Detection of Dips, Swells and Interruptions in DC Power Network

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Abstract— **The recent developments in power electronics have greatly increased the number of appliances that operate in DC and, contextually, the main distributed energy sources such as photovoltaic systems and fuel cells are inherently of DC nature. Therefore, a better integration of these devices into the electrical grid can be achieved with a direct connection in DC, avoiding all the additional losses due to the energy conversion stages currently employed in the traditional AC distribution grid. On the other hand, high voltage transmission in DC (HVDC) offers lower costs due to reduced losses in transmission. Nevertheless, at present, there is a lack of international standards that define Power Quality (PQ) metrics for DC grids. This paper makes a review of the technical report IEC-TR-63282 that is a first normative effort to this aim. Moreover, the authors suggest measuring methods to evaluate dips, swells and interruptions. The measuring method has been finally applied to PQ phenomena detected on simulated and experimental data to evaluate the effect of the time interval adopted in the assessment of these events.**

Index Terms--**DC Grid, LVDC, HVDC, Power Quality, Dip, Swell, Interruption.**

I. INTRODUCTION

Recent years have witnessed the spread of renewable energy sources (RESs) with the aim of reducing carbon dioxide emissions and coping with environmental issues. Despite the pandemic, the growth rate in RESs raised 3 % in 2020 [3]. Most RESs, such as photovoltaics, fuel cells, batteries, and other energy storage elements are inherently of DC nature and act as DC power sources. But typically, the electrical energy produced by these distributed sources is delivered to the traditional AC power grid for transmission and distribution. To this aim, DC/AC converters are adopted, introducing unavoidable losses due to these additional conversion stages that reduce the overall efficiency. In the management of energy storage systems, reciprocally AC/DC converters are adopted with a similar impact. A better integration of distributed energy sources can be achieved with the utilization of DC collecting grids at medium and high voltage without any DC–AC conversion, with an improvement of the total system power efficiency [2].

In DC networks it is possible to provide more energy per square meter over greater distances with lower losses and less space requirements than AC systems. High-voltage direct current (HVDC) transmission has been used for many years with numerous applications, for instance, submarine cable interconnections for offshore systems. Moreover, variable speed (wind) generators and large motor drives would benefit from connecting to DC feeders since only half of the power electronics are needed, compared to AC feeders [2]. In this context, the European supergrid is proposed to interconnect the existing HVDC lines in the North and Baltic seas and to provide transmission access for offshore wind farms. Finally, there are numerous studies on converting existing AC lines into DC in order to enhance power transfer and to provide full power control. Converting multiple AC lines into a DC network could significantly improve power trading [3]-[5].

In addition to the above, the development in power electronics has raised the number of appliances that operate in DC, so conversions from AC to DC form are necessary to supply them from the traditional AC distribution system. The resulting additional conversion stages, from DC sources to AC grid and back again to DC loads, cause energy losses and consequently reduce the overall energy efficiency of the system. This applies to most modern electronic loads such as computers, servers in data centers, light-emitting diodes, and electric vehicles that require DC power. But also, a traditional AC load such as an induction motor can be made to behave as a DC load when driven by a variable speed driver. In all these cases the direct use of DC distribution power systems can reduce the DC/AC and AC/DC power conversion, which consequently offers higher efficiency and reliability. These considerations are promoting the use of DC grids in industrial environments, commercial buildings, residential homes, telecommunication buildings, data centers, electric vehicles, aircrafts, ships, spacecrafts, and low-voltage (24 V) applications [6].

However, the proliferation of DC technologies in the near future is not a straightforward task. Low-voltage direct current (LVDC) systems and grids should at least provide the same level of operational reliability, and safety as their counterpart

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AC systems to support consumer and market confidence. In such a context, issues related to DC system operation, control, protection, and measurements need to be understood and resolved in advance, to allow a smooth integration and operation of RESs, storage elements, and the diversity of DC loads, all connected together by the DC network.

Another very important aspect to be evaluated is the level of electromagnetic emissions produced by both power sources and devices connected within the LVDC distribution grids, and the immunity of the DC loads to Power Quality (PQ), and other dynamic phenomena. The definitions and requirements for a certain level of PQ and electromagnetic compatibility (EMC) are therefore of paramount importance for the planning and operation of LVDC grids, as well as for the design and certification of equipment and systems to accelerate the emerging of DC technologies.

