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Overview of the Requisites to Define Steady and Transient Power Quality Indexes for DC Grids

Andrea Mariscotti

DITEN, University of Genova, Via Opera Pia 11A, Genova, Italy, andrea.mariscotti@unige.it

Abstract **– The work gives an overview of Power Quality phenomena of DC grids, relevant with respect to normative requirements and impact on equipment. The objective is defining the minimum requisites to define suitable PQ indexes that are able to quantify the severity of the impact (interference to equipment, network instability, stress and aging of components), fulfil existing normative exigencies and propose improvements to existing standards.**

I. INTRODUCTION

DC grids and distribution networks encompass Medium and Low Voltage applications of various extensions: MV is required where large power concentrations are found, such as large PV and wind parks [1], as well as distribution onboard ships [2][3]; another example of MV DC distribution is represented by DC railways and rapid transit systems featuring significant variations of the network impedance [4]. LV networks are more diffused and may be found onboard ships (when e.g. large loads of propulsion are separate), aircrafts and trains, as well as serving technological and residential centers and integrating various types of sources and loads [5]. The physical extension is in general limited from a hundred m to a few km, and in some cases up to several km [6]. A DC network, thanks to the direct connection of various types of energy sources and energy storage devices, guarantees high levels of resiliency and availability [6], allowing black start in extreme cases.

Tight integration of several types of equipment for generation, transformation, storage and utilization of the electric energy typical of smart and micro-grids necessitates a definition of parameters that characterize not only the quality of service, but also the effect of the interaction of the connected devices. Equipment is more and more interfaced by means of controlled static converters, featuring not only a variety of distortion patterns of the input and output electrical quantities, but also variable impedance, that at some extent may be controlled to prevent network instability [7][8].

As in all distribution networks, the primary quantity is the voltage available at equipment terminals, but current as well should be evaluated for the following reasons:

- high-performance control uses information on current not only to implement feed-forward methods, but also to indirectly control the terminal impedance [8][9];
- impedance by means of joint voltage and current reading [10] is also relevant for system protection [11];
- current supports transient identification [12];
- inrush current at connection of a device, faults and step loading can trigger instability and low frequency oscillations (LFO), and should be in principle limited;
- similarly high-frequency resonances may also arise, and the overall behaviour is quite complex depending on the extension of the network and the types of connected sources and loads [13]-[15];
- the ripple current is the reference quantity to estimate stress and aging of cables, of storage devices and filter (capacitors, supercaps, batteries) [16]-[20].

Considering that the network impedance is in general very low, estimating ripple current and its spectrum from voltage may lead to significant errors.

II. POWER QUALITY EVENTS AND RELEVANCE FOR NETWORK ELEMENTS

The definition of useful and suitable PQ indexes for DC distribution networks in a wide perspective needs to begin with the identification of typical electric phenomena and events (called for brevity PQ events), and how they affect the elements of the network: generation, loads, connecting components. PQ events affect the considered elements in various ways with different consequences and time scales, which by similarity with AC distribution networks may be listed as follows:

- interference to load operation, as an electromagnetic compatibility problem in terms of conducted disturbance interfering with e.g. the measurement and control of electrical quantities, although the levels of immunity are in general high;
- interference to loads as an operational problem, with poor voltage quality (fluctuations, swells, sags) causing transients in load operation, such as torque variation; this is a sensitive issue for which DC grids perform better thanks to scalable and distributed storage;
- issues of network instability and low frequency oscillation (LFO), in particular when stressed by major transients, that trigger undamped response of converter and machine control in particular situations;
- network resonances occurring at higher frequency, above usual control bandwidth, depending on physical extension, parasitics and load reactance;

- impact on components in terms of overheating and accelerated ageing, as for filter capacitors, cables, storage devices, and transformer insulation; ripple current and in general the rms value and the number of charging/discharging cycles are the main parameters, besides internal and ambient temperature.

III. RELEVANT PQ INDEXES AND PHENOMENA

Electrical phenomena as reviewed in the previous section may be synthesized and quantitatively described considering the applicable normative references [21][22].

A. Voltage swells, sags (dips) and interruptions

Overvoltages and undervoltages may be named swells and sags (or dips) with analogy to AC networks. Few standards specify requirements for PQ, performance and reliability of DC distribution: the MIL-STD-704F [23] for avionics and IACS Reg. E5 [24] for onboard ships.

