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DC Power Quality assessment on real MVDC and LVDC power systems

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SUMMARY

Development of HVDC standards started many years ago, but standardisation of MV and LV DC voltage and power quality issues is just being launched by several IEC Technical Committees coordinated by IEC System Committee on Low Voltage Direct Current. Therefore, only a few general standards and technical reports are currently available to guide actual MVDC or LVDC projects.

MVDC and LVDC systems are very different from HVDC systems: (i) HVDC systems have practically no customer load directly connected to DC, they feed loads only through DC/AC converter stations; (ii) while on MVDC and LVDC distribution grids, DC customers and DC/AC stations co-exist with common coupling points (PCC). Thus, the technical and economic issues arising in DC distribution grids are specific, in particular regarding the power quality (PQ) matters related to utilities, customers and equipment suppliers. On the end-user side, the power supply units of all the recent LV electric household appliances and IT devices have almost the same electronic structures. The difference between AC and DC fed equipment is roughly being with or without rectifier stage. Today, some DC appliances are already available on the market. Although these new devices are produced in small series or at a demonstration stage, DC PQ and electromagnetic compatibility (EMC) issues should be taken into account to support the fast development of local DC power distribution systems and various demonstration projects all over the world. The development of DC PQ standards needs relevant technical researches and assessment methods.

Power quality issues of AC power systems have been well covered by relevant international standards and grid connection contracts. Based on the AC PQ knowledge, this paper focuses on the researches of steady state DC PQ assessment methods, the recommendation of relevant DC PQ indices and computing methods. For power quality assessment in distribution grid, the integration of DC PQ indices in frequency domain simulation software is studied and verified by simulating equivalent grids of actual DC installations. Based on site recordings from 4 actual MVDC/LVDC projects, DC PQ indices are computed in order to quantify actual PQ levels and understand some recorded DC events.

KEYWORDS

DC power quality indices, ripple spectrum, DC disturbance modelling in frequency domain

1. Introduction

To deal with DC power system, we can consider that a DC signal modulated with some AC components is a general case of electric system. The well-known AC power quality phenomena are just a particular case where DC component is normally small or negligible. Consequently, DC power quality analysis may theoretically include all phenomena observed in AC system such as transients, short-duration root-mean-square (rms.) variations, long duration rms variations, imbalance, and waveform distortion. In this paper, DC power quality issues resulted from waveform distortion will be mainly studied.

AC voltage compatibility levels [1] and AC power quality measurement methods [2] [3] [4] provide an almost complete technical basis for building low frequency AC electromagnetic compatibility environment around the adequate compatibility levels with IEC 61000 series standards also defining emission limits and immunity limits of AC EMC. As the first stage of DC EMC environment building, DC measurement methods and compatibility voltage levels should thus be set in the near future accordingly, while DC EMC limits will be completed.

Historically, development of HVDC standards started many years ago, but standardisation of MVDC and LVDC (Medium Voltage Direct Current and Low Voltage Direct Current) standard voltage and power quality issues is just being launched by several IEC Technical Committees, like TC8, TC13, TC22, TC 64, SC8B and SyC LVDC. Only a few general standards and technical reports are currently available [5] [6] [7] to guide industrial MVDC or LVDC projects and products.

To illustrate the importance of studying and mitigating PQ issues in DC distribution grids, we provide some data from LV appliances designed for both AC and DC voltage supplies, and some feedback from real DC demonstration projects.

For example, Figure 1 shows the input current waveforms and spectra of an LED powered in AC and DC: disturbances below 2 kHz are much lower when supplied with DC than that with AC because of the lower AC undulations in DC supply. For frequencies above 3 kHz, the disturbances are almost the same in both cases as they are mainly caused by the inverter inside the appliance. This observation is true for all switch mode power supply units which are main parts of today's LV electric appliances.

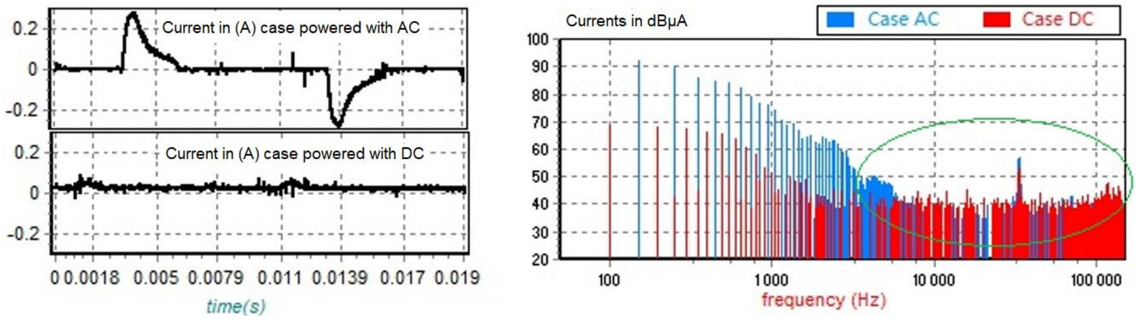


Figure 1 - Input current and spectra measured on a LV appliance fed with both AC and DC

