POWER QUALITY ASSESSMENT FOR AC/DC HYBRID NETWORK BASED ON NEW MODELLING METHODS AND ON-SITE MEASUREMENTS

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ABSTRACT

AC/DC hybrid network has become a new trend in power distribution and transmission system. It possesses the advantages like decreasing the power loss of AC/DC or DC/AC conversion by the direct power supply to AC and DC loads and increasing the reliability of network, etc. However, the power quality issues in this kind of grid have not been enough addressed and considered comparing to the individual AC network or DC network. How to evaluate power quality in DC grid and what's the influence between DC part and AC part? Even more questions related to power quality and modelling methods in AC/DC hybrid network need to be answered and explored.

The subject addressed in this paper is the power quality assessment which is carried out by new modelling methods and an experimental analysis of a real AC/DC hybrid network. DC voltage variation, voltage unbalance and harmonics (ripples in DC) in both AC and DC voltage are analysed in "grid-connected" mode or "islanding" mode. Furthermore, the dynamic impedance of battery converter is calculated during transient event, which is one of the key parameters to assess static power source behaviours and evaluate the potential power quality level when a new load is connected to the grid based on mainly power electronic interfaced supply sources. The simulated results are then validated by on-site measurements with very acceptable error.

I. INTRODUCTION

AC/DC hybrid microgrid has become an obvious trend in power distribution and transmission. But, the power quality analysis in this kind of microgrid has not been enough addressed or considered comparing to the individual AC or DC microgrid. In Ref. [1], power quality indexes are analysed in AC microgrid integrated with a large-scale PV plant through simulation tool and the on-site data. The power quality control and correction of DC microgrid has also been well studied theoretically in Ref. [2]. In this paper, the detailed power quality assessment for a typical AC/DC hybrid microgrid in Zhejiang province of China based on real on-site data is reported and some new modelling methods are presented.

Shangyu demonstrator provides a complete set of solution for AC/DC hybrid microgrid construction with high density access of distributed renewable energy, such as protection plan, operation control, and FRT realization, etc. It has achieved great breakthroughs in the development and manufacturing of the core equipment of AC/DC hybrid microgrid and laid technical foundation and engineering experience of AC/DC microgrid development in China. This paper gives a rough introduction on Shangyu demonstrator and conducted a detailed analysis on AC/DC power quality. The dedicated modelling methods are also presented.

The paper is organized as follows: Network configuration and harmonics and ripples modelling methods are presented in the 2nd and 3rd section, the 4th chapter presents the modelling results and on-site validation. Last section concludes the paper and expresses further level of research work to be investigated.

II. AC/DC HYBRID MICROGRID CONFIGURATION

The demonstrator is located in the south of China and has been in operation for about one year. The configuration is shown in the following figure.

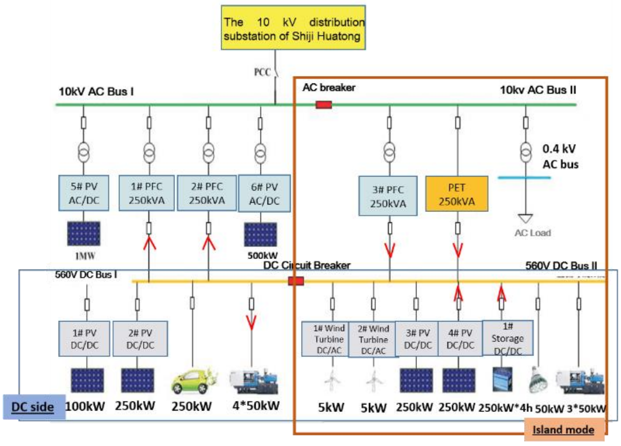


Figure 1: Shangyu AC/DC hybrid microgrid configuration

In this demonstrator, AC bus is 10kV and DC bus is 560V. AC and DC grid are connected and controlled by 3 PFC (Power Flow Controller) and 1 PET (Power Electronic Transformer). PFC works in virtual impedance droop control mode to realize the average distribution of power flow and the rated power is 250kVA for each PFC. PET transforms 10kV AC voltage to 560V DC voltage by using MMC (modular multilevel converter) topology and the rated power is 250kVA.

The hybrid grid contains a roof-top photovoltaic power station of 2350 kW, 7 plastic injection moulding machine of 50 kW and the LED lamps of 50 kW are connected as DC load. Besides that, the lead-carbon battery (the rated capacity is 50 kW×4h), 4 DC electric vehicle charging stations (60kW*4) and 2 direct-drive wind turbine generators (5kW*2) are connected to DC bus. AC loads are connected to 400V AC bus and mainly include computer, air-conditioning and the light.