For AC equipment immunity to voltage variations is tested with EN 61000-4-11 with EN 61000-4-14 specifying the characteristics of test setup and generator. A corresponding set of specifications for the test generator for DC immunity appears in EN 61000-4-29 [25], where ±20% variations and 30/60% dips are applied, as well as complete interruptions (100% dip), and the span of durations covers 10 ms to 1 s for variations and 1 ms to 1 s for interruptions. However, this standard is not sided by any immunity standard for equipment. For railway onboard applications the EN 50155 [26] defines tests for equipment connected to the dc battery voltage and is extensively applied.

In general, distinction is needed from other long-term transients (long interruptions and fluctuations), as well as from very short-term phenomena usually classified as spikes or surges (of modest entity here for the large deployed capacitance and low transient impedance).

Definitions of IEEE Std. 1159 and EN 61000-4-30 for AC systems indicate a voltage dip or swell when the rms crosses a threshold, its duration quantified measuring the time interval between two consecutive crossings [27]. This definition based on rms is possible because swells and dips are defined for durations > 1 cycle. The analogy with DC systems is not perfect and various time horizons for the estimate of the steady value may be used.

Line transients may thus be readily evaluated by their amplitude A (peak or average value) and equivalent time duration T_X (e.g. half-amplitude duration T_{50}). The combination of the two brings two intensity measures: area and energy, calculated over $[t_1, t_2]$ taking the ac portion $x(t)$ of the network quantity (voltage or current), having subtracted the steady value X.

$$S = \int_{t_1}^{t_2} x(t)\,\mathrm{d}t \qquad E = \int_{t_1}^{t_2} |x(t)|^2\,\mathrm{d}t \tag{1}$$

The mean square time duration may be defined, that measures the interval where the energy is concentrated:

$$\tau^2 = \int_{-\infty}^{+\infty} t^2 |x(t)|^2\,\mathrm{d}t \Big/ \int_{-\infty}^{+\infty} |x(t)|^2\,\mathrm{d}t \tag{2}$$

Area (or impulse strength) and energy are two measures of the impact on loads: the missing area or energy of a negative transient (a temporary reduction of the line voltage) will cause a reduction of the load quantities, partially compensated by filters, storage devices and DC springs, besides converters and generators control.

It is noted that protections are sized for the transient energy of the fault they have to extinguish (often named "I^2t" with the fault current as the primary quantity).

Any compensating action has its own limited dynamics due to a combination of control bandwidth and electrical characteristics of the circuit: rise time, equivalent time duration and peak amplitude define thus its dynamics, to compare with the capability of the system and its control.

Table 1 shows limits and reference values for voltage swells, sags and interruptions. Figure 1 gives insight in the time-amplitude limits of MIL-STD-704F.

Faster transients that have a repetitive nature are electric arcs: series arcs anticipate the failure of a connection and in railways are the common by-product of the current collection mechanism [12][28][29].

Table 1. Limits and reference values for transients (voltage swells, sags and interruptions) (E=emission, I=immunity, G=generator, A=ambient spec)

Standard	Vdc	Quantity	Limit/Ref.
MIL-STD-704F (see Figure 1)	28 V 270V	—	—
EN 61000-4-29 (I - dips)		V_{dip} T_{dip}	40,70% 0.01-1 s
EN 61000-4-29 (I – interruption)		V_{int} T_{int}	0% 0.001-1 s
EN 61000-4-29 (I – variation)		V_{var} T_{var}	85-120% 0.1-10 s
EN 50155 (I – variation)		V_{var} T_{var}	60-140% 0.1-1 s
EN 50155 (I – interruption)		V_{int} T_{int}	0% 0.01-0.03 s

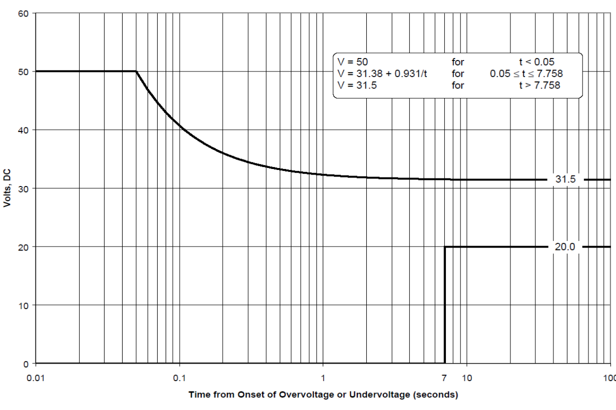

Figure 1. Profile of allowed transient overvoltage / undervoltage for avionics with DC bus 28Vdc [23].

