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Analytical derivation of PQ indicators compatible with control strategies for DC microgrids

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***Abstract*—Power quality related to DC microgrids is still on virgin grounds of research. However, it may play an important role both in the design stage and on the DC microgrid control scheme to be adopted. Currently there is no comprehensive, quantitative and qualitative analysis on which of the power quality features are the most stringent constraints to be taken into account. This work is an attempt of defining and quantifying a set of power quality indices for DC microgrids. We relate our analysis on the design aspects of DC/DC power converters that are the most critical elements interfacing sources and loads in a stand-alone low voltage DC microgrid.**

***Index Terms*— DC/DC power converters, DC microgrids, power quality, signal processing.**

I. INTRODUCTION

There is a tremendous increase in the distributed energy resources used for electricity generation in the low voltage layer of power distribution system, especially those enabling low CO2 emissions. This trend was favored by renewable and energy efficiency policies and – recently - by the need to increase resilience in emerging smart grids. DC low voltage (LV) microgrids are part of this recent trend where a blend of energy resources (mostly of renewable type), storage and power electronic interfaced efficient loads are connected together. They are all available for operation with direct current and they interface one another through one or more DC buses with various voltage levels. The whole DC microgrid is then connected to standard AC networks through DC/AC voltage source inverters with stabilized DC-link. A generic schematic of such a microgrid is presented in Figure 1. Note that most of the DC/DC converters supplying the load were designed only by considering the technical specifications of the associated load ignoring effects of interactions with other equipment connected at the same DC bus. The implications of this aspect on some power quality issues will be discussed in the next section of this paper.

A DC microgrid is a relatively new form of distribution power network, for which there is a substantial lack of standards and guidelines concerning Power Quality (PQ) and acceptable levels of conducted disturbances [1], [2]. One of the first attempts in defining significant phenomena for conducted disturbances for DC distribution power systems is presented in [1]. The study follows a close analogy with the definitions given on a set of Standards [3, 4] for electromagnetic compatibility (EMC). Parameters such as *voltage fluctuations* and *flicker*, *voltage dips* and *short interruptions*, *harmonics and interharmonics*, *ripple* and *voltage notches* are defined similar to their correspondents for AC networks. Among all these, only two of them were selected of interest for the derivation of PQ indices: the harmonic and interharmonic index [1] and the ripple power quality index derived in a later work of one of the same authors [2]. A literature review and discussion paper on the PQ aspects for DC distribution systems and microgrids is presented in [3]. The authors identify four possible "fundamental power quality concerns" such as: i) *harmonic currents* ii) *inrush currents*; iii) *fault current* and iv) *grounding*. This study however does not actually define and quantify power quality parameters.

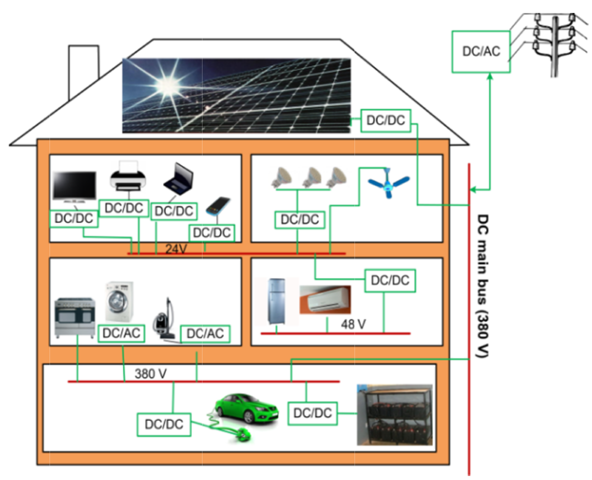

Figure 1: Generic DC microgrid

In [4] an experimental remote controlled monitoring system for a laboratory scale DC microgrid operating at 230 V was developed to extract voltage and current operation characteristics of several DC native loads and to calculate a range of power quality indicators. The study focused basically on the evaluation of PQ indices in time domain and do not consider specific time windows for performing the analysis.

This paper expands the work of [4] and [5] while re-evaluating former definitions and metrics proposed to quantify some of the PQ indicators in time domain. The challenge was to define metrics that avoid unquantifiable formulas for the perfect (desired) DC signal against which we will compare several real signals. Also, this study focuses on a general framework on how to derive and use PQ indicators that could be meaningful for the choice of power electronic interfaces as well as their operational orchestration and control strategy in a specific DC based microgrid.