This microgrid has four operation modes: “grid connection operation: two breakers close”, “DC bus II islanded：AC breaker close and DC breaker open”, “AC bus II islanded：AC breaker open and DC breaker close” and “islanding operation: two breakers open”. The switching between different modes is fast, reliable and smooth. In the first three operation modes, the system is connected with external distribution power network and the economic interest is the priority issue, but, in islanding operation mode, the system takes the high reliability of power supply as the main control target.

III. HARMONICS AND SUPRA HARMONICS MODELLING METHODS

This part introduces the conventional dedicated methods for modelling harmonics in frequency domain and also proposes new ones which are applied on AC/DC hybrid microgrid simulation. A set of solution is put forward to deal with DC component in frequency domain simulation tools.

a) Voltage and current source method with parameter variation for low frequency disturbance assessment

Using passive RLC and voltage/current source model with parameter variation is one of the conventional methods to modelling nonlinear loads and to assess low frequency disturbance.

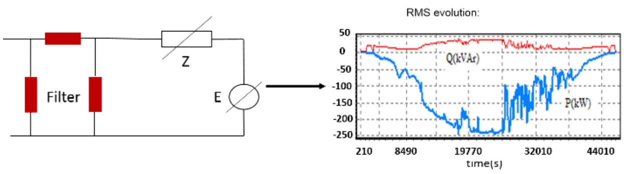


Figure 2： (a) RLC E/J Model; (b) Load flow and RMS evaluation

As shown in figure 2, the electrical and operational parameters could be impedance Z (f), current source J (f), voltage source E (f), or electric parameters U, I, P, Q, etc. The load flow and RMS evaluation results are shown in figure 2(b). It’s a well-accepted nonlinear load modelling methods in f domain. Besides that, equivalent frequency domain sources in figure 3 is also a well-used method for harmonic and other disturbance assessment.

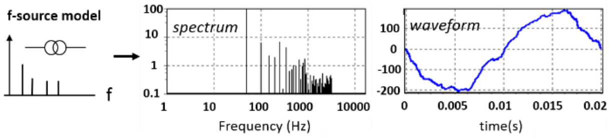


Figure 3: f-source model

But some particularities should be considered in using equivalent source method, like disturbance phase angle, disturbance sequence in 3-phase cases and disturbance impedance if available.

b) Embedded time domain simplified model to simulate disturbances>2 kHz

For modelling high frequency disturbances, the embedded time domain simplified model is proposed. The following figure is a typical power electronic structure and shows a time and frequency domain hybrid simulation.

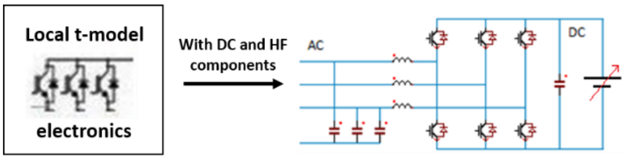


Figure 4: local time domain model

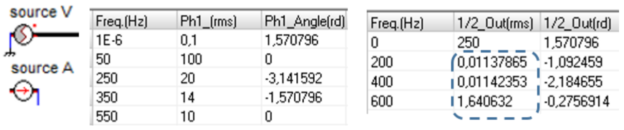
In figure 4, the whole circuit could be regarded as external loop and adopts frequency domain simulation. The electronic is internal loop and use time domain modelling to build f-domain spectra. The t-domain equations are discretised from f-domain ones and the above local t-domain converter models are expected to be launched in parallel computations in the future.

When DC component is taken into account in frequency domain modelling and simulation, the component models and f-domain computation should be firstly considered.

c) Considering DC components in frequency domain simulation tools

Until now, some general commercialized f-domain simulation tools can’t accept DC component due to its speciality in frequency domain. This part proposes several methods regarding how to deal with DC component in frequency domain simulation tools in order to make the power quality study of AC/DC grid can be carried out by frequency domain simulation tools with acceptable computation time.

The component models, like source, transformer, line, cable, etc. should firstly be modified. In figure 5(a), a minimal frequency value f_{dc} (1e-6Hz for example) should be set as DC threshold for f-domain computation solver. For data pre-processing in figure 5(b), the magnitude of DC component in different frequency should be set at RMS value and use the mean value as the magnitude for f_{dc}.