B. Ripple, harmonics and periodic variations

In principle harmonics can be estimated with several different techniques for amplitude and phase at integer multiples of the fundamental, where some amount of stationarity must be assumed. The EN 61000-4-7 [30] is a well-structured and complete standard that covers methods and algorithms quantifying spectral harmonic components, including interharmonics. However, the underlying assumption is always that of a fundamental and its harmonics, including interharmonics, e.g. caused by variable frequency drives.

It is generally agreed that DC networks can be characterized with the ripple, that EN 61000-4-17 [31] describes as composed of "power frequency or its multiple 2, 3 or 6", focusing with a limited view on the mechanism of production by classic AC/DC conversion (based e.g. on diode and thyristors rectifiers). Ripple is thus a repetitive phenomenon superimposed to the DC nominal value (or local mean value, accounting for long-term changes). Modern AC/DC and DC/DC converters and poly-phase machines for renewable energy sources are used extensively to improve PQ and for ease of interfacing in modern micro-grids and smart-grids; this leads necessarily to a reformulation of the concept of ripple to a more general definition accounting for non-harmonically related components, possibly non stationary including location on the frequency axis.

This is particularly evident considering the emerging phenomenon of conducted disturbance located in the 2-150 kHz frequency interval, above classic harmonics, but below the commonly recognized radiofrequency conducted phenomena: the name "supraharmonics" was chosen (with obvious meaning) and they originate from a variety of switching components [32]. For AC networks a basic standard for immunity to supraharmonics appeared years ago (EN 61000-4-19 [33]), not yet applied. No specific standard was devised for DC networks, although extension to DC grids is straightforward.

The concept of ripple is widely applied in DC networks in place of focusing on specific harmonics, especially when the "fundamentals" may be several and not stable. These phenomena are well documented in EN 61000-4-7 and 61000-4-30 [34] for AC networks applications. It is observed that DC networks have a much lower harmonic content thanks to the large deployed capacitance and in general the lower impedance in the harmonic frequency range, as it was demonstrated for railways in [35], comparing harmonic power terms in AC and DC systems. A lower network impedance keeps harmonic voltage components low, while amplifying current distortion, as sources see a quasi-short-circuit condition: excessive current distortion will flow in filter capacitors, capacitor banks, and energy storage devices with consequential overheating, stress and possibly accelerated ageing.

For supraharmonics (2-150 kHz) the network response is more complex and the impedance has larger changes, similar to AC distribution, for which similar methods may be used. Significant distortion is expected from high-performance interface converters, although the wide use of zero-current and -voltage switching techniques: time-domain signals are characterized by bursts of oscillations at the switching fundamental and ringing [36]. A straightforward DFT-based approach may lead to inaccuracy due to the very nature of the signals, which are non-stationary and modulated, resulting in significant spectral leakage and poor instantaneous frequency estimation. The use of analysis methods with a short time support is suggested, with propensity for wavelet-based or Empirical Mode Decomposition [37][38].

Basically speaking ripple may be made correspond to the peak-to-peak or peak excursion of network voltage, but other measures of it (rms, percentiles, ...) were proposed in the past [39]-[43]. Ripple addresses two objectives at once quantifying the spread of instantaneous values and network distortion (ripple was defined both in time and frequency domain [40][41]). The explicit connection between ripple and DFT (including harmonics as such and other components) was given in [40] with the index D_{LFSD} and in [39] with *RDF*.

The ripple can describe the quality of the delivered voltage in terms of fluctuations and excursion, as well as when applied to the flowing current the presence of significant load steps, inrush phenomena (e.g. when switching on an item of equipment with its filter capacitors or a storage device).

Table 2 summarizes normative limits and reference values for ripple and distortion. The following quantities are derived from the used standards:

<u>MIL-STD-704F [23]:</u>

- *DC steady voltage* V_{dc} is the average value over no more than 1 second;
- *distortion D* is the rms value of the ac components;
- *distortion factor* $DF = D/V_{dc}$;
- *ripple R* is the maximum absolute difference between an instantaneous value and the steady value V_{dc};

<u>EN 61000-4-17 [31]:</u>

- *generator output ripple* $V_{rip\text{-}gen}$ is the peak-to-peak value of ac components ratioed to the nominal dc voltage (taken equal to V_{dc} for ease); $V_{rip\text{-}gen}=2R$;

Figure 2 shows the limit of distortion of the 28 Vdc distribution as per MIL-STD-704F [23]: it is evident that limits extend to high frequency, reported up to 500 kHz where the limit value is 1 mVrms (60 dBμV).

