Power quality based key performance indicators compatible with control schemes in DC microgrids

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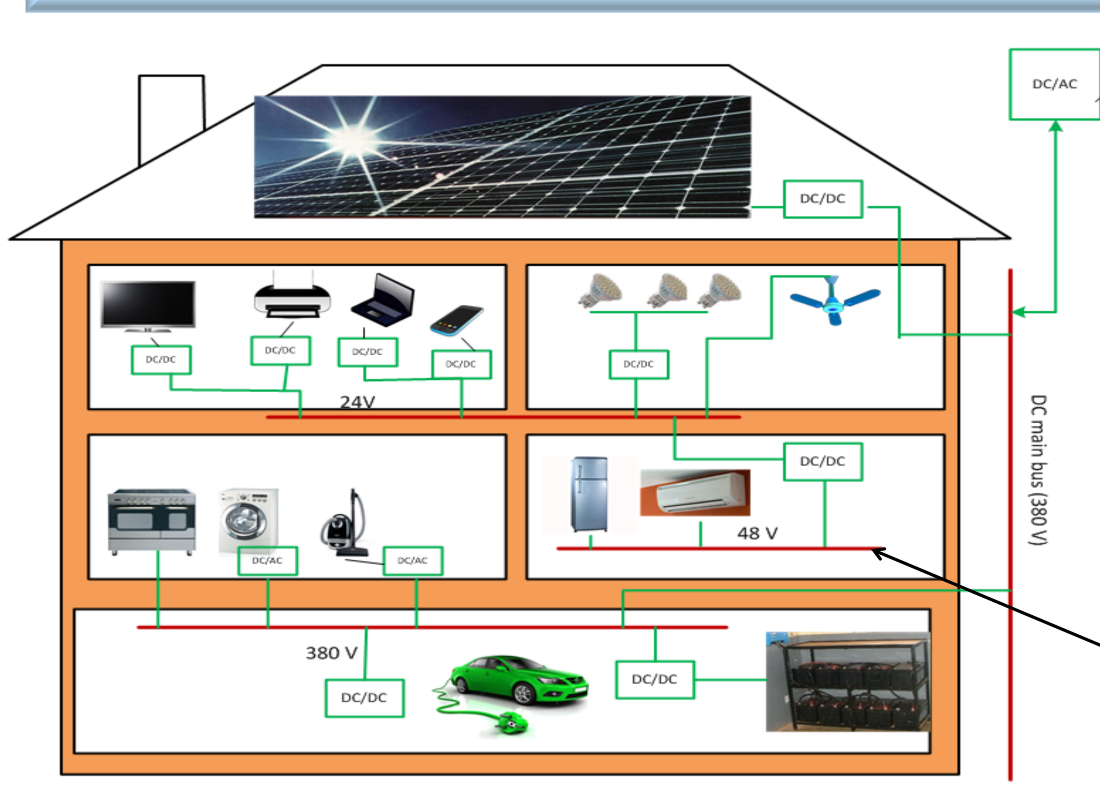
Motivation:

Microgrids present tremendous advantages when it comes to resilience of the distribution sector in power systems. The DC supply of such small power networks is also appealing due to more and more site based energy harvesting (e.g. RES generation) and electricity storage that is present at building level, as well as more and more domestic and office appliances are DC native loads or DC compatible. There are increasing number of studies with respect to possible architectures and control schemes of such systems, however there is very little work when it comes to power quality (PQ) aspects. The objective of this work is to make useful qualitative and quantitative appreciations into the possible distortions that might appear on the DC bus supplying the loads in a DC microgrid.



General architecture of a building-level multi –voltage DC microgrid

Focus of the analysis on voltage and current waveforms on a common DC bus within the DC microgrid

Preliminaries of the methodology

Note: *This work is an extension of [1]. All definitions and rational of choosing the following distortion metrics calculated for the time domain on the first level data aggregation was given in [1]. For convenience, here we just repeat the mathematical formulations.*

Decision on the first level for data aggregation (T_{a0}):

We are looking on a set of indicators both for time and frequency domains taking into account the first level of data aggregation (T_{a0}) of 1 second. The rationale of this choice is to be able to monitor the rapid change of voltage and current signals on the DC bus where all our DC sources and DC loads are connected within our test system DC microgrid. Also, the value of 1 second T_w was chosen in order to be compatible with the approach indicated in the IEC 61000-4-30 [2] standard as the methodology to capture rapid voltage changes (RVC) in the case of non-sinusoidal waveforms.