II. Background and Preliminaries

A. Design and control aspects for DC/DC converters

For the simplicity of analysis and understanding we limit our discussion to the design parameters of DC/DC switching converters only. The DC/AC inverters, which might interface the whole DC LV microgrid with the AC bulk power network or other AC based sources or loads, were left on purpose out of the scope of this study.

Designing DC/DC switching converters according to technical and operational specifications (e.g., rated power, output voltage, range of input voltage, voltage ripple, converter efficiency) implies to calculate and appropriately select the circuit components (e.g., inductor, capacitor, type of diode and switch) for the largest possible range of operational conditions [6]. It is possible that the parasitic components (e.g., inductor resistance, capacitor resistance or diode voltage drop) are ignored in the design phase. Then, principles such as inductor-volt balance, capacitor charge balance and small ripple approximation are used for such calculations. Note however, that all design parameters are calculated under steady-state conditions in order to be able to apply the analysis simplifications, and they are further used during the controller design phase, either in the current or in the voltage controller according to the intended operation. Besides voltage ripples, we may notice that either high frequency or low frequency components in the input signal might be filtered out according to the chosen LC filters of the DC/DC converter.

B. Decision aspects on data aggregation

The following analysis on the derivation of useful and meaningful PQ indicators for the design and control of DC microgrids aims at defining a set of indicators relevant for time and frequency domains taking into account two levels of data aggregation. The rationale of this choice is: (i) to allow monitoring the rapid change of voltage and current signals on the DC bus of interest (where some of the DC sources and DC loads are connected); and (ii) to capture and identify non-stationary events that may impact the quality of the DC waveforms under monitoring. Therefore, we have chosen the one second window for the first level of data aggregation, denoted from now on as T_{a0}, and ten seconds for the next level of data aggregation, also called analysis time window, and denoted from now on as T_w. The duration of T_{a0} was chosen in order to preserve compatibility with the approach indicated in the most recent IEC 61000-4-30 Standard [7], where it is proposed a methodology for data aggregation, with the difference that instead of three seconds (for voltage) or 200 ms (for all quantities), the analysis window is proposed to be one second. The one second window is proposed in [7] to capture rapid voltage changes (RVC) and it is found as the best window to discriminate steady-state from dynamic state in LV AC grids. Further, the rationale of choosing T_w=10s for data analysis proposed in this paper is to remain compatible with the current practice for PQ evaluation in AC power networks and still comply with the practical situations of low inertia and high dynamics that characterize DC low voltage microgrids, which is the target of this study.

C. Minimal Requirements for Data Analysis

The methodology proposed is based on statistical analysis methods. Considering that the sampling frequency should be at least twice the bandwidth of interest, it is recommended when conducting measurements tests to use at least a 1 kHz sampling rate which would give reasonably accurate results.

III. Methodology to Derive PQ indicators

The proposed methodology for evaluation of PQ in DC microgrids can be described as a sequence of two steps:

Step 1: On each block of data samples defined above as the first level of data aggregation (T_{a0}=1 s) we perform a set of algorithms mathematically described below, providing as output a set of metrics (average quantities).

Step 2: Using the averaged quantities calculated at Step 1, another algorithmic round is performed on the analysis windows T_w of ten seconds (10s Moving Average with steps of 1s, T_{a0}) on a section of continuously monitored signal of one minute**.** In other words, if considering a sampling rate of 1kHz, we perform 10s Moving Average of the 1kHz sampled values of the signal (10000 samples), with a step of 1 s (1000 samples), for a total duration of 1 minute. The rationale of this approach is to be able to capture the dynamics of the signal over a larger monitoring window, but with the minimal loss of information that appears due to averaging operations. Ten minutes observation intervals recommended for PQ assessment in AC systems were considered too large for the scope of this study. Note that in our experiment and simulation we have used 10kHz sampling rate of the signal (1kHz being the recommendation of minimum sampling rate required for meaningful results).

For the definition of PQ indicators for DC LV microgrids it is intuitive to resort to indices expressed as ratios of two quantities, where the upper quantity represents the disturbance from the desired/ideal signal, and the lower quantity represents an average of the DC component of the signal under monitoring. Indicators of this kind recall the noise-to-signal ratios and can be found in different forms.