2. Studies of DC power quality indices

Some DC PQ descriptions, recommendations and limits [5] [6] [7] [8] have already been published, but these technical documents mainly focus on DC PQ phenomena raised by traditional AC/DC converters such as diodes and Thyristors based converters. In modern MVDC and LVDC systems, voltage source converter (VSC) types of installations are often used; in consequence, more adequate measurement methods, power quality indices and limit values should be further studied to support upcoming DC projects and installations.

It is considered that there is no reason to dissociate the development of DC PQ standards from existing AC PQ standards since there is almost no significant difference in low frequency conducted disturbance fields, and disturbance sources (power electronics) and sensitive equipment (control and regulation parts) are similar in both modern AC and DC systems. The first purpose of this paper is to define dedicated DC PQ indices, computation methods and modelling approaches that will help electric system operators to assess DC grid performance from project level to commission stage.

Basic electric value measurement methods for steady-state DC PQ applications and recommendations

Before going through all possible DC power quality indices, some definitions relevant to DC parameter assessment methods should be pre-used or recommended:

- root-mean-square value (rms) in general [2]: square root of the arithmetic mean of the squares of the instantaneous values of a quantity taken over a specified time interval and a specified bandwidth.
- rms value refreshed each half-cycle in AC system: value of the rms voltage or current measured over 1 AC cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle. In DC system, half-cycle may be replaced only by fixed duration.
- T_i: instantaneous rms measurement duration. T_i is the unit duration of rms value computation for some DC power quality indices such as fast voltage fluctuation or peak-peak ripple.
- T_w: measurement window's length. T_w is used to compute some common DC power quality indices. T_w is also the window length of spectral analysis (DFT for example).
- T_m: PQ integration period. T_m is used to record steady state DC power quality indices, i.e. PQ indices are measured during T_w and integrated during T_m, and $T_i < T_w < T_m$.

Based on the existing AC power quality measurement knowledges [3], it is recommended to use the following measurement periods for computing some common DC power quality indices < 9 kHz:

- Voltage dip, surge, peak-peak ripple min, max and mean values: $T_i = 10$ ms
- Spectral window length and ripples computation duration: $T_w = 200$ ms or more if high resolution of rms undulation is studied, 1 s for example (see case **d** in section 4).
- rms value integration period or power quality recorded duration: T_m =1 min, 5 min, 10min or 15min as already adopted in AC system. T_m is often used in PQ standards.

Study of steady-state DC power quality indices

Ripple is the variation of voltage about the steady state DC voltage during steady state electric system operation. Sources of ripple may include, but are not limited to, voltage regulation instability of the DC power source, commutation/rectification within the DC power source, and load variations within utilization equipment. Ripple amplitude is the maximum absolute value of the difference between the steady state and the instantaneous DC voltage.

Some on-site observations and achievements from various industrial projects illustrate the practical needs of adequate DC power quality indices to quantify power quality levels of actual DC applications. In DC systems, peak-peak ripple value is one of the existing power quality indices, but it is not sufficient to quantify DC power quality with modern converter technologies [5].

The following DC power quality indices are recommended for future DC system:

- Peak-peak ripple: it is the maximum difference between max rms value and min rms value during T_w divided by DC component. The rms values are computed during T_i.
- Distortion in a DC system: DC distortion is defined as total rms value of all alternating voltage components on the DC voltage during T_w.
- DC rms ripple or distortion factor. DC distortion factor is the ratio of the DC distortion to the mean DC voltage during T_w.
- Ripple spectrum or distortion spectrum. The distortion spectrum quantifies AC components in terms of the amplitude and phase of each frequency component. The distortion spectrum includes the components resulting from amplitude and frequency modulation as well as harmonic and non-harmonic components of the waveform, i.e. everything except the DC component.
- rms ripple (or integral value, or spectral energy) is measured in each frequency band of interest with adequate time and frequency resolutions. According to frequency ranges, measurement methods may be different [2] [3] [9] [10].

All final DC steady-state power quality indices may be recorded every measurement cycle T_m.

Using above PQ quantification methods, almost all steady state conducted disturbance phenomena may be identified and quantified such as electromagnetic interference (EMI) issue or instability issue. Some EMI phenomena are observed in recent DC applications with power electronic converters (see case studies in section 4).