The 704F standard does not specify how the distortion spectrum should be assessed (frequency or time domain measurement). It clarifies that all components, harmonic and interharmonic, and also those resulting from amplitude or frequency modulation, are included. The minimum frequency for which the limits are specified is 10 Hz, that represent thus the largest possible frequency resolution for a DFT/FFT approach. It is known, however, that for broadband or transient components using a lower frequency resolution (that is not prohibited) will lower the spectrum profile, so that with a conservative approach the 100 ms time window (leading to the 10 Hz frequency resolution) is advisable.

C. Frequency intervals and band limited ripple index

We can take a further step introducing the concept of frequency band and frequency content, as the ripple quantity itself does not discriminate the dynamics of the collected components (their instantaneous frequency), nor the statistics proposed in [42][43] help in this sense. In [41] distinction was made for the excursion of a ripple index defined on the absolute value only of spectrum components (worst-case spread of values) and including phase information (better representing the relationship between components and the real signal excursion). Then, the use of a band-pass filter [41] introduced the possibility of an efficient estimate of ripple, alternative to a DFT calculation and successive grouping of intervals of frequency bins, and at the same time opened the door to the definition of band-limited indexes and different weighting of frequency intervals.

The accurate distinction of components in terms of amplitude and frequency may be unnecessary, as long as the examined phenomena of interference and impact on devices (that would justify limitation of specific components or groups of them) apply looser information limiting to e.g. low, medium and high frequency. Overheating and aging of filters and storage components can be related to concepts of total rms or "high frequency content" to our best (as outlined in sec. II). The test of susceptibility to ripple [31] is limited to the effects of very old and basic conversion methods, referring to the already mentioned definition of ripple for few characteristic harmonics up to the 6^{th} of an upstream ac fundamental. It is reasonable, in view of the wide range of emissions of modern static converters, to focus on conveniently defined frequency intervals, where steady and transient components may be located [32][34].

Table 2. Limits and reference values for ripple and distortion (E=emis., I=immun., G=gen., A=ambient)

Standard	Vdc	Quantity	Limit/Ref.
MIL-STD-704F (A)	28 V	*DF*	3.5%
	(22-29)	*R*	1.5 V
MIL-STD-704F (A)	270 V	*DF*	1.5%
	(250-280)	*R*	6.0 V
EN 61000-4-17 (G)		$V_{rip\text{-}gen}$	2,5,10,15%
IACS UR E5 (I)		R_{rms}^{a}	10%
EN 50155 (A)	24-110 V	*R*	5%

Notes: [a] accompanied by a not better clarified specification of "voltage cyclic variation" of 5%.

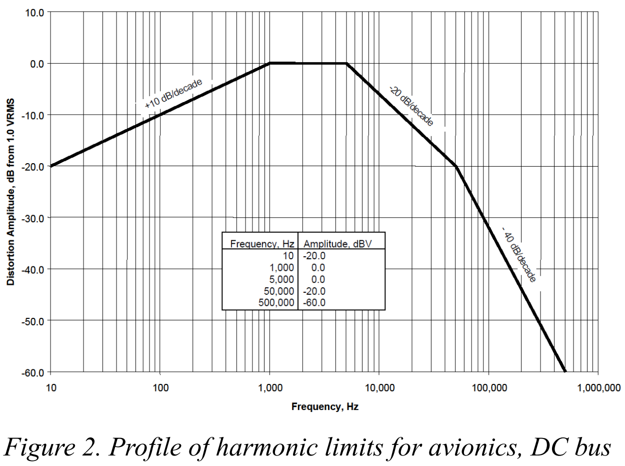

Figure 2. Profile of harmonic limits for avionics, DC bus 28Vdc (for the 270Vdc bus limits are 10 dB higher) [23].

D. Network resonances and oscillations

Special consideration is given to phenomena of network instability and resonance, identifying the relevant characteristics and verifying which class of PQ indexes better suite their monitoring, tracking and possibly prevention. Resonances and instability are narrow-band phenomena contrasted to the already examined transients, ripple and band-limited ripple.

