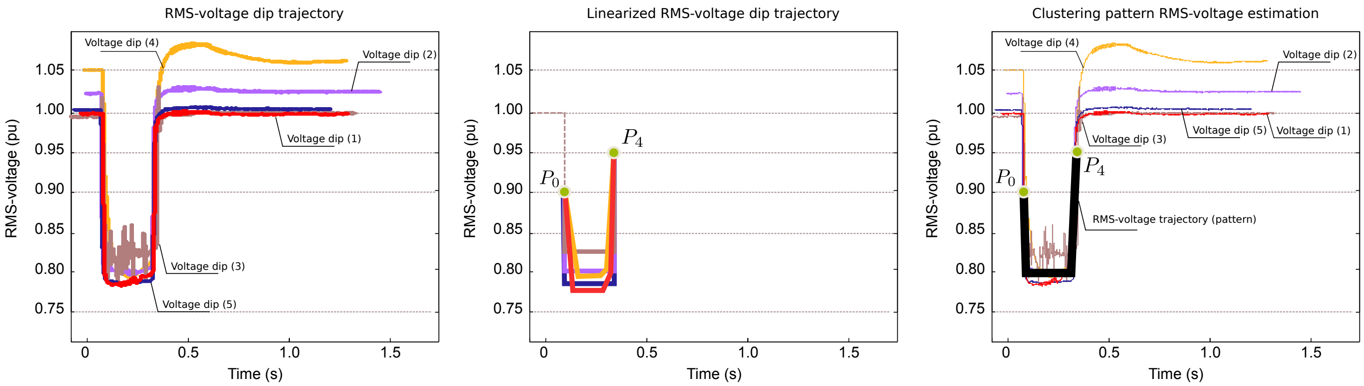

Fig. 4: Example of clustering RMS-voltage pattern estimation: Groups of voltage dips (wind power plant in Spain)

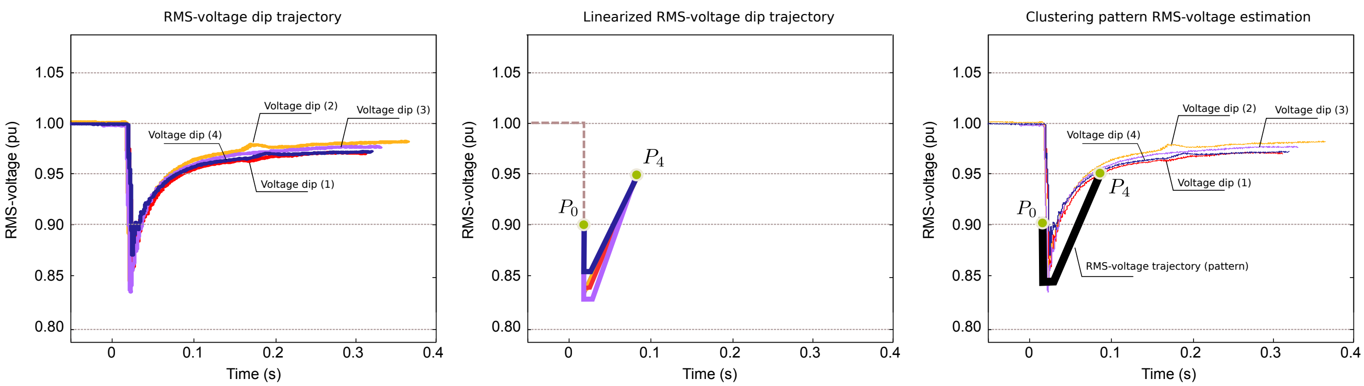

Fig. 5: Example of clustering RMS-voltage pattern estimation: groups of voltage dips (PV installation in Spain)

III. Estimation of RSM-Voltage Patterns by K-means Clustering Analysis

Exploratory data analysis is a data mining task that establishes relationships among features and the intended objectives [41]. Several statistical tools can be used for this purpose, such as principal component analysis, Fisher discriminant analysis, projection pursuit exploratory data analysis, or cluster analysis [42], [43]. In this work, to identify RMS-voltage patterns and groups of voltage dips among a large data set of events, a K-means clustering process has been selected using the set of lengths described in Section II-B as input variables. It provides insight with respect to time duration, residual RMS-voltage, and severity of disturbances within a real data set. These approaches are introduced by the authors and are not found in other contributions. This approach offers several remarkable advantages because the identification of patterns and similarities of voltage dips significantly reduces the number of events to be represented. These representative RMS-voltage profiles can be compared to current grid code requirements, giving an averaged estimation of the severity of disturbances in terms of the RMS-voltage limitations required by the operational procedures.