Decision on the analysis time window (T_w):

All phenomena that impact the quality of an ideal DC waveform are non-stationary events. Therefore, there is a need to develop PQ indicators relative to an analysis TW that will allow us to capture the dynamics of such non-stationary phenomena and still be compatible with the current practice for PQ evaluation in AC power networks.

Observation:

The PQ indicators are developed such that they can be evaluated against "perfect PQ“ concept, where a “perfect PQ” value for specific indices is to be defined accordingly.

Minimal analysis requirement:

Sampling frequency has to be at least two times higher than the bandwidth of interest, while the reporting rate for aggregated indices should correspond to existing methodologies (it is recommended that at least 1kHz reporting would give reasonably accurate statistical results).

Methodology to derive PQ indicators

On each T_{a0}=1sec block of data samples from the collected piece of signal (voltage and current) we perform a set of algorithms that give us as output a set of metrics (average quantities). Then, another algorithmic round is performed on the analysis window (T_w=10 sec) using overlap on each consecutive 1 sec, such that to capture the signal variability in these moving averaged quantities on the analysis T_w.

Consider a waveform $x(t)$ provided in the form of discrete samples x_i for $i = 1..N$.

Time domain metrics computed on each T_{a0}=1sec:

As they are defined in [1].

1. Average DC component: $X_{DC} = \frac{1}{N}\sum_{i=1}^{N} x_i$, with N total number of samples in T_{a0}.
2. Median of the samples: $X_{DC,m} = x_{50\%}$
3. y*th* percentile variation: $x_{y\%} = (x_{y\%}^{+} - x_{y\%}^{-})/X_{DC,m}$
4. Peak-to-peak variation (might be in some sense similar to ripple): $x_{pp} = \frac{X_{max}-X_{min}}{X_{DC,m}}$, where $X_{max} = \max_i\{x_i\}$, and $X_{min} = \min_i\{x_i\}$, $i = 1 \dots N$
5. RMS variation: $x_E = \frac{X_E}{X_{DC}}$, where $X_E = \sqrt{\frac{1}{N}\sum_1^N (x_i - X_{DC})^2}$ and, two displacement factors:
6. y*th* percentile displacement factor: $\xi_{y\%} = (x_{y\%}^{+} - X_{DC,m})/(X_{DC,m} - x_{y\%}^{-})$, where $\xi_{100\%}$ is the particular case of the peak-to-peak displacement factor.
7. RMS variation displacement factor: $\xi_{RMS} = \left|10\lg\left(\frac{\sum_{x_i > X_{DC}}(x_i - X_{DC})^2}{\sum_{x_i < X_{DC}}(x_i - X_{DC})^2}\right)\right|$
8. Combined RMS displacement factor: $\xi_{RMS}^{*} = \xi_{RMS} * x_E$

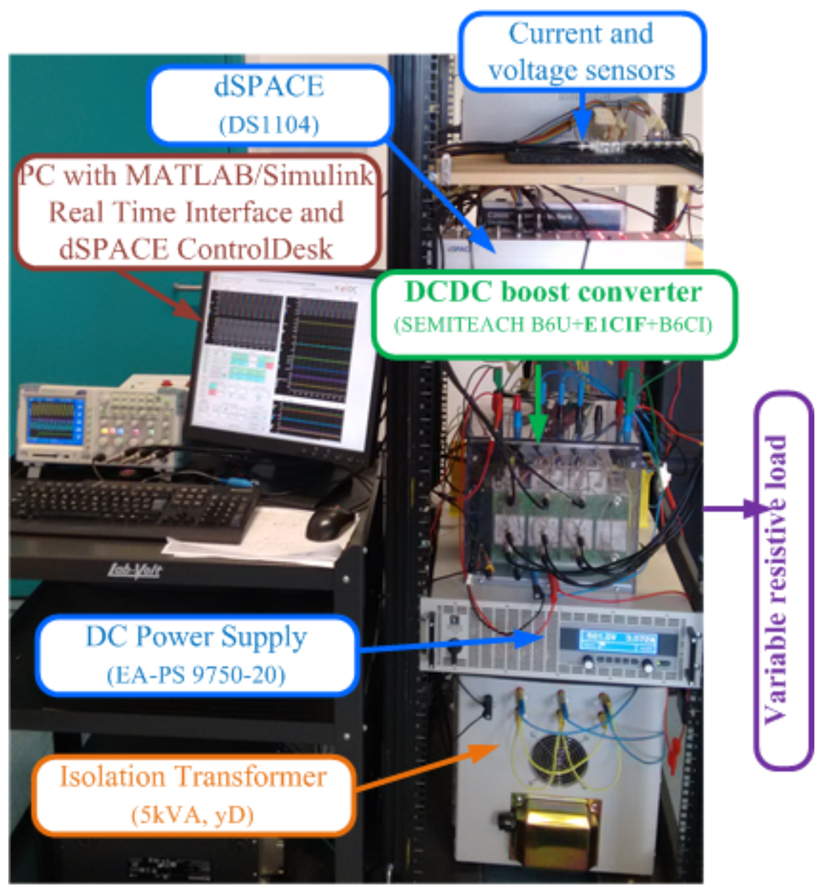
Derivation of frequency domain metrics:

In [3] a low frequency sinusoidal distortion (LFSD) index was derived similar to the total harmonic distortion (THD) index in AC, assuming the steady state DC value as known and constant on the analysis T_w. This however might not be true, as it can be seen from the analysis results below.

Another way to quantify the amount of LFSD in a more comprehensive manner is to evaluate the total energy of dominant frequency components against the total energy of the signal corresponding to the analysis T_w. The following practical steps were applied:

1. Calculate FFT of the signal on each T_{a0}, and on the T_w.
2. Determine the dominant frequency bands from (1) and calculate their energy
3. Calculate Energy distortion factor, $\xi_{En} = \frac{\sum_{i=1}^{fB} En_i}{Total\ En}$, where $En_i = \frac{1}{2\pi}\int_{\omega_{i-1}}^{\omega_i} |X(\omega)|^2 d\omega$ is the energy of the signal in the frequency bandwidth $[\omega_{i-1}, \omega_i]$.

Experimental set-up



The experiment is configured to emulate an energy source connected to the DC supply bus through a boost DC/DC converter and a variable resistive load directly connected to the DC bus.

Equipment used:

(i) a DC power supply (EA-PS 9750-20) for emulating the injected power by a renewable into the DC-link,

(ii) a 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.

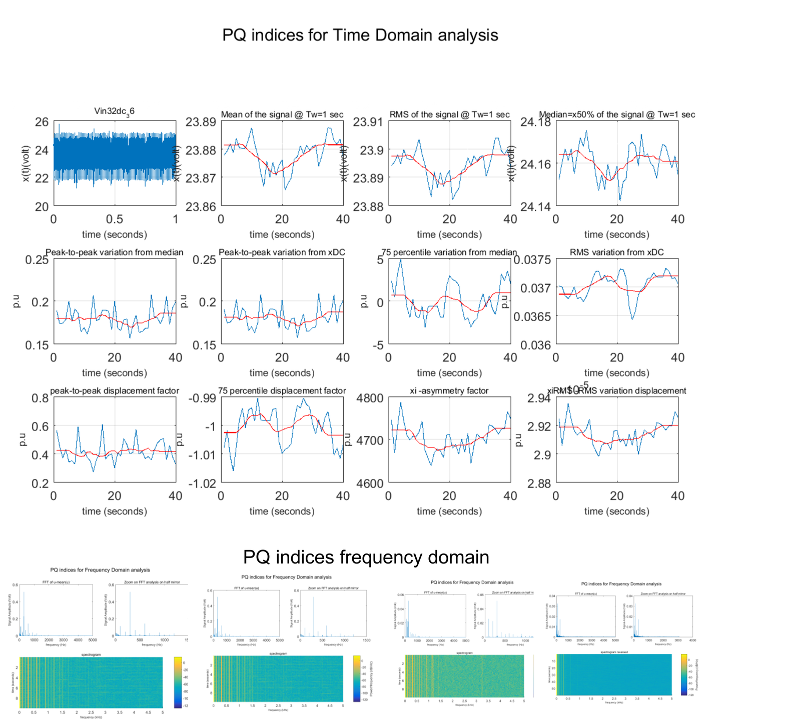
(v) current sensor (LEM LTSR 6-NP), with upper noise bound = $0.008\overline{x_p}$

(vi) voltage sensor (LEM LV25-400) with upper noise bound $=0.01\sqrt{2v_{sensorRated}}$.

