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A critical review of power quality standards and definitions applied to DC microgrids

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HIGHLIGHTS

- A review of the power quality standards to verify the applicability to DC microgrids.
- An encompassing overview of the power quality issues in DC microgrids.
- A simulation example to exemplify the less conceivable DC power quality issues.

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ABSTRACT

As compared to AC microgrids, DC microgrids reduce the hardware complexity of converter-dominated power distribution in the presence of a high number of renewable energy sources, energy storage systems and energy efficient loads. Another frequently highlighted advantage is their resiliency and tolerance against AC grid disturbances resulting in improved overall power quality. However, with respect to power quality, the question arises whether existing international power quality standards and metrics remain applicable in DC microgrids or require adjustments. Therefore, this paper critically revises the definitions and power quality indicators specified in IEC 61000 and IEEE Std1159. The resulting review is essential to unambiguously define the responsibilities of the microgrid operators, customers and device manufacturers. Apart from that, causes and consequences of power quality issues in DC microgrids are discussed.

1. Introduction

Considering the increasing number of distributed generation, electric vehicles, energy storage and energy efficient loads that inherently generate or consume DC power, DC microgrids () offer a promising alternative to the AC counterpart [1]. The improved compatibility between the DC devices and a DC power backbone reduces and simplifies the power conversion steps, thereby reducing the power conversion losses and increasing the component-level reliability [1]. Efficiency gains in the range of 12–18% have been reported [2]. Apart from the improved compatibility, enable to transfer more power per conductor cross-section [3] and allow to actively control the device currents by means of the switch-mode DC-DC converters that interface the DC devices with the network. Applications considered are electric vehicle charging stations [4] and other charging applications [5].

Increased power quality is often highlighted as a distinguishing feature of DC microgrids [6]. Because the DC voltage is tightly controlled, in part by AC/DC converters connected to an overlay AC grid, the is more tolerant against AC side disturbances [7]. Power quality is thus highly intertwined with voltage stability, as the DC voltage is a metric for the power balance in the system and needs active stabilization [8]. But it is unlikely that high levels of power quality remain assured when multi-vendor will develop, each adhering to their own guidelines and requirements. Standardization is frequently mentioned as a hurdle for the wide-scale deployment of [9]. An important part of standardization encompasses power quality standards and metrics, required for ensuring interoperability and assigning quantifiable responsibilities.

Available literature regarding power quality in primarily focuses on solutions addressing specific power quality issues. A first solution focuses on reducing voltage oscillations by implementing active damping [10]. Alternatively, voltage oscillations are reduced by implementing nonlinear controllers [11]. Another solution applies converter interleaving to reduce the voltage ripple in the network [12]. Nuutinen et al. have investigated common-mode and radio-frequency electromagnetic interference due to pulse-width modulated inverters in a public

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distribution low-voltage DC (LVDC) research site [13]. Although the proposed solutions definitely enhance the power quality of , it remains unclear what is required from the system-level perspective.

From the system-level point-of-view, Magro et al. proposed DC power quality indices for low-frequency sinusoidal disturbances and voltage ripple [14,15]. Whaite et al. have addressed interharmonics and the impact of fault and inrush currents on the voltage in [16]. However, there remains a need to critically review whether existing power quality standards are applicable to or require adjustments.

Therefore, the present work serves as a starting point by revisiting the current international power quality standards IEC 61000 and IEEE Std1159. The paper thereby excludes radiated phenomena, electrostatic discharge and nuclear electromagnetic pulse as classified by IEC 61000 [17]. The aim is to revise the current power quality framework and verify its applicability to , targeting all stakeholders that should address particular issues listed in this paper.

This paper is structured as follows: the next section revisits the concept of power quality as defined by different international standards and verifies the applicability of the definitions to . The third section presents a classification of DC power quality issues, its causes and its consequences. As some power quality issues in DC are less understandable, the fourth section will present simulation results as an example. The last section concludes this paper.

2. Power quality definitions

The first concern when dealing with power quality is the availability of a proper definition that is sufficiently general to encompass both AC and DC power quality. The definition provided by the IEC 61000 is suited in that sense as it makes no distinction between AC and DC power quality when stating that "Power quality encompasses the characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters" [17]. Other references provide different definitions for power quality, but none of them makes a distinction between AC and DC power quality:

- Power quality is the combination of voltage quality and current quality. Thus power quality is concerned with deviations of voltage and/or current from the ideal waveform [18].
- Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment [19].
- Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment [20].

