CHARACTERIZATION OF POWER QUALITY PERFORMANCE AT NETWORK BUSES USING UNIFIED POWER QUALITY INDEX

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ABSTRACT

Power Quality performance is a critical issue for both contemporary and future distribution networks operation and planning. DSOs started to pay significant attention to the levels of the PQ provided in their networks for many reasons, such as, the current deregulated electricity markets, increased DG penetration, regulatory frameworks and the increased numbers of sensitive loads to voltage variations. Although main PQ phenomena are well defined in international standards, there is no standard way to evaluate the PQ as a whole for a site or a network. This paper presents a methodology to comprehensively evaluate the PQ for a network considering both the suggested planned levels set by the utility and the expected different customers' PQ requirements. The suggested index is calculated using numerical consolidation of several separate indices. The considered phenomena in this paper, to demonstrate the methodology, are voltage harmonics, unbalance and flicker. The results are presented in a 295-bus Generic Distribution Network.

INTRODUCTION

The PQ performance can be considered an issue driven mainly by the customers' requirements. Utilities are trying to minimize their cost while respecting different customers' needs for certain level of PQ. The Council of European Energy Regulators (CEER) considers the assessment of the impact on customers as the main reason for monitoring and regulating PQ, "The ultimate aim of voltage quality regulation is to ensure that the functioning of equipment is not impacted by voltage disturbances coming from the network" as it is stated in [1].

Almost all main PQ phenomena are well defined in international standards. Indices for evaluating, methodologies for calculation and measuring the phenomena and other characterizing parameters are usually defined in these standards. For example, harmonic performance planning and compatibility levels are described in IEC 61000-3-6 and IEEE 519, the voltage unbalance calculations and emission limits are described in EN 50160 and IEC 61000-3-13, also the voltage flicker planning and compatibility levels can be found in IEC 61000-3-7 and IEC 61000-2-12. Nevertheless, there is no standard way to describe the overall PQ performance for a site or a network, furthermore, how to characterize the PQ performance, represent the results and quantifying the disturbances impact are still undergoing research areas.

Recent publications discuss unified PQ for bus characterization. Methods like Analytic hierarchy process (AHP), numerical consolidation and fuzzy logic were adopted. The methodology suggested in [2] for overall PQ evaluation compares the ideal waveform to the recorded waveform of the voltage and the RMS error is calculated and compared. The methodology is capable of capturing event-type disturbances like voltage sag and continuous-type disturbances like harmonics. Number of references also suggested the application of fuzzy systems for unified PQ evaluation [3-6]. The fuzzy system is an efficient tool when it comes to considering many uncertainties involved in the PQ evaluation and also the different weights (importance) of the different PQ phenomena in the overall evaluation. Also, a number of references adopted the AHP model for unified PQ evaluation [7-9]. The AHP model can be used to assign different priorities to different phenomena, for example based on the expected cost of each phenomenon/disturbance, the overall expected cost of PQ at the buses can be determined. This is a useful index especially for the network reinforcement planning purposes. References [10, 11] proposed a framework for unified PQ evaluation. The suggested index is calculated using multi-stage framework in which the recorded data for different PQ phenomena are compressed in each stage to give a single index describing the PQ. The compression can be performed either for time or space data, i.e. for data from long term measurements and then for the data from different sites and feeders. The unified index proposed is based on normalization and numerical consolidation, the normalization was based on the thresholds of the considered phenomena, and then the exceeding phenomena scores are consolidated in one index. The index is unity or below in case of no exceedances for all considered phenomena. Further improvement of the index proposed in [11] was presented in [12] where the concept of the 'distance' between performance levels and thresholds (PQ reserve) is suggested for the evaluation. The proposed methodology compares number of phenomena reserves, using equation (1) below where r represents PQ reserve, m represents the actual level of performance and g represents the adopted threshold.

$$r = 1 - {}^{m}\!/_{g} \qquad (1)$$

The index is calculated by taking the minimum reserve (in case of no exceedances) or the summation of the exceeding phenomena reserves (negative reserves) as the index to describe the site performance.

Building on the work presented in [11][12] an index based on the normalization and numerical consolidation of different PQ phenomena reserves is proposed in this paper. The methodology proposed here takes into account the perspectives of the utilities regarding the suggested accepted levels (planning levels) and the customers' perspectives regarding the variable required levels of performances (compatibility levels). By comparing the planning levels with spatially probabilistically varying compatibility levels, using heat maps, the areas of expected inadequate PQ can be pinpointed. The methodology is demonstrated on a case study of generic distribution network (295-bus) considering voltage harmonics, unbalance and flicker as the phenomena of interest.