3. Recommended DC power quality algorithms and integration in a simulation tool

In this section, some steady state DC power quality indices and computation methods are detailed and recommended.

Peak-peak ripple value (Vrpl_pp)

For DC power supply system, it is recommended using the following formula to quantify peak-peak ripple value (Vrpl_pp) of each measurement window T_w (Figure 2):

$$Vrpl\_pp = \mathrm{abs}(\frac{V_{max} - V_{min}}{V_{mean}}) * 100\%$$

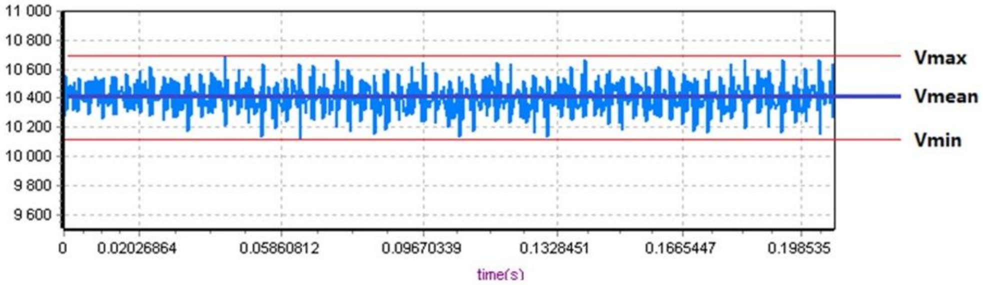


Figure 2 – Illustration of DC ripple computation

Vmax, Vmin and Vmean are maximal, minimal, and mean rms values in each measurement period T_w and individual rms values are measured in each measurement duration T_i.

Vrpl_pp gives the absolute RMS variation compared to DC voltage. It is similar to d_{max} used in IEC 61000-4-15 for AC fast voltage fluctuation assessment [4].

Ripple spectra (ripple deformation)

Spectral analysis of DC ripple should be done during each measurement period. DFT or FFT decomposition may be used according to sampling number. In DC systems, measurements are synchronized with the system time as defined in [3], as zero crossing synchronization cannot be used.

Based on spectral analysis results, rms value of voltage and current can be computed in frequency domain. Value **m** is the maximal harmonic referred to DFT/FFT window frequency f1. f1 has not the same fundamental frequency meaning as in AC systems:

$$V_{rms} = \sqrt{\sum_{k=0}^{m} (V_k{}^2)}$$

DC rms ripple value (Vrpl.rms)

DC rms ripples of voltage and current during each measurement period may be computed both in time domain and in frequency domain [7]. Here is the frequency domain formula:

$$V_{rpl.rms} = \frac{\sqrt{V_{rms}{}^2 - V_0{}^2}}{V_0} * 100\%$$

Where V_0 is DC component.

For frequency ranges above 9 kHz, power quality level definition and measurement methods are referred to CISPR16 [9] [10] [11].

For total DC distortion assessment, two frequency ranges are recommended:

- The 0 – 9 kHz range, referred to low frequency disturbances of AC system, quantified with IEC methods [2][3][4].
- The > 9 kHz range, referred to conducted disturbances of AC system, quantified with CISPR16 method with quasi peak detector [9] [10].

The original CISPR16 measurement method is based on analogical heterodyne frequency analyzer. In recent digital applications, digital implementation of the CISPR 16 method with 200 Hz resolution is recommended [10] [11]. The digitized input voltage signal is decomposed into frequency components using a spectral analysis tool such as overlapping DFT or digital filters with compliant resolution bandwidth. The amplitudes of each frequency component are weighted by simulation of analogue quasi-peak (QP) detector, which smoothens the time variation. Based on the guidance on FFT-based EMI receivers in CISPR/TR 16-3 (non-normative), some approaches are selected for implementation:

- Digital receiver, with simultaneous measurement of the entire frequency range
- Continuous measurement of the input signal (no gaps)

The parameters are set to comply with “CISPR 16 band A” requirements:

- Window function according to CISPR 16-1-1 Annex A.2 or CISPR 16-3 TR
- Time overlaps according to CISPR 16-3 TR
- Charging/discharging time constants of quasi-peak detector defined in CISPR 16-1-1
- Compliance with the calibration process described in CISPR 16-1-1

Simulation of DC PQ indices by means of frequency domain simulation algorithms

This section describes frequency domain computation of power quality indices in presence of DC components, i.e., possibility to simulate DC PQ indices. Power quality study of AC/DC grid can be carried out by frequency domain simulation tools with acceptable computation time. However, general commercialized frequency domain simulation tools cannot accept DC components. Some adaptations and developments are necessary to cover DC PQ analysis.