Freq.(Hz)	Ph1_(rms)	Ph1_Angle(rd)
1E-6	0,1	1,570796
50	100	0
250	20	-3,141592
350	14	-1,570796
550	10	0

Freq.(Hz)	1/2_Out(rms)	1/2_Out(rd)
0	250	1,570796
200	0,01137865	-1,092459
400	0,01142353	-2,184655
600	1,640632	-0,2756914

Figure 5: (a) solver and electric source model; (b) data processing

For transformer, line/cable and load models, avoid using pure parallel inductance model.

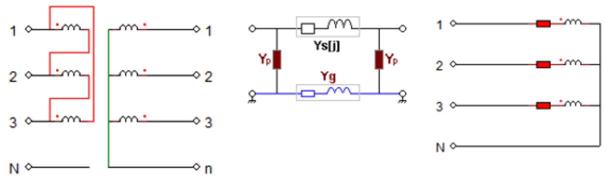


Figure 6: transformer, line/cable and load models

The computation of power quality indices for DC grid, such as DC ripples, DC unbalance, etc., should be referred to on-going IEC technical reports of TC8.

d) Dynamic impedance identification during transient events

In general, the power supply based on power electronic converter can only offer 1.2 to 1.5 pu of steady state short circuit power. But in small signal transit mode or power quality domain, this short circuit power deduced from steady state value can't be used to compute equivalent source impedance. That's why the identification of small signal equivalent impedance Z (f) or dynamic impedance of power electronic converter should be done in order to assess power quality behaviour of static power source.

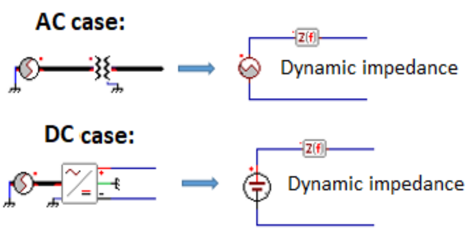


Figure 7: dynamic impedance illustration

The dynamic impedance of the battery converter in this demonstrator is calculated based on the transit event shown in figure 8 and the simulation results are presented in the third part of chapter IV.

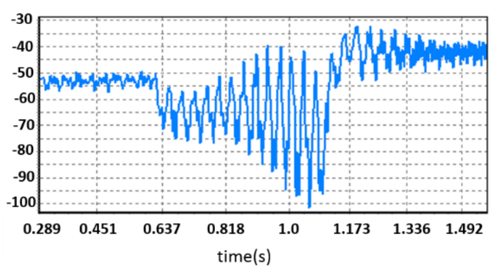


Figure 8: measured battery current

The dynamic source impedance could be used to evaluate the impact of new end-user or new electric installation and assess over-all power quality level and margin for further customer connection. It could be also regarded as a solution to pre-size the power quality mitigation.

IV. MODELLING RESULTS AND ON-SITE VALIDATION

Simulations, on-site tests and measurements have been carried out for verifying AC voltage harmonics and DC voltage ripple (future IEC power quality indices for LV DC applications), voltage unbalance and harmonics. The equivalent dynamic impedance of power electronic interfaced converters is also evaluated.

a) AC grid power quality assessment

AC voltage unbalance

Unbalance voltage and current is one of the main power quality issues in the network. It refers to any deviation of phase voltage and current from its rated value with respect to the magnitude and phase angle. The equation to calculate the degree of voltage unbalance noted as α which is shown in *Eq.*1, where V_12, V_23, V_31 are the line voltages [3].

$$\alpha = \sqrt{\frac{6\times({V_{12}}^2+{V_{23}}^2+{V_{31}}^2)}{(V_{12}+V_{23}+V_{31})^2} - 2} \qquad \textit{Eq.1}$$

Fig. 9 gives the waveforms of 3 phase voltages in the islanding operation mode. The rate of unbalance is 0.20% after calculation. According to the Chinese network standard GB/T15543-1995, the maximum allowable unbalance voltage level is 2% for normal operation [4]. So the AC voltage unbalance is acceptable.

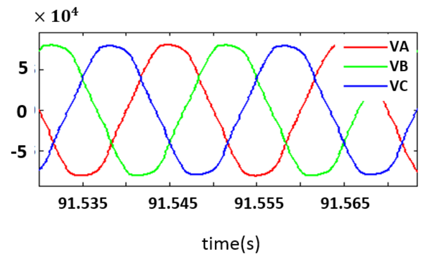


Figure 9: AC voltage waveform

AC voltage harmonics evaluation

Four scenarios have been used for frequency domain power quality analysis: grid-connected operation without APF, grid-connected operation with APF, islanded operation with APF and islanded operation without APF. They are respectively represented by E1, E2, E3 and E4. APF (active power filter) is used for PQ mitigation and connected to DC bus II.