K-means clustering is a method for finding clusters and cluster centers in a set of data. The user needs to specify the number of cluster centers and the initial guess for them, and the K-means procedure iteratively moves the centers to minimize the total within the cluster variance. Concretely, given an initial set of centers, the K-means algorithm alternates the two steps: (i) each point is assigned to its closest center; and (ii) the means of each variable for the data points in each cluster are computed, and this mean vector becomes the new center for that cluster. These two steps are iterated until convergence. Typically, the initial centers are randomly chosen observations from the training data. For more information, see page 460 of [44].

As a first attempt to show the proposed clustering process, Figure 4 shows an example using disturbances collected from a wind power plant in Spain. Several voltage dips are depicted by considering the phase most affected by the disturbance. From these real data, the RMS-voltage evolution profiles are automatically linearized through the segments introduced in Section II-B. Finally, the RMS-voltage trajectory pattern is estimated and represented together with the initial RMS-voltage dip trajectories. In a similar way, Figure 5 shows the results for events collected from a PV installation in Spain. As shown, the estimated patterns for both examples are significantly different; and their comparisons to current LVRT requirements provide different results in terms of the severity of the faults, as discussed in the following section.

IV. Results and Discussion

Different voltage dip surveys have been carried out in renewable sources connected to the grid: (i) three PV power plants in Spain are located in regions with high radiation levels, and (ii) one wind power plant in Spain is located in a region with

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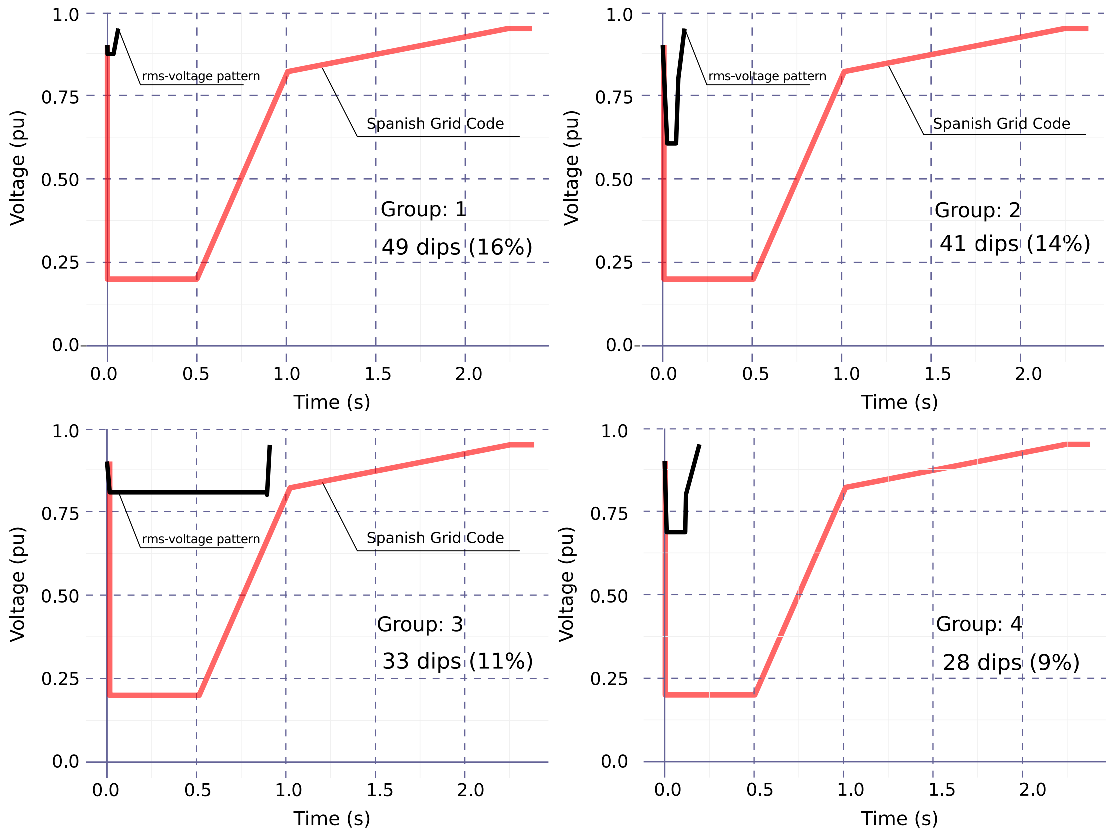