The first objective is to study the computation methods enabling to deal with DC component in frequency domain simulation tools. The results of our research show that it is possible to study DC PQ indices with a frequency domain simulation tool, but some adaptations and extra modelling have to be done. Here are the actions taken in our grid simulation software:

- Frequency domain computation solver for power quality set at the minimal frequency value (1E-6 Hz for example, equivalent to an AC cycle > 377 hours). This DC threshold is sufficiently distinct from general power grid electrotechnical computations.
- Modification of component models (power source, transformer, line, cable, load, post-data processing, etc,) to avoid pure inductance branches.
- Data processing of DC value with mean value used instead of AC peak value.
- Computation of DC grid power quality indices such as DC ripples, DC unbalance, etc. (referred to on-going IEC TS 63282) in frequency domain or stability simulations

Besides DC component which needs to be adapted in frequency domain, all existing models of AC grid components can be reused for DC power quality simulation. The above-mentioned DC PQ computation methods and indices have been integrated into ExpertEC, an AC power quality simulation software of Electricité de France [12], used in the case studies of section 4.

4. Application of DC power quality computation with actual data recorded from laboratory measurements and industrial projects

In this section, some laboratory measurements, and on-site recordings of ongoing MVDC projects are used to compute and simulate DC PQ indices as recommended in the above sections. The main aim is to verify the feasibility of studied DC PQ indices and to explicate real phenomena observed in actual industrial MV and LV DC projects, each of which has specific objectives in DC PQ assessment.

a) Application of DC power quality computation and definition of PQ frequency ranges

Figure 3 illustrates DC voltage and current waveforms measured at the input of a new LVDC load (electronic dimmer) and their FFT analysis. The spectra show that the load current contains a large range of spectra covering mainly from 100 Hz to 150 kHz. The potential impacts of these spectra of DC voltage are surely different in each range of frequencies because the impedances of DC power supply and distribution links are function of frequency as well. In this case, computed DC PQ indices are: rms ripple is 2.33% for DC voltage and 215% for DC current in the range of frequency < 9kHz. For information, the observed disturbance voltage level 9 – 150 kHz is about 86 dBμV which is lower than the existing AC voltage compatibility level defined by [1].

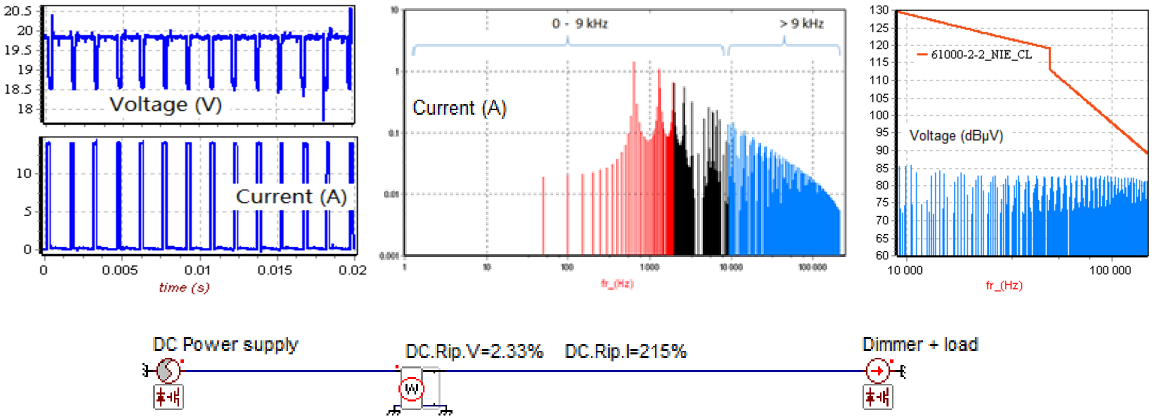


Figure 3 – Voltage and current waveforms and spectra measured on an electronic appliance

b) DC power supply capacity assessment by fast load current variations

In low frequency AC grid power quality assessment, the grid short-circuit power at the point of common coupling (PCC) is often used as one of the key input parameters for power quality simulation and estimation. In DC distribution system, DC power supply is generally built with power electronic interface, so it is almost impossible to get a frequency domain source impedance. In fact, short-circuit power in a converter-based power source has not the same meaning as in conventional power generator.