A. PQ indicators in time domain

Considering a waveform $x(t)$ provided in the form of discrete samples $[x_i]$ for i=1..N, available for a data window T_{a0}, then a set of statisical parameters are defined and calculated as follows:

1. the average DC component of $x(t)$ can be written as:

$$X_{DC} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

with N being the total number of samples in each T_{a0}. For 1 kHz sampling rate we have N=1000. The computation process associated with T_{a0}. is presented here because it is a classical statistical metrics (average) that may be part of the calculations of other parameters to be defined later. Note that the main scope for this calculation is to mirror classical waveform information concentrators such as RMS value.

2. the median of the samples is defined as:

$$X_{DC,m} = x_{50\%} \tag{2}$$

Even though both mean and median are two forms of averaging, for some of the PQ indices to follow it was preferred the use of median in order to overcome one of the major disadvantages of mean that is affected by any single value being too high or too low compared to the rest of the samples. This might be the case in DC LV microgrids where several DC/DC power electronics are interfacing loads, sources and storage components and they may have slower of faster transients of the corresponding controllers.

3. the y^{th} percentile variation is written as:

$$x_{y\%} = \frac{x_{y\%}^{+} - x_{y\%}^{-}}{X_{DC,m}} \tag{3}$$

where, $x_{y\%}^{+}$ is the y^{th} percentile of the samples (of which values are exceeding the median of the sample vector), and $x_{y\%}^{-}$ being the (1-y^{th}) percentile of the samples. This parameter intends to quantify the amount of deviation (% from the total number of samples) from the mid-point in one side or the other (up or down of the mid-point or the ideal targeted DC signal). For example it could capture the percentage of spikes (e.g. from controllers transients or from propagated faults) that are present in the signal compared to the close to mid-point values.

4. the peak-to-peak variation is defined as:,

$$x_{pp} = \frac{X_{max} - X_{min}}{X_{DC,m}} \tag{4}$$

where, $X_{max} = \max_i\{x_i\}$, and $X_{min} = \min_i\{x_i\}$, $i = 1 \dots N$

The peak-to-peak variation might be in some sense similar to the ripple from AC PQ analysis and here it the special case of (3) of 100% percentile.

5. the RMS variation from the mean is defined as:

$$x_E = \frac{X_E}{X_{DC}} \tag{5}$$

where, $$X_E = \sqrt{\frac{1}{N}\sum_{1}^{N}(x_i - X_{DC})^2} \tag{6}$$

For this parameter the mean was used instead of median, in order to keep the classical definition of the RMS value.

6. the y^{th} percentile displacement factor is defined in such a way so as to have a measurable output also in the case of a perfect DC signal. Thus, we define it as,

$$\xi_{y\%} = (x_{y\%}^{+}/x_{y\%}^{-}) \tag{7}$$

where, $x_{y\%}^{+}$ and $x_{y\%}^{-}$ are defined above.

Note that $\xi_{100\%}$ is the particular case of the peak-to-peak displacement factor.

$$\xi_{100\%} = X_{max}/X_{min} \tag{8}$$

7. the RMS variation displacement factor is derived from a quantity that catches the asymmetry in the signal shape, as it is given in (9). In order to avoid large scales that may appear in large variations, a logarithmic scale is then applied, as presented in (10).

$$\xi = \frac{\sqrt{\frac{1}{N}\sum_{x_i > X_{DC}}(x_i/X_{DC})^2}}{\sqrt{\frac{1}{M}\sum_{x_j < X_{DC}}(x_j/X_{DC})^2}} \tag{9}$$

$$\xi_{RMS} = \left|10lg\left(\frac{\sum_{x_i > X_{DC}}(x_i/X_{DC})^2}{\sum_{x_i < X_{DC}}(x_i/X_{DC})^2}\right)\right| \tag{10}$$

8. the combined RMS displacement factor is then defined as a product of RMS variation and the RMS displacement factor in order to penalize asymmetric large variations around the average.

$$\xi_{RMS}^{*} = \xi_{RMS} * x_E \tag{11}$$

B. PQ indicators in frequency domain

In [1] a low frequency distortion (LFD) index was derived similar to the total harmonic distortion (THD) index for an AC system, assuming the steady state DC value is known and constant over the analysis time window, T_w. These assumptions however might not be true, as it can be seen later. Thus, we propose to quantify the amount of LFD as an energy distortion factor that is the ratio between the total energy of dominant frequency components and the total energy of the signal corresponding to the analysis window T_w. The rational for this choice is that in DC LV microgrids due to low inertia and sudden changes that can take place at both source and load sides we may experience voltage and current signals that are both asymmetric and non-periodic. The following steps were followed:

1. Calculate the DFT of the signal on each T_{a0}, and on each $\boldsymbol{T_w}$. Indeed a DFT is always associated with spectral leakage. In power systems, AC PQ standards promote the Hamming window. We expect that home appliances of regular office equipment's suitable to be directly connected at a DC microgrid (now and in the near future) would be susceptible to the main frequency components similar an AC system. That is why it is always a tradeoff in choosing a simple or a more complicated window type. However, the proposed algorithm tries to put this tradeoff on a secondary position of concern as long as a moving average is implied.