Up to the present moment, there are still some technical deficiencies that affect DC power systems such as 1) difficulties in managing the power imbalance among power sources and loads, 2) the unstable bus voltage oscillation due to rapid time-varying power loads, and 3) the bus voltage fluctuation due to intermittent RESs and those that are not yet fully studied.

All these issues introduce serious concerns about PQ of a DC grid and microgrid systems. These concerns are mainly DC voltage dip, voltage swell, voltage spikes and transients, voltage fluctuations, voltage flicker, circulating currents and voltage oscillations. At present, the existing international standards define only a wide set of PQ indices and algorithms specifically conceived for AC grids, and so are not directly applicable to DC distribution grids. On the other hand, a through survey of the available literature has indicated few proposals regarding PQ metrics for DC systems [7].

In [8], several ripple indices based on frequency or time domain estimated quantities are described. The main advantage of defining DC PQ metrics in the frequency domain is that they can keep the similarity with AC PQ metrics, while the time-domain does not need to deal with the lack of the fundamental and harmonics. In [9], the standards IEC 61000 [10] and IEEE Std. 1159 [11] are reviewed to evaluate the existing definitions of PQ and consider if they are sufficiently general to encompass DC grids and a simulation of PQ disturbances produced by power electronic converters is presented. The first initiative to provide some standardised guidance in regards to PQ requirements for LVDC grids is reported in IEC-TR-63282 [12]. It is worth noting that this document only provides some recommendations for PQ phenomena that are relevant to be considered in LVDC networks, and some guidance for the measurement window lengths over which the assessment of certain DC PQ indices should be calculated. Assessment methods of PQ in DC are not recommended by the document yet, and, for this work, reference is still made to IEC Std. 61000-4-30 [10], although the PQ phenomena in DC are different from the phenomena in AC grids. In addition, it is not clear whether the time durations of DC PQ events and their magnitude variations are similar to those in AC, enough to say that the AC threshold levels and measurement window sizes are appropriate to detect and classify disturbances such as voltage dips, voltage swells, and voltage transients in DC grids.

Thus, to foster the development of DC grids, it is fundamental to define common standards to characterize PQ in distribution networks. To this aim, this paper analyses the main indices that characterize the supply magnitude variations (dip/swell/interruption) starting from the definition and implementation employed in AC systems, evaluating the possibility and the effectiveness of their extension to DC networks. The activity has been carried out within the EMPIR 20NRM03 DC Grids research project focused on traceable measurement and characterization of PQ phenomena to support standardization in the further development and future use of DC grids and to ensure future customer confidence. In the following sections, section II is a review of the technical report in regards to what voltage levels are reported; section III introduces the definition of DC voltage magnitude; in section IV detection algorithms for short-time phenomena such as voltage interruptions, dips and swells are proposed, and in section V the capability of different measurement window sizes to detect voltage disturbance events is assessed; in section VI conclusions are drawn from the paper.

II. VOLTAGE LEVELS IN LVDC SYSTEMS

LVDC distribution systems have recently been recognized by many stakeholders as an alternative approach to provide efficient power supply to consumers. LVDC covers a wide range of power applications from low power USB-C up to megawatts for aluminium smelting. The standardization of voltage levels and PQ phenomena of LVDC distribution is a key issue, and urgent work is needed. Existing LVAC systems have different standardised voltages, depending on the geography and application. The PQ phenomena of the DC power distribution are not identical to AC PQ phenomena while there are some common issues. Since many of the main PQ phenomena are strictly linked to the voltage level, it is fundamental to establish the limits of deviations from the normal operating range. A common guideline is needed to establish the voltage ranges for temporary and continuous operation in LVDC grids. IEC-TR-63282 [12] proposes the operation voltage ranges with respect to time, as shown in Fig. 1. The voltages are divided into 7 bands denoted by Bi, where i varies from 1 to 7, and each band is delimited by an upper limit Ui. Moreover, 4 operating states are defined, of which 3 states (S1 to S3) are transient states and 1 state (S4) is the steady state.