The following example shows how we apply one of the power source capacity quantification methods under laboratory condition. A chopped electronic DC load is used to identify DC power supply frequency impedance at chopping edges, i.e., small signal analysis and steady state frequency impedance building. The two power supplies are switching-type DC power sources (one is 20V, 10A, another is 20V, 8A). Figure 4 shows the power supply voltage, the load current and the identified equivalent supply power source impedance in function of frequency from 0 up to 200 kHz. This impedance represents small signal short-circuit power level of the DC source and may be used to carry our steady state DC PQ assessment.

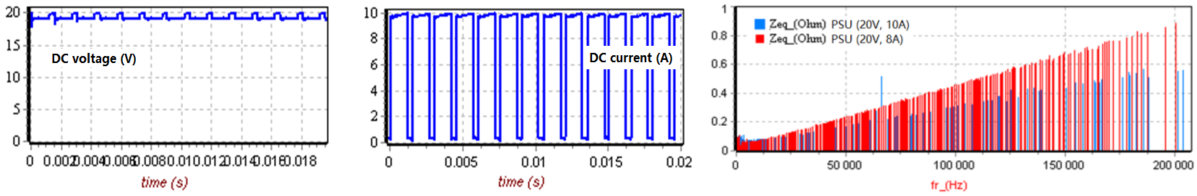


Figure 4 – Voltage, current and estimation of supply source impedance

This frequency-dependant impedance may be used to assess steady state DC power quality if new loads are connected to the same power supply. In future DC supply systems, one of the technical requirements will be that power source converter suppliers should provide the frequency dependant impedance of power supply converter in each range of power in order to carry out the whole DC system power quality assessment and planning.

c) <u>LVDC project: AC harmonics and DC ripples at each side of AC/DC converters</u>

Three phase AC currents of a PWM AC/DC converter station of a 10 MVA LVDC application and DC voltage and current of one converter (Figure 5) are recorded.

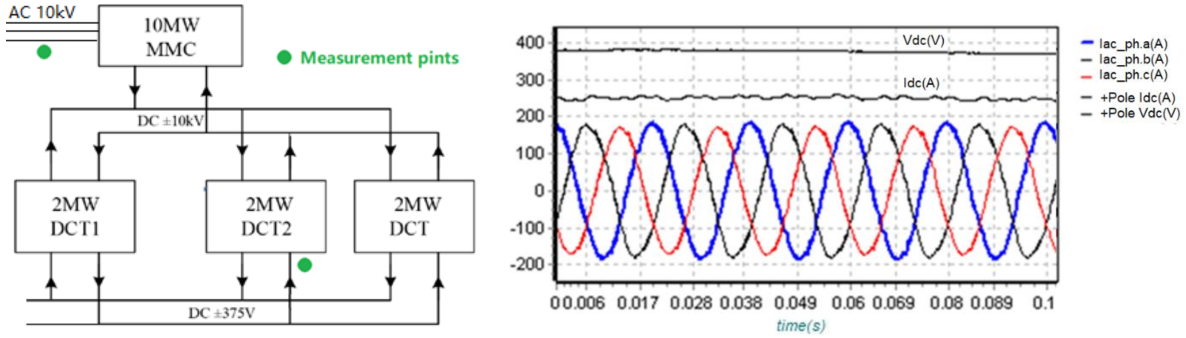


Figure 5 - Input AC current and output DC voltage and current of the converter station

Spectral analysis is carried out on the total input AC currents and DC output voltage and current (Figure 6). It is observed that AC current spectrum content around 3 kHz results from the AC/DC converters as there were no obvious spectrum content in the same frequency range on the DC side. If relevant AC PQ contracts or IEC EMC reports are applied, power quality of the AC current of this converter station is fairly good (total current harmonic distortion is about 3.54%). The spectrum peak at 4 kHz of DC current results from the switching frequency of electronic loads.

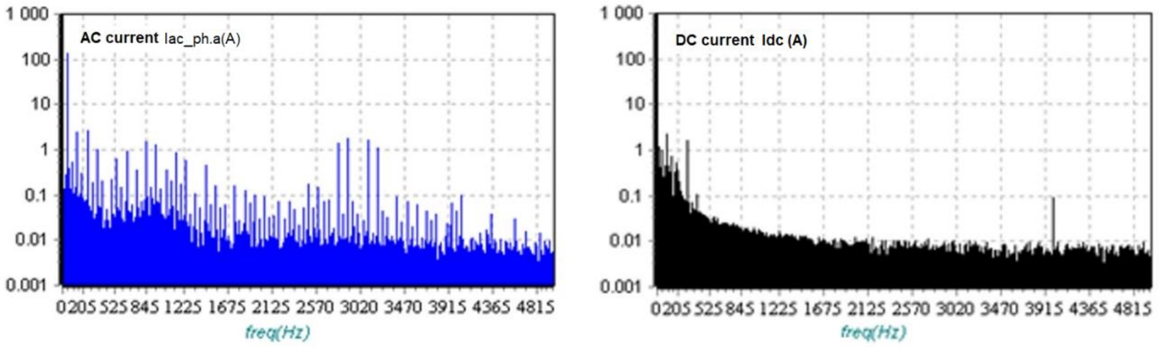


Figure 6 – Spectral analysis of input AC current and output DC voltage and current

With these on-site recordings with sampling frequency 10 kHz, frequency domain simulations and computations have been carried out to obtain some AC and DC power quality indices (Table 1). Similar results are obtained for DC negative pole.