Fig. 6: Clustering RMS-voltage pattern estimation (black) compared to Spain's grid code requirement (red) at a wind power plant.

significant winds. The field-measurement campaigns have taken five years, from 2008–2013 for the PV installations and from 2006–2011 for the wind power plant. RMS-voltage values have been estimated from the instantaneous collected voltage values corresponding to transient events over a sliding window based on [45]. According to the definitions given in [46] and [47], 439 events have been identified: 133 voltage dips and 8 momentary interruptions ($<$ 3 seconds of duration) in PV installations, and 298 voltage dips in wind power plants.

Some examples of collected data are shown in Figure 2 and 3, wherein the RMS-voltage linearization process is discussed and applied on real voltage dips. In addition, examples of the clustering process are shown in Figure 4 and Figure 5, wherein an estimated RMS-voltage pattern trajectory is determined for each case based on a set of disturbances previously clustered. Taking into account the collected events, and automatically applying the proposed solution to the global groups of disturbances, Figure 6 and Figure 7 show the results corresponding to the most likely patterns for both renewable sources: wind and PV power plants, respectively. As shown, each cluster is labeled according to the number of events considered and the percentage of all events. In addition, each RMS-voltage trajectory is compared to the RMS-voltage limits allowed by Spain's transmission system operator. This comparison gives extensive information regarding the most likely RMS-voltage trajectories and their similarities or discrepancies with the corresponding LVRT requirements. Moreover, it suggests a visual tool to identify typical trajectories for disturbances in a specific location, which can be used as an additional data set for LVRT testing. In fact, and according to recent contributions such as [48], a series of LVRT tests must be defined for the power converters to meet current LVRT capability. Subsequently, we propose the most likely RMS-voltage patterns as additional profiles to test power converters by considering locations and specific grid characteristics not previously taken into account in other works. On the other hand, full information regarding the group of segment lengths defined in Section II-B can be compared though their box plot distributions. As an example, Figure 8 compares the length distributions for cluster number 2 (wind and PV installations). This graphical representation is able to assess the variabilities of the length for l_1 to l_4 within each cluster as well as their average values that correspond to the RMS-voltage pattern estimations. The cluster selection is usually a critical stage in most clustering processes, and this box plot representation can give significant information to modify (or not) the selection criteria of clustering. Additionally, these box plots allow us to compare most likely RMS-voltage profiles in terms of linearized trajectories by means of the defined segment lengths (l_1 to l_4).

A comparison to previous approaches can be found in Figure 9. The collected events are depicted according to their residual RMS-voltage values and global duration, giving minimum information regarding the dips in comparison to the proposed estimated RMS-voltage pattern. All events are colored depending on the clustering classification, in this case for clustering 2