The spectrum diagram and calculation results are given in figure 10 and table 2. Table 1 describes the Chinese grid standard (GB/T14549-93) for harmonics level [5].

Rated voltage(kV)	THD (%)	Odd harmonic ratio (%)	Even harmonic ratio (%)
10	4.0	3.2	1.6

Table 1: Harmonic limit of 10kV grid of GB/T14549-9

Time domain	RMS value	Td f1 (%)	Thd f1 (%)	Thd RMS (%)
E1 U (V)	5828.03	3.51	3.41	3.41
E2 U (V)	5835.74	3.51	3.48	3.48
E3 U (V)	5857.56	3.37	3.26	3.26
E4 U (V)	5847.73	3.56	3.48	3.47

Table 2: harmonic results of AC bus voltage

From table 2, it could be drawn that there is low voltage harmonics (for f<2 kHz, Thd<3.5%) and in figure 10, the characteristic harmonic of PWM converter with the order of (6k±1, k=1, 2, 3…) is the main source of harmonics. The maximum odd harmonic ration appears at 250 Hz with a value of 2.39%, and the maximum even harmonic ratio is 0.04% at 100Hz. So the AC bus voltage power quality confirms with the national standard. There exists some high-frequency disturbances beyond 2 kHz though its level is low: some spectra near 4.8 kHz (about 11V) and near 6 kHz (about 8V only in the cases with APF). Whereas, there is no compatibility level for these frequencies on LV grid yet [6].

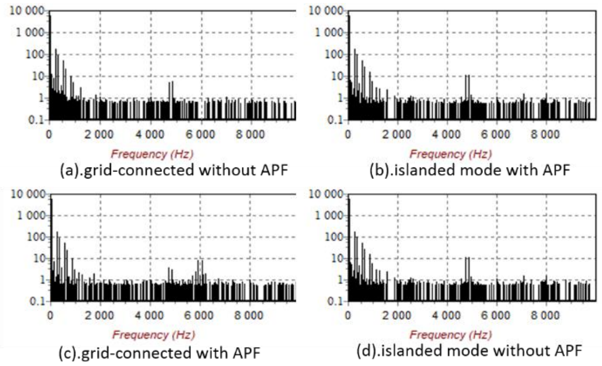


Figure 10: harmonics spectrum for AC bus voltage

b) DC grid power quality assessment

Transient DC voltage variation

DC Ripple is the residual periodic variation of the DC voltage. When DC is generated form a rectifier, the DC voltage varies directly with the peak AC voltage. This produces a varying voltage about the DC level which corresponds to the ripple. It can be also due to the pulse width modulation (PWM) switching or the DC load.

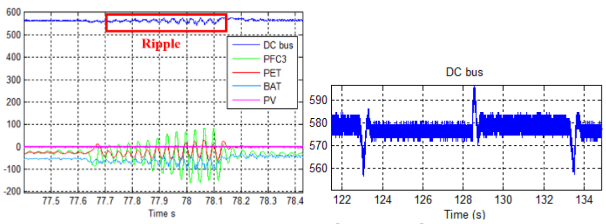


Figure 11: DC voltage ripple

Fig. 11 shows an important transient event recorded in grid connected mode operation, in which the ripple waveform has been measured. The ripple factor γ is defined as the ratio of root square mean (RMS) value of AC component to the DC voltage. In this case γ=V_RMS/V_DC = (13.5 V)/ 571.3V=2.4%, which is below the acceptable level 5% of IEC TC8-WG9 [7]. Besides that, the voltage swells and voltage dips with an amplitude of 20 V and a duration of 0.3 seconds are also recorded. However, recommended values of limitation about these events are still not available until now.

DC voltage harmonics and ripples

In terms of the harmonics of DC bus voltage, the definition given by IEEE and CIGRE of the harmonic order is the ratio of its frequency to the fundamental frequency on AC side (if exists) of the converter [7], which is 50 Hz in this case. Fig. 12 gives the spectrum diagram and calculation results of DC bus voltage are shown in table 3.