The most intuitive method is that of a real-time DFT followed by detection of abnormal increase of components with criteria of frequency adjacency. This may work well for high-frequency network resonances, with frequency f_r usually located in the kHz range (up to a ten of kHz) [13]-[15]. The factor of merit Q_r of resonances is usually not small, up to about 10-20, taking into account the non-negligible damping caused by skin effect in cables, increased equivalent series resistance of storage devices and capacitors, and the passivity of converter controls in this frequency range. The corresponding bandwidth $\Delta f_r = f_r / Q_r$, implying that a resolution frequency of tens of Hz is sufficient and adequate with a corresponding DFT time window T_w in the order of some tens of ms.

However, low frequency oscillations (LFO), as resulting from instability of converters and machines control, are located at a much lower frequency [13]-[15], and may be more difficult to track using DFT, as the necessary time window would be in the order of a second or longer, heavily exposed to spectral leakage and non-stationarity.

The band-limited analysis of ripple may be exploited and extended to cover LFO, either using a low-pass filter or MSD methods. The low-pass filter would collect also the DC component itself with an unfavourable reduction of the dynamic range for low-frequency ac components; it was shown in [41] that a very low cut-off frequency is hard to implement efficiently with digital filters and the choice converges always on Infinite Impulse Response architectures. MSD can output band-limited channels in the very low frequency range, in particular the Wavelet Packet Decomposition and its equivalent implementation as filter bank, that scales linearly the frequency axis [44]. Conversely narrow-band resonances are better identified by monitoring the bins of a DFT, although a suitably narrow WPD is able to quickly spot out a narrowband energy increase, and is a candidate for transient detection.

IV. EXAMPLES AND EXPERIMENTAL RESULTS

An example of the discussed band-pass ripple index y_{BP} is shown with steady and transient signals measured over a DC railway [28]. Figure 3 shows steady ripple profiles and two events during traction and braking: voltage ripple is very low (< 0.5%) and the profile follows arc events and filter oscillations (at about 15 Hz) afterwards if the lower cut-off frequency f_1 allows that; increasing the upper cut-off does not improve accuracy. The y_{BP} index is able to detect the arc events and a suitable f_1 value allows even arc re-ignition detection without a significant bandwidth as one might think.

V. CONCLUSIONS

This work has discussed the characterization of PQ in DC distribution from two standpoints: the typical phenomena and problems analyzed in the literature and the requisites and information appearing in the standards. The objective is to define a set of PQ indexes able to cover all relevant phenomena effectively and with a low computational burden, with the objective of assessing and preventing PQ issues.
The band-pass ripple index has been demonstrated as a PQ quantifier and transient detector with the help of recordings from a DC railway.

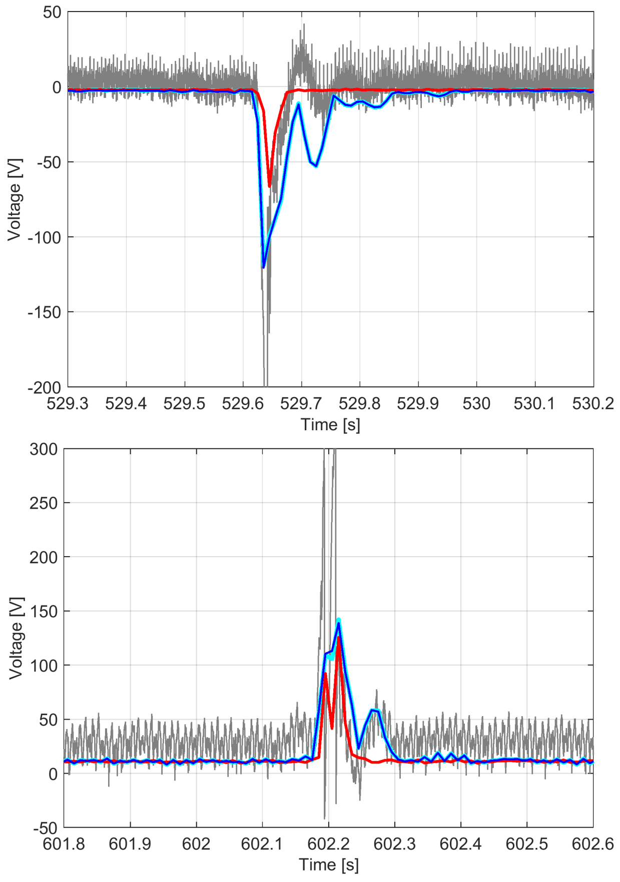

Figure 3. RMS of the bandpass (f_1–f_2) Butterworth (order 8) ripple index for 5-1000 Hz (cyan), 5-5000 Hz (blue) and 50-1000 Hz (red) (negative rms is for display purposes).

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