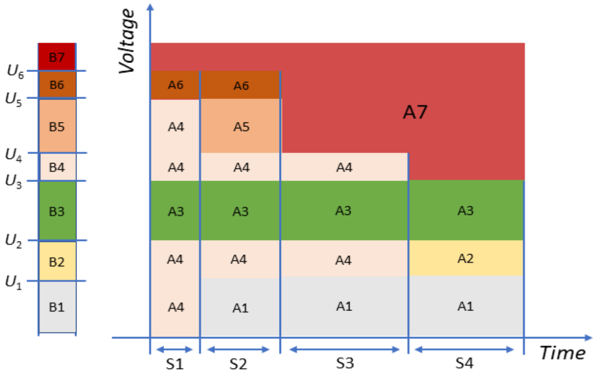

Figure 1. Voltage range versus time

TABLE I. DC VOLTAGE AREAS CLASSIFICATION

Voltage areas	*Denomination*
A7	Prohibited State
A6	Overvoltage with clamping
A5	Overvoltage state without clamping
A4	Abnormal state
A3	Nominal band
A2	Emergency state
A1	Blackout state

In general, a PQ issue can stress the dielectric material of a connected system for limited time. So, the IEC technical report relates the voltage level with time duration. The same undesired voltage level will conduct the system in different states as time elapses.

The lowest band B1 (Blackout band) is allowed only for short transient phenomena (S1 state), because for a wider time interval it would cause a shutdown of all the devices. The band B2 (Emergency band) can occur in the case of high overload that brings the voltage level below B3 (Nominal band). On the contrary, voltages higher than U_3, are generally due to a sudden change of current: if the voltage rise lies in the band B4 (switching, commutation and protection devices operation band), surge protection devices are not triggered, while the band B5 (Overvoltage protection devices operation band) is characterized by the intervention of the protection devices. In the band B6 (Overvoltage trip band), overvoltages that last for intervals longer than S2 can cause damages to the equipment. For voltages higher than U_6, that correspond to band B7 (Prohibited band), even fast-transient phenomena of duration lower than S2, can cause a breakdown of the whole system. Since, as mentioned before, the capability of electronic devices to tolerate voltage disturbances is strictly dependent on time, the areas given by the intersection of bands and states represent the operating conditions of the system. The areas are defined in Table I. The blackout state (A1) indicates that the supply voltage is not sufficient for device operation. The emergency state A2 occurs when the system works for an indefinitely long time in the band B2, in which the devices keep operating but with reduced performances. The nominal band A3 identifies the normal operating condition. The system can remain in the abnormal state A4, which identifies voltage levels just outside B3 (higher or lower), for a limited time. The states A5 and A6 occur as result of overvoltages, nevertheless while A5 is tolerated for short transient (S2), A6 identifies an area of immediate clamping. Permanent equipment failure is likely to occur in the last area A7.

This approach is considered a helpful solution to standardize the voltage requirements regardless of the specific application. When the voltage falls below U1, the S1 interval distinguishes dips from interruptions. Interruptions clearly correspond to area A1. The emergency state A2 is a clear condition in which poor PQ will affect the performance of systems involved and additional power sources or load shedding actions are required to resolve the otherwise permanent overload condition. For what regards voltage overshoot, in the A6 area clamping will protect systems from failure. Surges and swells mostly fall inside areas A4 and A5 in the bands B4 and B5, but in those areas no intervention of protection is foreseen, therefore if the voltage remains at those high levels for a longer time, the system will fail, going into A7.

It is evident that the described approach is based on a continuous monitoring of the amplitude of the DC supply voltage, on the comparison of its magnitude with the different thresholds and on the counting of the residence times in the various zones. To this aim, a standard measurement procedure that allows to quantify the magnitude of the supply voltage, accounting its characteristics when no other PQ event applies, is required.

III. DC VOLTAGE MAGNITUDE DEFINITION

It is worthwhile noting that perfectly constant voltage (see Fig. 2) is not feasible. In most cases, the DC supply is obtained by converting the voltage generated from AC sources to DC through a rectifier (passive or active). Photovoltaics, fuel cells, batteries, and other energy storage elements are inherently of DC nature and could directly supply DC distributions. Anyway, to adapt the voltage level and to perform a voltage regulation also in this case, DC-DC converters are adopted. Of course, various kinds of converters can have a different behaviour that entails different voltage shapes, the same for the various types of rectifiers.