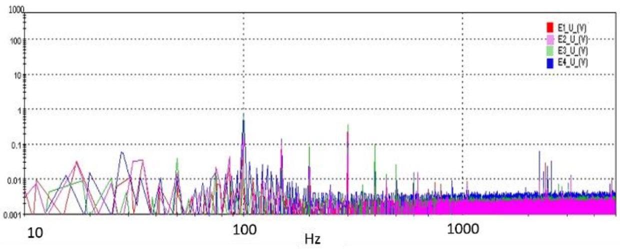


Figure 12: harmonics spectrum for DC bus voltage

Time domain	RMS value	Max	Min	DC Ripple (%)
E1 (V)	568.68	576.67	558.67	0.30
E2 (V)	569.44	576.67	558.67	0.34
E3 (V)	564.22	569.33	560	0.29
E4 (V)	564.24	576.67	544	0.38

Table 3: calculation results

Overall voltage quality of DC voltage is excellent for these 4 operation modes (ripple<0.38%). The result shows that there exist characteristics and non-characteristic harmonics, inter-harmonics and voltage disturbances>2 kHz which is mainly caused by chopping frequencies of converters. Besides that, the most important DC ripple is near 100Hz about 0.75V in island mode where the 50Hz sinusoidal voltages are built by PWM inverters. As PWM chopping frequency is not enough high, only 2.5 kHz, there is a little asymmetry on AC voltage waveform.

c) Modelling results for identifying dynamic impedance

The dynamic impedance of battery converter is calculated based on the transient event shown in figure 8 and the equivalent model is in figure 13.

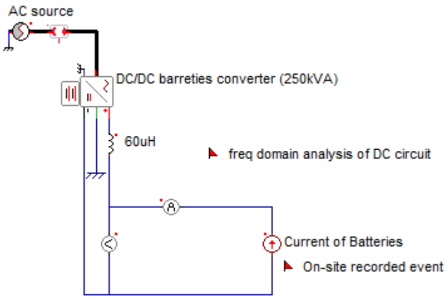


Figure 13: equivalent model

The data in figure 8 is imported as on-site recorded event and shown in figure 13. For evaluating dynamic impedance of battery converter, two methods have been used: 1). By Z=V/I in frequency domain; 2). By simulation in varying converter internal impedance value until the measured DC bus voltage curve is as near as possible the measured one.

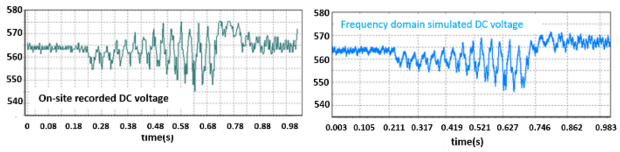


Figure 14: (a) on-site recorded DC voltage; (b) frequency domain simulated DC voltage

The equivalent dynamic impedance obtained is about 0.4 Ohm from 10 to 100Hz and this value is considerably lower than that deduced from the steady state parameters of battery converter (250kW, 560V). If Ssc=1.25pu, the equivalent steady state impedance is 1.0Ohm. That is why the impedance 0.4 Ohm is applied in the microgrid modelling to assess power quality indices.

d) Conclusions

The main results are:

i. Simulations with estimated dynamic impedance of the power electronic converters give acceptable power quality assessment compared with on-site measurements;
ii. Presence of characteristic and non-characteristic harmonics, inter-harmonics and voltage disturbances >2kHz (mainly the chopping frequencies of different power electronic converters);
iii. The most important DC ripple is near 100Hz in islanding mode where the 50Hz voltages are built by PWM inverters. As PWM chopping frequency is not enough high, only 2.5 kHz, there is a little asymmetry on AC voltage waveform which is mirrored to DC power supply voltage.
iv. Over-all voltage quality of the DC voltages is excellent for the 4 operation modes (ripple < 0.38%);

The modelling and on-site analysis on this demonstration project give not only the actual power quality levels, and also the validation of the new power quality modelling methods for future AC/DC hybrid distribution network. The identified dynamic impedance of power electronic source converter is not directly given by manufacturer but it is a key parameter to evaluate the supply capacity of battery converter in the DC grid and to assess the power quality before integration of a new load to the grid.

V. CONCLUSIONS AND PERSPECTIVES

In this study, power quality issues like voltage variation, voltage unbalance and harmonics were analyzed and quantified in AC/DC hybrid microgrid through an experimental approach.

Considering the fact that power quality indices and actual requirements for the DC power have not been completely developed yet, thus the results extracted from this study could be used as a guideline to complete the on-going IEC DC power standards. Besides, dynamic impedance identification could assess the inverter-based power source behavior and power quality level when a new load is integrated. Furthermore, similar to the AC power system, the DC voltage also contains AC component of some specific frequencies because DC loads are composed of power electronic converters as well. So the impact of conducted disturbances on DC loads will be further studied by concrete DC distribution project already launched in China.

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