2. Select the frequencies of which magnitudes are exceeding a threshold of 30% from the largest amplitude found in the FFT and construct their associated bandwidths. We have chosen +/-5 Hz in our analysis example. Note however that other values might be used according to the power spectrum of each signal and the chosen sampling frequency. Then, calculate the respective energy of each dominant frequency bandwidth. It is expected that the energy of the DC component to be much greater than all other frequency components, therefore we have performed the analysis separately for the acquired signal before and after subtracting the median (similar to the DC component). Good PQ level for a system with energy transfer in DC would mean an energy of the DC component higher that 98% of the total energy of the signal.

3. Calculate the overall distortion factor as the ratio between the sum of the energy in the dominant frequency bandwidths and the total energy of the system.

IV. Experimental Evaluation of PQ indices

For validation of the meaningfulness of the proposed PQ indices the following simplistic experiment was set up. The electric circuit of the experiment is presented in Figure 2: a controllable DC energy source was connected to the DC supply bus through a realistically designed boost DC/DC converter. The DC bus supplies energy to a variable resistive DC load directly connected to the DC bus. The experimental setup used the following equipment (Figure 3): (i) DC power supply: EA-PS 9750-20; (ii) SEMIKRON Semiteach configured to emulate a boost converter; (iii) a variable resistive load; (iv) a dSPACE (DS 1104) controller board where the boost converter scheme has been developed using the MATLAB/Simulink RealTime Interface; (v) current sensor (LEM LTSR 6-NP), with upper limit of errors with uniform distribution of 0.005A and (vi) voltage sensor (LEM LV25-400) with limit of errors with uniform distribution of $0.001V_{in}$, where V_{in} is the input voltage for the DC/DC boost converter (in the range of 20-25V) The following four signals were monitored simultaneously: input and output current and voltage of the power DC/DC converter for two duty cycle set-ups (0.32 and 0.57, respectively) and two values of the resistive load (228 Ω and 144 Ω, respectively).

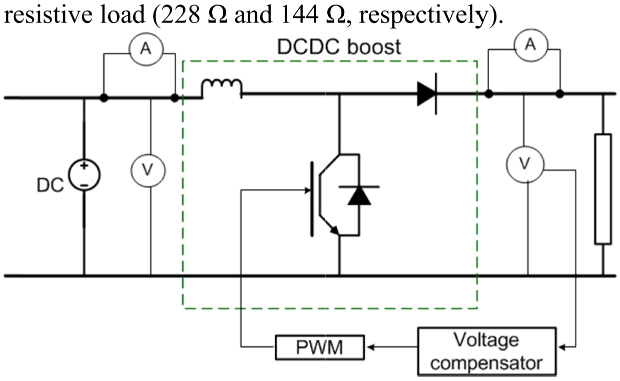

Figure 2: Electric circuit of the simple DC microgrid: experimental setup

A MATLAB/Simulink simulation model was developed in discrete-time according to the experimental setup (Figure 2 and 3), using a fix solver step of T_{solver}=0.002ms. The controller of the DC/DC converter has also been designed in discrete-time with sampling rate of 10 kHz. The model considers the presence of harmonics of order 5 and 7 coming from interconnection with the grid, as they appear in real interconnected DC microgrids [8]. The measurement quality of the sensors was also emulated by using the same uniform distribution of measurement errors and bounds as of the real sensors used in the experiment.