To better clarify this aspect, focusing on the source side, the typical waveform at the output of common rectifiers can be considered. As examples of ripples the output voltages of single-phase and three-phase filtered rectifiers are shown respectively in Fig. 3 and Fig. 4. It is worthwhile underline that the reported waveforms are ideal and are obtained neglecting the reactive behaviour of line and load. The DC output voltage of full-wave rectifiers can be analytically expressed as:

$$v(t) = rep_T\,[V_p\cos(\omega t)], \qquad (1)$$

$$\text{with } \theta_1 \leq \omega t \leq \theta_2,\ T = (\theta_2 - \theta_1)/\omega$$

where V_p is the peak of the input AC voltage, and θ_1 and θ_2 are given by:

$$\theta_1 = -(m!\,\pi/12), \quad \theta_2 = +(m!\,\pi/12) \qquad (2)$$

where $m = 3, 2, 1$ for single-phase, three-phase and hexa-phase rectifiers respectively. This entails that the output voltage of rectifiers is affected by periodic fluctuations compared with the average value. From (1), it is evident that an increasing number of pulses allows a rectified voltage closer to the ideal DC, because it is characterized by a lower amplitude deviation. On the other hand, a higher number of pulses implies higher ripple frequency.

The first task of PQ monitoring is the assessment of the supply voltage magnitude. Given information about the level of stress of all the devices supplied, it can be used for predictive maintenance purposes. The magnitude calculation can be done in two ways through the root-mean-square (rms) method or a straight DC method:

$$U_{rms} = \sqrt{\frac{1}{n}\sum_{i=0}^{n-1} u_i^2} \qquad (3)$$

$$U_{DC} = \frac{1}{n}\sum_{i=0}^{n-1} u_i \qquad (4)$$

where u_i are the samples of the voltage and n depends on the sampling frequency and the time interval.

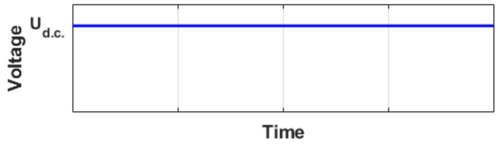

Figure 2. Ideal DC voltage

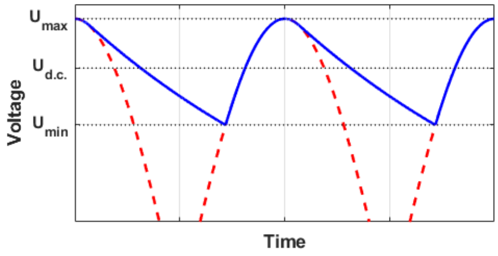

Figure 3. Filtered single-phase rectified voltage

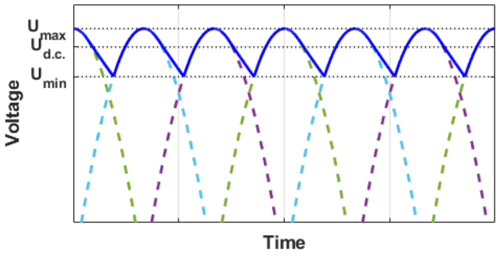

Figure 4. Filtered three-phase rectified voltage

IV. MEASURING PROCEDURE DEFINITION

Equations (3) and (4) are examples of theoretical definitions of the quantities of interest. They are not sufficient for standardized monitoring, but it is also necessary to define completely and univocally the measurement procedure. The first initiative to provide some standardized guidance in regards to PQ requirements for LVDC grids is reported in the technical document IEC-TR-63282 [12]. It is worth noting that the document only provides some recommendations for PQ phenomena relevant to be considered in LVDC networks, and some guidance for the measurement window lengths over which the assessment of certain DC PQ indices should be calculated. Assessment methods of PQ in DC are not yet recommended by the document, and reference is still made to IEC Std. 61000-4-30 [10], although the PQ phenomena in DC are different from the phenomena in AC grids. In addition, it is not clear whether the time durations of DC PQ events and their variation magnitudes are similar to those in AC, in order to conform that the AC threshold levels and measurement window sizes are appropriate enough to detect and classify disturbances such as voltage dips and voltage swells in DC grids.

Obviously, the first attempt, before starting to define new specific measurement procedures, is to verify the applicability of definitions and procedures already established for AC power supply systems. To this end, reference could be made to the IEC 61000 family standards [10]. So, in the following work some of the main aspects of dips and swells measurement procedures will be discussed, identifying problems and limitations to their applicability to DC system. The goal is to propose an extension with minimal changes so maintaining a certain degree of compatibility of obtained results.