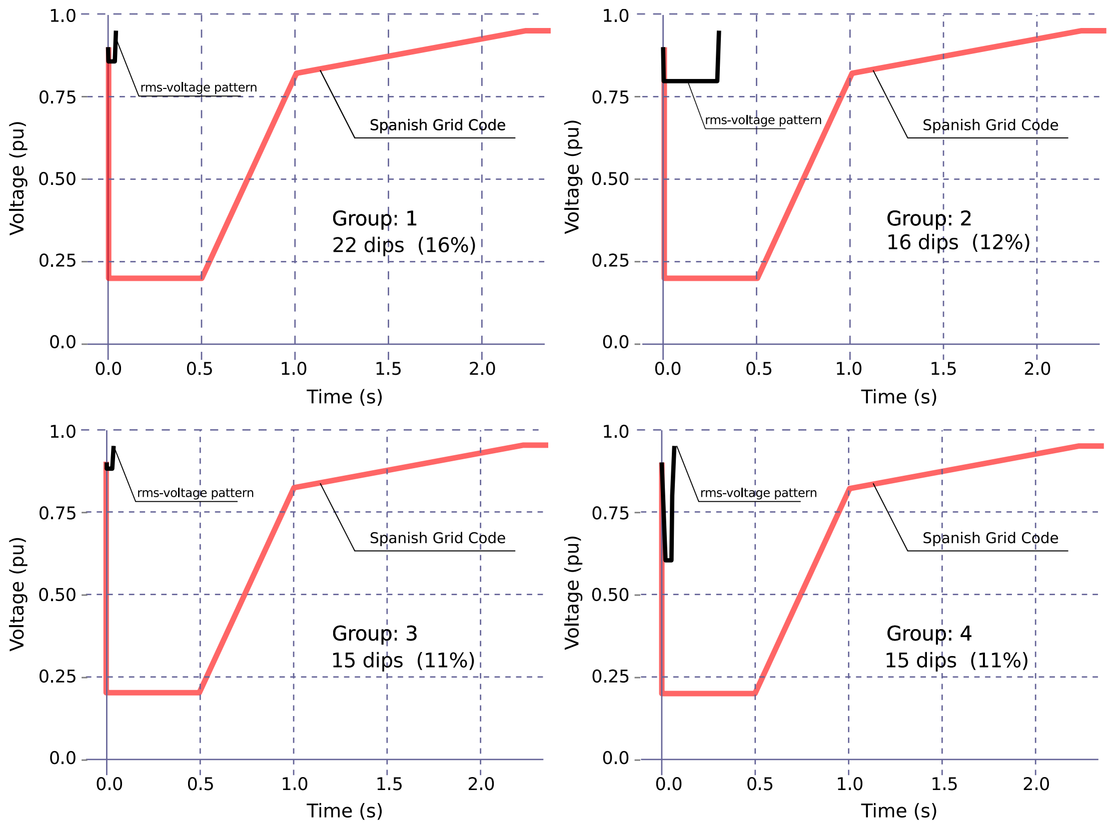

Fig. 7: Clustering RMS-voltage pattern estimation (black) compared to Spain's grid code requirement (red) at a PV installation.

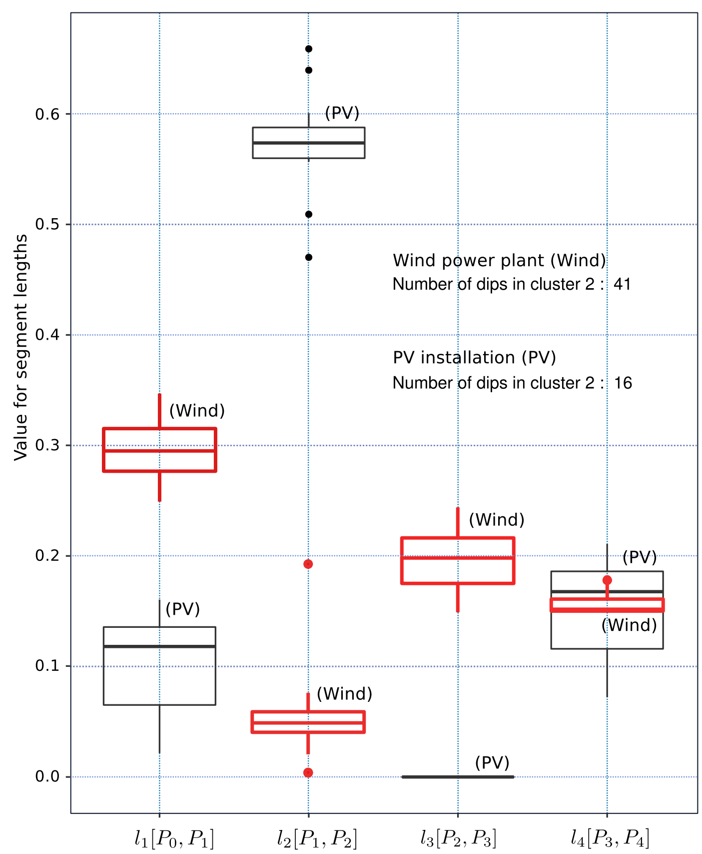

Fig. 8: RMS-voltage pattern estimation: comparison of segment distribution (box plot).