METHODOLOGY

Framework

The general framework of the proposed methodology is shown in Fig. 1. The overall PQ index is calculated in three steps:

- PQ measurements/simulation: in this step the different PQ phenomena are analysed separately, by using the indices proposed in the standards. For each phenomenon, the indices are averaged over short periods (e.g. 10-min averages), then for a longer study period (e.g. a week) the 95th percentiles are taken as the measures of the phenomena, as suggested in the standards.
- PQ Evaluations and Bus Sensitivities: in this step the separate phenomena performances are compared to predefined thresholds, either from the standards or based on customers' requirements. Then, the different phenomena are weighted for the overall evaluation based on the utility's planning levels. The planning levels can be suggested based on the importance of the bus or the bus dominant equipment type, e.g. for induction motor dominant buses the most weighted phenomenon will be unbalance (customers' size). Or based on expected customers' financial losses (customers' sensitivity). Or it can be suggested based on expected disturbances (increase of DG or EV).
- Overall PQ evaluation: in this step the different phenomena performances are combined, considering different weights, to come up with a single index for the PQ performance. Different techniques are proposed for combining the indices, as summarized in the previous section. In this paper, the index is calculated using numerical consolidation.

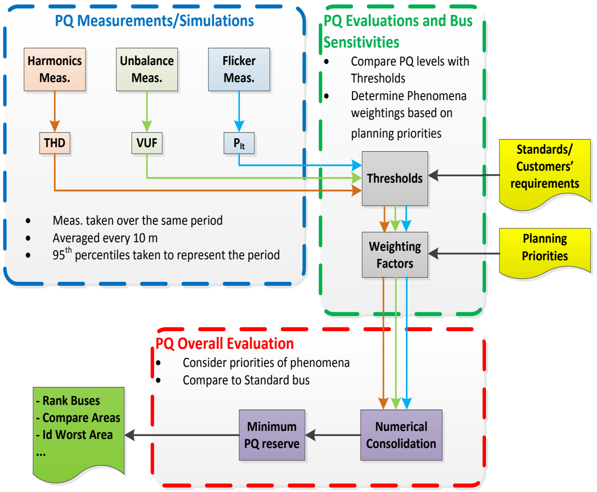


Fig. 1 Framework for PQ combined evaluation

Planning levels

The planning levels reflect the utility perspectives regarding the different PQ phenomena. They are usually less or equal to the compatibility levels. Planning levels are difficult to determine as they can vary from site to site based on the importance and sensitivity of the customers, therefore they are not usually suggested in standards (except for flicker). To illustrate the proposed methodology, the selected planning levels are uniform for all network buses and arbitrary selected to be 2.5% Total harmonic Distortion (THD), 1.6% Voltage unbalance Factor (VUF) and 0.7 p.u. Long term Flicker index (P_{lt}) for the harmonics, unbalance and flicker, respectively. These planning levels, when compared to standard compatibility levels, i.e., 5% THD, 2% VUF and 1 p.u. P_{lt} show the planned performance distance from thresholds, i.e. PQ reserves. By applying equation (1) (multiplied by 100%) the expected reserves for the considered phenomena are 40%, 25% and 30% for harmonics, unbalance and flicker respectively. These values reflect the importance of each phenomenon from the utility's perspective (harmonics are the most important phenomenon based on the adopted values). The ratios of these planned reserves to the total sum of reserves are adopted as weighting factors for the phenomena when evaluating the overall performance. This gives the following weighting factors w_{har}=0.5, w_{unb}=0.2 and w_{flk}=0.3 (*e.g* w_{har}*=50/50+20+30*).

Compatibility levels (Thresholds)

Due to the variations in the load sensitivities, the PQ compatibility levels may vary between different types of customers. Furthermore, although the suggested compatibility levels in the standards are usually adopted by equipment designers and manufacturers, there will be still uncertainties and variations in the equipment behavior in practical applications. For example, for the same equipment type, some can sustain normal operation beyond the threshold while others may trip or mal-operate under levels below the thresholds. Therefore, the compatibility levels are best described on probabilistic basis. In the proposed methodology, the compatibility levels (thresholds) were varied between different buses randomly, suggesting that loads have different requirements (spatial variation of thresholds). However, the assigned values were constant throughout the study period, without considering the uncertainty of the threshold itself or the temporal variation, for the sake of simplicity. For the harmonics and unbalance phenomena compatibility levels were sampled from normally distributed ranges with mean values at the suggested standard values, i.e., 5% THD (IEC 61000-3-6) and 2% VUF (EN 50160), as shown in Fig. 3. For the buses under evaluation the VUF compatibility levels ranged between 0.9% and 3.1% while the THD levels ranged between 3.1% and 6.6%. For the flicker, a uniform compatibility level was adopted, i.e. P_{lt} = 1.0 p.u. (EN 50160).