The standard [10] states that the detection and measurement of non-stationary disturbances such voltage dips, swells, surges, interruptions and transients should be obtained by measuring the rms voltage over 1 cycle, starting at a fundamental zero crossing, and refreshing every half-cycle. For DC, the lack of a “fundamental component” leads to the impossibility of adopting the same approach for synchronization, thus reference to the absolute time is required for the definition of the measurement time interval. Nevertheless, for compatibility issues, the same time interval could be adopted: the magnitudes in (3) and (4) can be calculated over a time interval of 20 ms and refreshed every 10 ms referring to absolute time. Both of these time intervals should be verified on experimental analysis to assess their usability in coherence of actual non-stationary disturbances that occur in DC systems so that they can be enlarged or reduced if needed. It can be noticed that the interval of 10 ms is also the minimum event duration accounted in [10].

To define PQ phenomena related to voltage level, it is first of all necessary to uniquely define the measurement procedure for voltage level. Hereinafter this standardized voltage level will be indicated as the “basic supply level”. Voltage interruptions take place when “basic supply level” falls below a certain threshold (i.e. 5-10 % of nominal amplitude for [12]) for a certain time. With reference to Fig. 1, this threshold can be employed as U1. Moreover, it is necessary to define the duration of S1. This time interval is defined in [12] as 10 ms. Thus, the averaging interval must be shorter than the 20 ms usually adopted in AC. Otherwise, even under U1, abnormal state, shorter than 10 ms, cannot be detected. A voltage dip/swell begins when the “basic supply level” falls/rises below/above a certain threshold (U2/U3) and ends when the voltage rises/falls above/below the dip/swell threshold plus the hysteresis voltage. The purpose of this hysteresis is to avoid counting multiple events when the magnitude of the parameter oscillates about the threshold level. The suggested hysteresis in [10] is 2 % of the nominal voltage. The same value could be adopted also for DC.

The voltage dips/swells are characterized by measuring the duration and the minimum/maximum voltage magnitude during the event. In [10], the adopted thresholds are 90 % and 110 % of the nominal amplitude. These thresholds can be employed to define the levels U2 and U3 of Fig. 1. For what regards time duration, according to the IEC technical document [12], S2 is some tens of ms, S3 some hundreds of ms and S4 some seconds. A voltage variation can be classified as a dip/swell, if it lasts for a time interval that ranges from around S2 up to S4.

V. NUMERICAL TESTS

Different measurement window lengths are considered and tested to determine their ability to detect and quantify voltage surge, voltage dip, and voltage swell disturbances occurring in LVDC grids. At some higher DC voltage levels, surges are among the primary causes of insulation degradation leading to partial discharges, electrical treeing, space charge accumulation in electrical cables, and dielectric breakdown [14] – [16].

As mentioned above, IEC-TR-63282 [12] recommends a 10 ms window length for estimating voltage dip and voltage swell magnitudes in LVDC networks. In such a context, in this section some voltage disturbances are extracted from real and simulated signals for testing and evaluating the impact of three measurement windows sizes, respectively 5 ms, 10 ms, and 20 ms, on voltage swell/dip and surge detection. The window size of 5 ms is selected to correspond to one-quarter of a cycle in 50 Hz AC signals.

The DC voltage signals on Fig. 5.a and Fig. 6.a were simulated at the DC side of an active neutral point clamped converter in a 1.5 kV DC system using MATLAB/Simulink [17]. The voltage disturbances were generated by introducing a sudden growth/drop into the DC loading. The dip, swell and surge thresholds have been calculated as U2 (90 %), U3 (110 %) and U4 (120 %) of the DC rms voltage respectively (see Fig. 1). The rms values estimated based on 5 ms, 10 ms, and 20 ms window lengths are shown in Fig. 5.b, 5.c, and 5.d, for the dip event, and in Fig. 6.b, 6.c, and 6.d for the swell event. The use of the three measurement window lengths leads to different deviations between the residual voltage and the minimum DC voltage recorded during the dip event, i.e., 14.3 V, 77.8 V, and 87.5 V for the 5 ms, 10 ms, and 20 ms windows respectively. Likewise, the differences between the maximum DC voltage recorded during the swell event and the swell voltage are estimated to be 62.6 V, 80.8 V, and 120.9 V based on the three window lengths respectively. The smallest differences are achieved when estimating the results over 5 ms measurement windows, though the 5 ms window length has the potential to indicate incorrect results (e.g., showing an extended swell event) in situations where repetitive voltage surges can occur with very short-time differences between the surge events.