On the other hand, the IEEE recommended practice Std1709 addresses 1–35 kV medium-voltage DC (MVDC) distribution systems and defines power quality as "compliance with specified voltage tolerances and voltage ripple" [21]. That definition clearly narrows down power quality to *voltage quality*, which is a fundamental characteristic of DC power distribution systems as the DC voltage is a distributed measure of the power balance in DC power distribution systems.

3. DC power quality issues

Fig. 1 classifies the power quality issues that are conceivable within DC distribution systems based upon the duration of the phenomenon (time axis) and the frequency content of the voltage waveform (frequency axis). The time axis is subdivided between short-duration, transient phenomena and long-duration, steady-state phenomena. The frequency axis in turn is subdivided in high-frequency components (typically in the range of the switching frequency 1 kHz and above), components in the order of magnitude of the control bandwidth of the voltage controllers present within the and in DC components. The

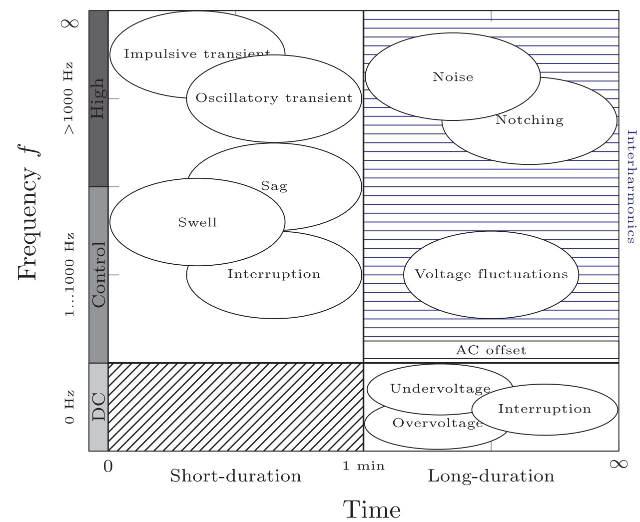

Fig. 1. Time–frequency classification of DC power quality issues.

power quality issues that will be subsequently discussed are also summarized in Table 1, including the indicators to quantify them, possible causes and consequences.

3.1. Transients

According to the IEEE Std1159 [22], *impulsive transients* are sudden, nonpower frequency changes from the nominal condition of voltage, current, or both that are unidirectional in polarity. Accordingly, *oscillatory transients* are sudden, nonpower frequency changes in the steady-state condition of voltage, current, or both, that include both positive and negative polarity values. The impulsive transients are characterized by their rise time, fall time and peak magnitude, while oscillatory transients are characterized by their frequency spectrum and duration. In IEEE Std1159 [22], low-frequency (< 5 kHz), medium frequency (5–500 kHz) and high-frequency (0.5–5 MHz) oscillatory transients are distinguished. Similarly, the EN50160 [24] defines transient overvoltage as a short duration oscillatory or non-oscillatory overvoltage usually highly damped and with a duration of a few milliseconds or less. According to IEC61000 (Annex A.3) [17] a transient designates "a phenomenon or a quantity which varies between two consecutive steady states during a time interval short when compared with the time-scale of interest". The proposed definitions are equally applicable to .

Impulsive and oscillatory transients in are possibly caused by lightning strikes or sudden switching operations causing induced voltages. They typically occur beyond the frequency range of the controller bandwidth. This may cause insulation breakdown or trigger system resonances.

3.2. Short- and long-duration variations

Voltage variations in may be categorized based upon their duration, magnitude and direction of change, similar to the IEEE Std1159 [22]. Short-term and long-term variations are distinguished, primarily based upon the underlying causes. *Short-term variations* are caused by switching operations, faults and large power fluctuations on the system, while *long-term variations* occur in steady-state due to power flow variations. An arbitrary boundary of one minute is used in practice for AC to distinguish both and a further categorization in terms of instantaneous, momentary and temporary variations is made [22].

Based on the direction of change and their magnitude, three rms voltage variations may occur: sags, swells and interruptions. According to IEEE Std1159 [22], a *sag* is defined as "a decrease in rms voltage between 0.1 and 0.9 p.u. for durations from 0.5 cycles up to 1 min". A