Electric values	**Iac_ph.a (A)**	**Idc (A)**	**Vdc (V)**
RMS Values	129.26	249.22	375.83
Min values	-187.50	235.18	367.53
Max values	187.29	263.66	384.88
Mean (DC)	0.00	249.16	375.80
Peak-Peak Ripple(%)		11.43	4.61
RMS Ripple(%)		2.18	1.27
Td_f1(%)	4.30		
Thd_f1(%)	3.54		

Table 1 - AC and DC PQ indices recorded at each side of a 2 MW PWM AC/DC converter station

d) Bipolar MVDC project: Analysis of DC ripple resulted from load current variation

Figure 7 shows voltage and current waveforms recorded on main DC bus of a bipolar MVDC distribution system (+/-10kV) with their spectral analysis and PQ computations. These measurements indicate the existence of a DC voltage undulation and a DC load current variation. From spectral analysis, it is recognized that voltage spectra > 100 Hz is not caused by the load current variation but the AC/DC converter.

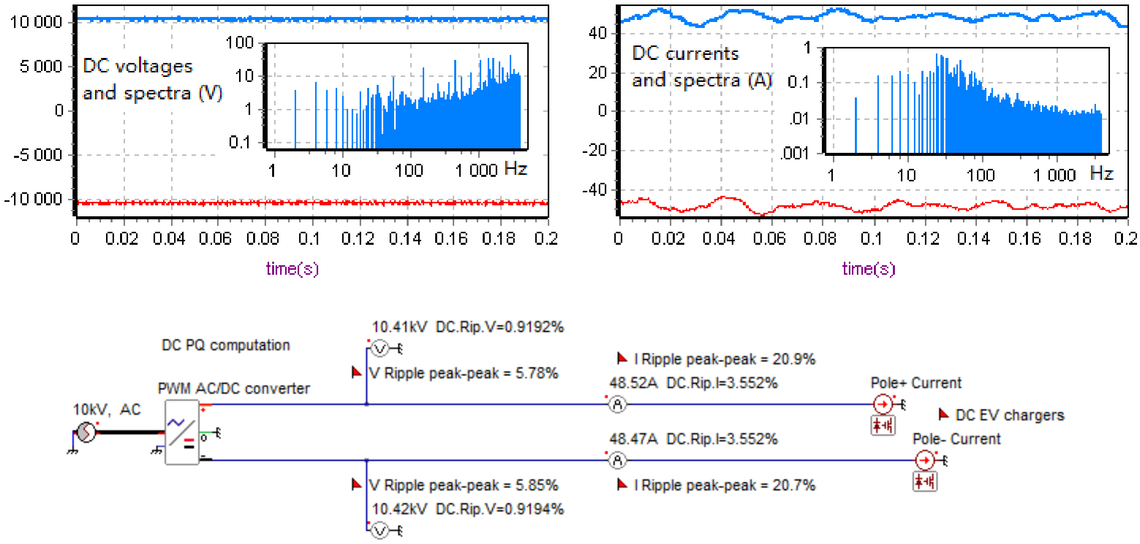


Figure 7 – MVDC voltage and current ripple computation

On the basis of recommended methods in sections 2 and 3, DC peak-peak ripples and rms ripples in time and frequency domain are simulated with the above measurements. The results show that ripples of DC bus voltage are 5.78% (peak-peak) and 0.919% (rms).

e) Rural LVDC project: DC PQ levels in an office building with DC appliances

DC voltage and current waveforms are measured on main DC bus +230V of a single polar LVDC distribution system, a rural LVDC project commissioned in 2020 by Golden cooperate Ltd [13]. Spectral analysis shows that DC rms ripples are 0.5% (voltage) and 51% (current). Both voltage and current contain a 50 Hz component and its harmonics < 2.5 kHz. The reasons of the 50 Hz relevant spectra are 1) the presence of residual AC voltage components: AC/DC converter may not be fully filtered, 2) the connected DC loads are extremely sensitive to supply voltage variation and the dynamic load regulation amplifies this variation. In fact, detailed power spectral analysis at 50Hz show that the magnitude is important, and the active power is negative, i.e. 50 Hz power flow is from the office loads to the DC power supply because the real part of equivalent supply source impedance at 50 Hz is -0.158 Ohm.