In such a context, the 10 ms window length proposed by the standard seems to be more appropriate for estimating voltage dip and voltage swell events. But, when using the standard window size [12], differences arising from the severity of the phenomenon and where it is accommodated within that window will lead to significant magnitude variabilities for the same voltage phenomenon (same characteristics) occurring at different times. The latter reinforces the differences between the DC and AC PQ disturbances and the need for having more clearly defined PQ measurement and evaluation methods specifically for LVDC applications.

The presented voltage signals on Fig. 7.a and Fig. 8.a were recorded during the measurement campaign on a 1.5 kV DC distribution network feeding a metro system [18], using a sampling frequency of 50 kHz. Despite the nominal voltage level of 1.5 kV, the monitored metro system operates at an average voltage of 1650 V. This is a common practice in metro and railway system to reduce losses due to distribution. For this reason, a swell threshold 110 % of 1650 V has been considered. Fig. 7.b, 7.c and 7.d, and Fig. 8.b, 8.c, and 8.d represent the voltage rms values estimated over 5 ms, 10 ms, and 20 ms window lengths respectively for two particular voltage variations. This analysis shows that the 10 ms window length proposed by [12] does not detect the considered disturbances even though the measured samples cross the swell threshold level. In contrast, the 5 ms window captures the event and thus provides useful information in regards to event classification. It is obvious, that due to their short time durations these events cannot be considered as voltage swells but at the same time cannot be counted as voltage surges either, since the 10 ms measurement window size proposed by the standard is not able to detect them. So, based on this analysis, it may be proposed even at this stage of PQ investigation an analysis, that a future window size of 5 ms could be considered for estimating the DC voltage rms magnitude for voltage surge and voltage transient detection and classification.

Additional measurement campaigns in LVDC grids are planned as part of the European project "Standardisation of measurements for DC electricity grids", and the recorded disturbance will be fed to test other DC PQ metrics and evaluate the effectiveness of the proposed windows sizes by the relevant standard.

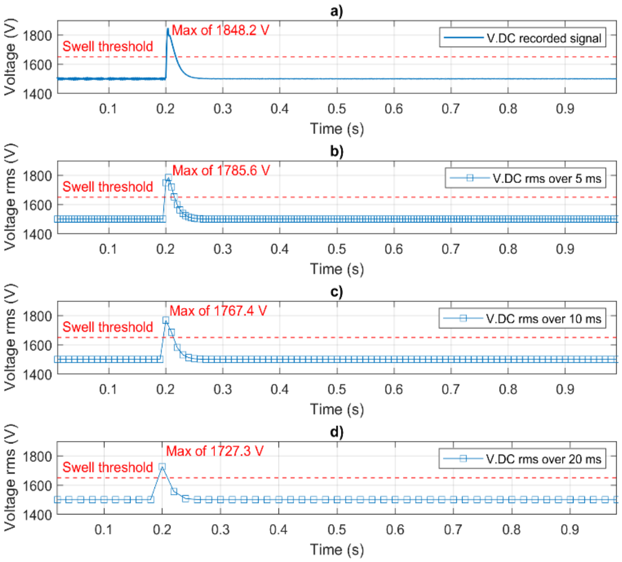

Figure 5. The DC voltage time series (a) and their rms values estimated over 5 ms (b), 10 ms (c), and 20 ms (d) windows for the simulated voltage swell event.