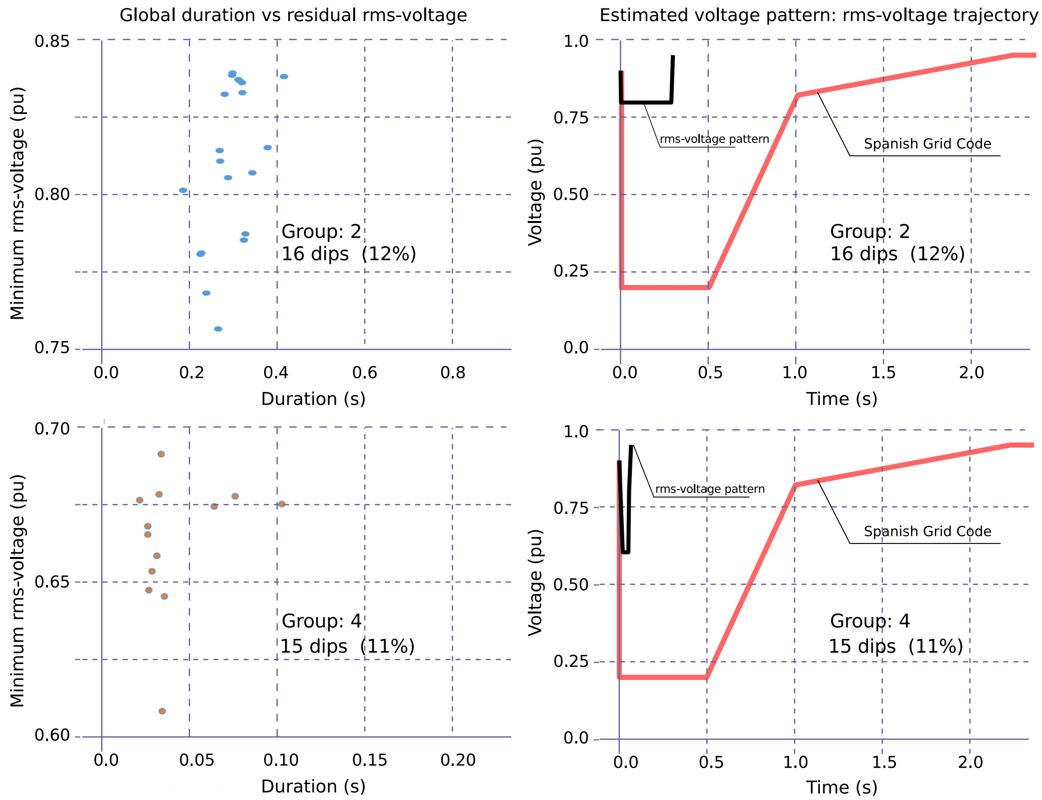

Fig. 9: PV power plant measurements: example of distribution of events vs estimated RMS-voltage patterns.

and 4. As shown, disturbances with similar RMS-voltage residual values and/or durations might differ significantly in terms of RMS-voltage profiles, and thus they require an extensive analysis in terms of transient voltage evolution and not only considering limit values for voltage and time.

V. Conclusion

An alternative characterization and classification of voltage dips based on linearized RMS-voltage trajectories and the clustering process is discussed and assessed. The proposed solution gives extensive information on the events severity by a simple but complete visualization of the most likely linearized RMS-voltage patterns. These averaged patterns are compared to current LVRT requirements to determine similarities or discrepancies with the LVRT requirements by an intuitive characterization and visualization. To assess the proposed methodology, it has been applied to compare real disturbances collected from renewable generation units in Spain that are connected to the grid and facing LVRT requirements. Using previous field-measurement campaigns carried out by the authors, more than 400 events have been automatically linearized and classified by means of a clustering process to estimate the most likely RMS-voltage trajectories. From the data, 15 averaged RMS-voltage profiles have been determined and compared to current LVRT requirements to estimate the severity of the events in terms of not only duration and residual RMS-voltage but also considering their evolution throughout time. A comparison to previous classification approaches is also discussed. From this comparison, the proposed methodology offers a novel and significant tool to analyze large numbers of disturbances with negligible computational time costs.

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