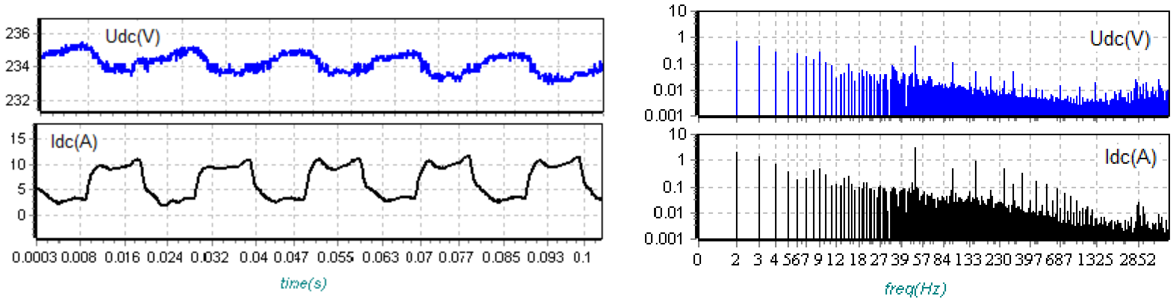


Figure 8 – DC voltage variation caused by dynamic DC current fluctuation

DC stability simulation is performed with recorded rms voltages. Although a digital IEC61000-4-15 flicker meter model indicates DC bus flicker level Pst is 1.834 (Figure 9), the lamps in the office have no visible blinking effect, i.e., the used DC LED lamps are not as sensitive to fast voltage fluctuation as incandescent lamps. This is one of the useful information for supporting future DC flicker standardization work.

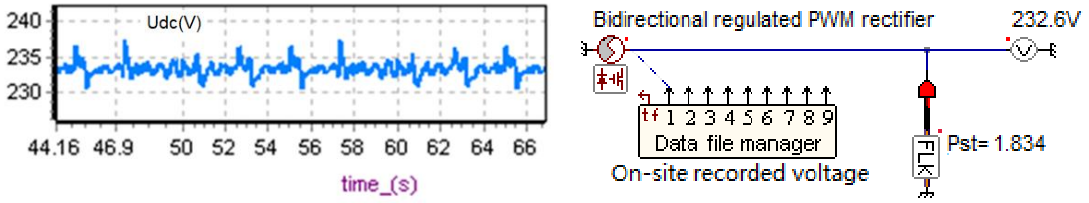


Figure 9 – DC voltage variation and flicker level assessment

f) <u>DC PQ simulation: temporary oscillation occurred in actual 20 MW bipolar MVDC and LVDC project</u>

Figure 10 illustrates the general structure of a MVDC and LVDC project commissioned by JS EPRI in China: MVDC at +/-10kV, LVDC at +/-375V and total capacity is about 20 MVA.

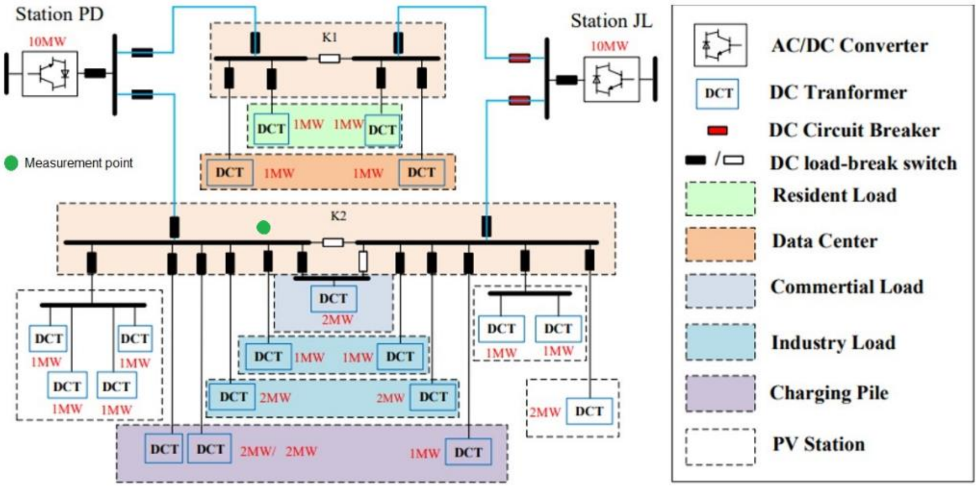
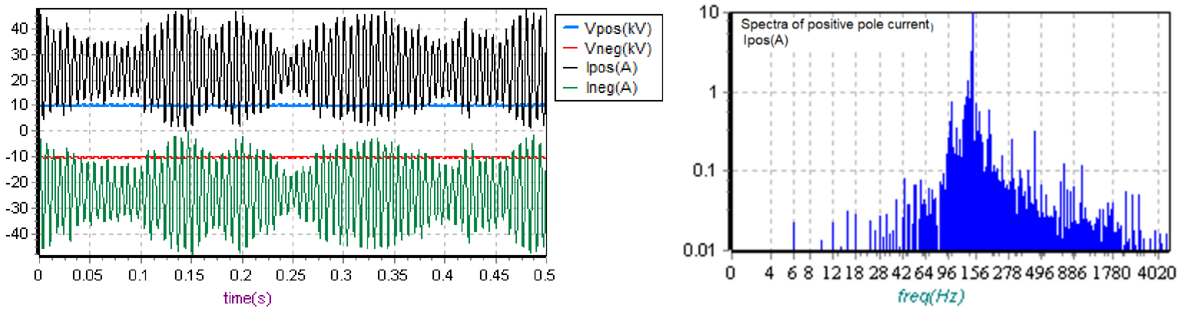