Input current and voltage and the output current and voltage were simultaneously acquired for a period of 2 minutes continuously, in order to study the effects of the power electronic interface in distorting the DC bus signal, for two duty cycles set-ups (0.32 and 0.57, respectively) and two values of the resistive load (228 Ω and 144 Ω, respectively).

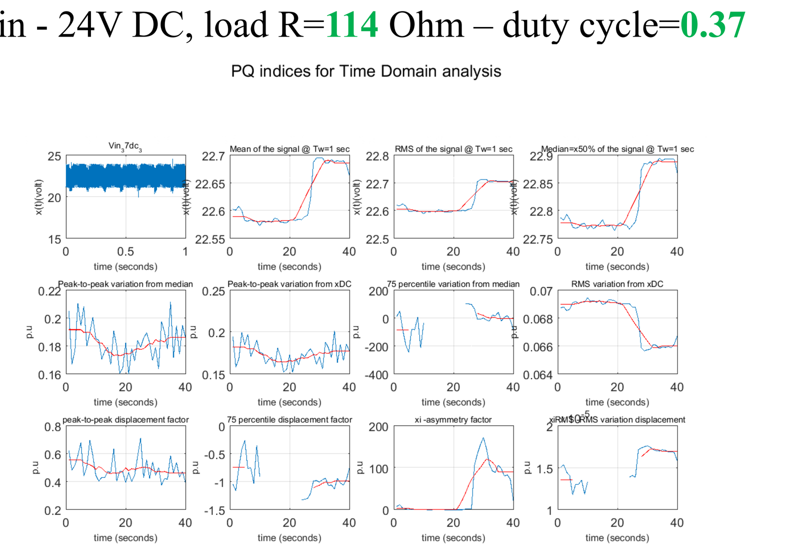
Analysis of results

Vin - 24V DC, load R=228 Ohm – duty cycle=0.32

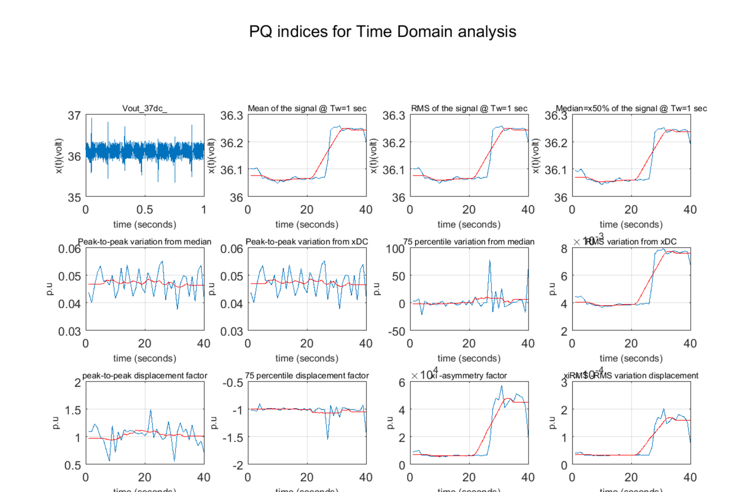


Vout- 36V DC, load R=228 Ohm - duty cycle=0.32

Vin - 24V DC, load R=114 Ohm – duty cycle=0.37



Vout- 36V DC, load R=114 Ohm - duty cycle=0.37



Conclusions and Future work:

Derivation of power quality indicators that may impact the design of the control schemes on a DC LV microgrid were studied using concepts borrowed from the signal processing domain. An experimental set up for a simplistic DC microgrid with only one source connected to a DC link through a boost DC/DC converter, serving a variable resistive load was used to exemplify the analysis. Few indicators may need further tuning for special cases when the denominator is close to zero. This work open the path for further research towards control schemes that are able to compensate more that the classical peak-to-peak variation.

References:

[1] M. Albu, E. Kyriakides, G. Chicco, M. Popa, and A. Nechifor, “Online Monitoring of the Power Transfer in a DC Test Grid,” *IEEE Transactions on Instrumentation and Measurement,* vol. 59, no. 5, pp. 1104-1118, May 2010.

[2] IEC Standard 61000-4-30:2015 “Electromagnetic compatibility (EMC) - Part **4-30**: Testing and measurement techniques - Power quality measurement methods”.

[3] M. Caserza Magro, A. Mariscotti, and P. Pinceti, “Definition of power quality indices for DC low voltage distribution networks,” in Proc. IMTC Conf., Sorrento, Italy, Apr. 24–27, 2006, pp. 1885–1888

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