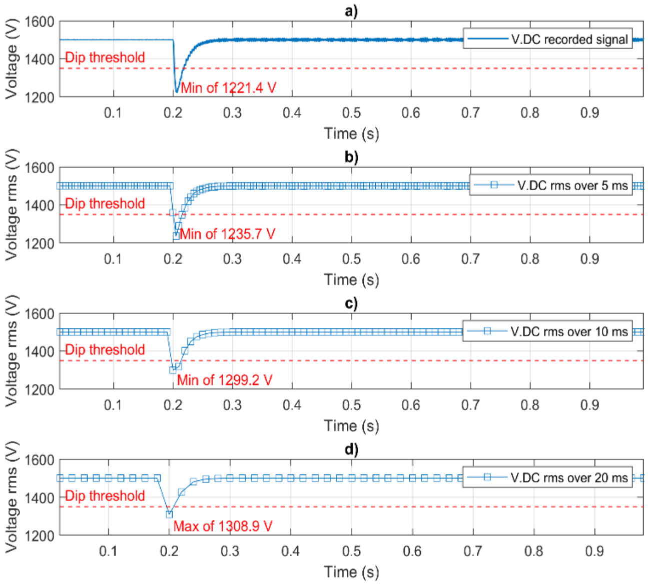

Figure 6. The DC voltage time series (a) and their rms values estimated over 5 ms (b), 10 ms (c), and 20 ms (d) windows for the simulated voltage dip event.

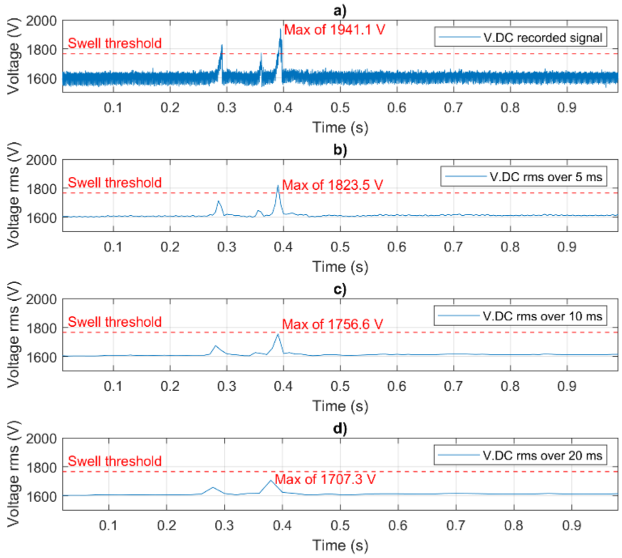

Figure 7. The DC voltage time series (a) and their rms values estimated over 5 ms (b), 10 ms (c), and 20 ms (d) windows for the first disturbance event.

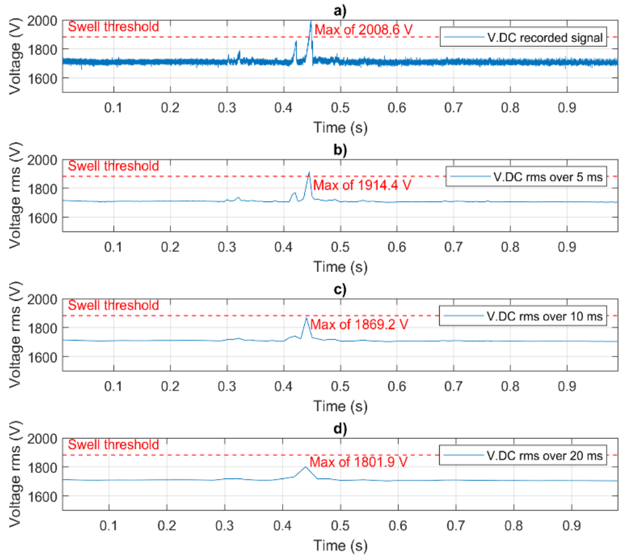

Figure 8. The DC voltage time series (a) and their rms values estimated over 5 ms (b), 10 ms (c), and 20 ms (d) windows for the second disturbance event.

VI. CONCLUSION

The concept of different voltage bands introduced by the IEC-TR-63282 technical report has been discussed and considered useful to relate the PQ events with the operating states of the grid. The applicability of AC PQ measurement procedures and metrics to simulated and real-world DC signals also has been evaluated as part of this paper.

Several measurement window lengths have been considered to estimate their appropriateness in detecting voltage dip, voltage swell, and voltage surge disturbances. For voltage dip and voltage swell disturbances, the analysis has shown that the 10 ms measurement window proposed by the technical report produces consistent results for detecting dip and swell events, but it reveals not suitable to detect transient and surge events. A shorter measurement window size equal to 5 ms has been proposed for estimating voltage surge and voltage transient magnitudes. The analysis has shown that the proposed window size outperforms the capability of the 10 ms measurement window size proposed by the relevant technical report for the detection of short-time voltage events.

The need to redefine measurement methods for DC applications also has been emphasized as being fundamental to allow the correct estimation of electromagnetic disturbances.

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