Figure 10 – General structure of MVDC and LVDC project

Measurements at the output of one converter station show that a temporary MVDC voltage and current oscillations occurred at 10 kV level during on-site adjustment. The measurements and PQ indices analysis confirm that important DC voltage and current ripples can be used to identify, or at least quantify the oscillation taken place in this application. Main oscillation frequency of the case is around 150 Hz with important peak-peak ripples (Figure 11).



	Positive Pole(A)	Positive Pole(V)	Negative Pole(A)	Negative Pole(V)
RMS Values	26.38	9980	26.49	10500
Peak-Peak Ripple(%)	198	12.8	199.6	7.91
RMS Ripple(%)	48	2.7	48	1.27

Figure 11 – Voltage, current, waveforms, spectra, and DC PQ indices computation

As indicated [8], one of the origins of DC ripple is power source instability. Oscillation issues may be caused by both dynamic sources and loads, or by multiple bidirectional power converters. This on-site investigation shows that oscillation occurs during some regulation modes (negative resistance for example) in presence of several bidirectional converters, and optimised regulation parameters are necessary to damp or remove this type of oscillation.

5. Conclusion and recommendation

The article introduces DC PQ indices for modern MV and LV DC systems. These indices could be integrated into common grid PQ measurement devices and simulation tools to assess actual PQ performance of DC distribution systems.

As the basis of future DC power quality indices, some electric value measurements and spectral analysis are firstly recommended such as instantaneous rms measurement duration, DFT/FFT window length, DC PQ integration and measurement recording period. These recommendations are already used in AC power quality assessment. The on-site measurements show that in some DC distribution voltages, AC fundamental frequency related spectra still exist.

Based on the existing AC grid power quality methodologies, some steady-state DC power quality indices are studied and recommended such as peak-peak ripple, rms ripple and DC deformation. For DC spectral analysis, it is suggested to start with two frequency ranges: the 0 – 9 kHz range using IEC measurement methods and the > 9 kHz range using CISPR 16 measurement methods.

Measurements from six MVDC, LVDC actual projects and laboratory tests are used to verify the digital data processing and to confirm the applicability of recommended DC PQ indices. These knowledges may be used in future development of DC PQ standardisation.

The proposed adaptation and development within a general AC PQ simulation software enable to easily study DC PQ under frequency domain simulation tools. So, fast assessment of PQ levels and disturbance propagations in DC distribution grids may be achieved.

6. Perspectives

This paper recommends some DC power quality measurement methods and indices which are mainly derived from existing AC power quality methodologies. The main reasons are to start DC power quality assessment with acquired know-how on AC power quality such as frequency bands and measurement window lengths, try to convert existing PQ monitoring technologies, and adapt simulation tools for DC grid PQ assessment. This is just first step and with arising development of DC applications, evolution of DC PQ assessment method will continue.

As one of the missing blocks in the standardization context, next steps could be the assessment of voltage immunity levels of mass LVDC power electronic devices.

The most important requirement in DC PQ standardization is to define voltage compatibility levels as soon as possible because they are the base of EMC coordination.

In future industrial DC power supply system, one important technical requirement is that power source converter suppliers should provide the frequency dependant impedance Zf of the converter in each range of power. Zf is somehow equivalent to short circuit power level and it may be used for carrying out whole DC system steady state power quality assessment.

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