The evaluation of PQ indices defined in Section III over two out of the four collected experimental and simulated signals

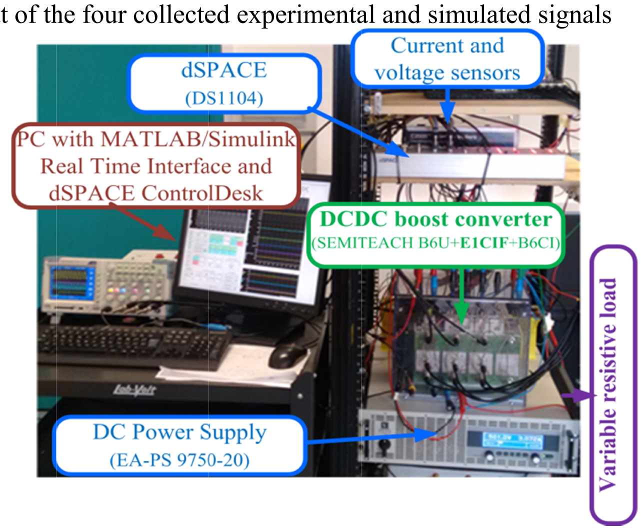

Figure 3: Laboratory data acquisition and experimental setup

are presented in Figures 4 to 9. Figures 4 to 6 summarize the proposed frequency spectrogram analysis of the three signals studied: voltage at the DC bus supplying the load (output of DC/DC boost converter) from the experimental signal acquisition; the same voltage signal from the emulated DC microgrid; and the input voltage coming from the DC source, respectively.

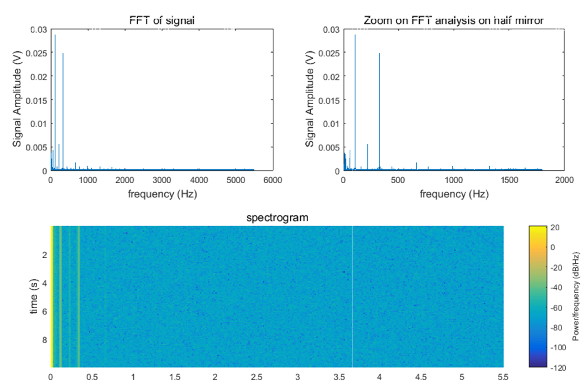

Figure 4: PQ indicators for the supply voltage - frequency domain; experimental setup: V_{out} referenced for 48V

Comparing Figures 4 and 5 (spectrograms) one may notice that most of dominant frequency components up to 0.5 kHz are captured in both emulated and experimental signals. However, a smaller number of frequency components in the emulated signal are present because it is hard to trace harmonic components propagated from the grid through rectifiers.

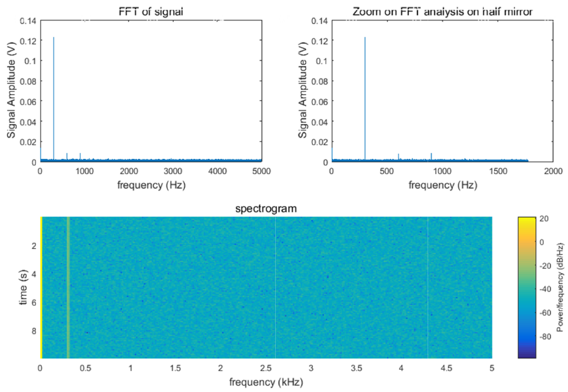

Figure 5: PQ indicators for the supply voltage - frequency domain, numerical simulation: V_{out} referenced for 48V

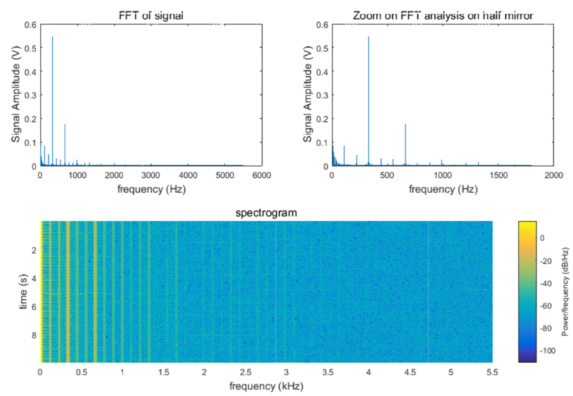

Figure 6: PQ indicators in frequency domain for the input voltage signal, experimental setup: V_{in} is set at 21V

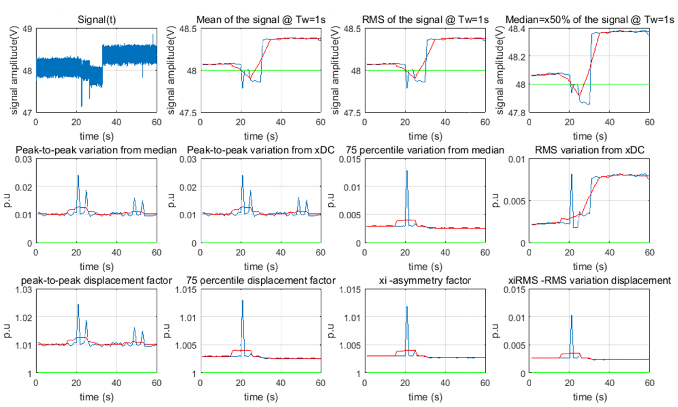

Figure 7: PQ indices in time domain, experimental setup: $\boldsymbol{V_{out}}$ referenced for 48V, duty cycle of 0.57, 50% of the rated load. Legend: blue- one second calculated indices; red- 10 second moving average indices; green- index value for the ideal, reference DC signal

Comparing Figures 4 and 6 (spectrograms) of input voltage signal versus output voltage signal of the DC/DC boost converter one may notice that the high frequency components from the input were filtered out by the DC/DC converter showing a more "clean" voltage signal at the load bus, as expected.

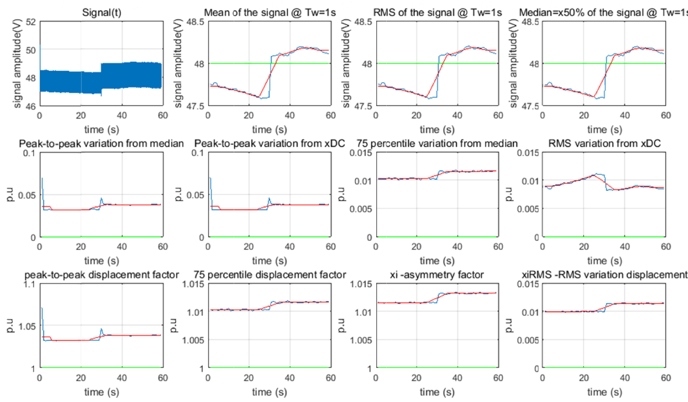

Figure 8: PQ indices in time domain, experimental setup: $\boldsymbol{V_{out}}$ referenced for 48V, duty cycle of 0.57, 50% of the rated load. Legend: blue - one second calculated indices; red- 10 second moving average indices; green- index value for the ideal, reference DC signal

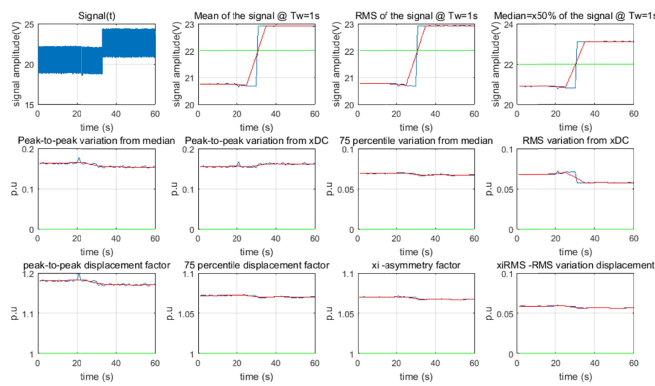

Figure 9: PQ indices in time domain: input reference voltage 21 V. Legend: blue- one second calculated indices; red- 10 second moving average indices; green- index value for the ideal, reference DC signal

Comparing the time-domain PQ indices for the simulated and experimental signals (Figures 7 and 8) one may see that they have a similar scale of variation and similar shapes, however with lower number of peaks in the simulation. Dissimilarity in the number of peaks is expected as long as not all frequency components of the signal were simulated. Figure 9 evaluates the time-domain PQ indices for the input voltage signal coming from the DC source in the experiment.

If for the frequency domain evaluation we have noticed more low frequency components in the input signal compared to the output of the DC/DC converter, the time domain analysis shows a smoother, close to ideal DC signal for the input. For a clear picture of PQ aspects there is a need to consider both time and frequency domain evaluations.

V. Conclusions

This work proposed a set of time and frequency domain indices to quantify possible PQ issues in DC microgrids. Design aspects of power electronic interfaces that are core components in DC LV microgrids were also discussed in relation with the proposed PQ indices. Experimental and simulation evaluation of acquired voltage signals of a simplistic DC microgrid were used to emphasize their meaning and usefulness when assessing PQ issues in DC microgrids. This work open the path for the next step of evaluation of sensitivity of loads, storage components and power electronics controller design with respect to the proposed PQ indices.

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