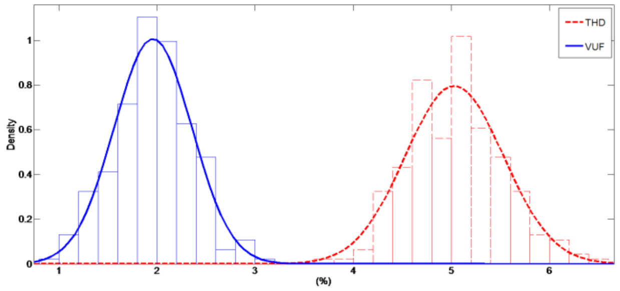


Fig. 3 Harmonics and unbalance compatibility levels (THD red/dashed, VUF blue/solid)

Calculating the index

Based on simulated results of PQ performance, and by applying equation (1), the reserve of each phenomenon is calculated, considering that the thresholds g_i in equ (1) vary at different buses. By comparing the calculated reserves for the considered phenomena, the overall PQ index is calculated, differently for each of the following two cases. In case of no exceedance (+ve reserves) the minimum reserve is selected as index for the PQ performance. In the case of –ve reserves, the index is calculated by taking the weighted average of the exceeding phenomena reserves, equation (2). The weighting factors are selected based on the planning reserves as mentioned above.

$$r_{overall} = \begin{cases} \min r_i & all\ r_i > 0 \\ \frac{\sum_i w_i \times r_i}{\sum w} & r_i < 0 \end{cases} \qquad (2)$$

Test network

The test network used in these studies is the 295 bus Generic Distribution Network (GDN), Fig. 2. The network parameters are based on realistic UK distribution network parameters [13, 14]. The network consists of 295 buses, 276 branches (overhead lines and cables), and 37 transformers with various winding connections. The network comprises five 400 kV buses, and four 275 kV buses (transmission level connection points) a sub-transmission level of twenty-three 132 kV buses and twenty-five 33 kV buses, and a distribution level of 231 buses of 11kV level and four 0.4kV buses. Detailed description and parameters of the network can be found on [15]. Three types of loads are modelled in the network; domestic, commercial and industrial. Also, three types of DG are modelled; fuel cells, photovoltaics (inverter interfaced) and wind turbines (DFIG based), with maximum penetration not exceeding 30% of the feeder load throughout the year. The PQ evaluation of the test network was performed at 16 representative hours during the year. At each hour a random group of disturbing loads were selected. The selection of the hours was based on load clustering and some extreme cases, e.g. industrial peak load, maximum DG outputs, maximum PV outputs, etc. The evaluation was performed for the 11 kV level only (231 bus, blue shaded area in Fig. 2) to make the illustration of results simpler.

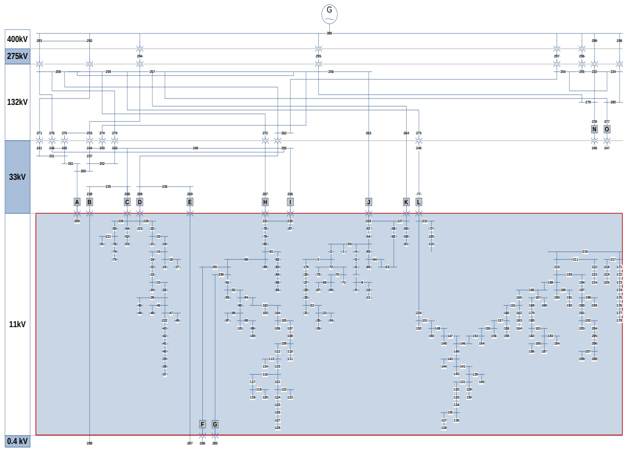


Fig. 2 Test network

RESULTS AND ANALYSIS

Heat maps were used to present the results of the methodology. Fig. 4 shows a heat map that identifies the sensitive buses, i.e., the buses where performance at the planning levels will not be adequate for certain phenomena. The map was plotted by applying the proposed methodology (minimum reserve as index) under the assumption of uniform performance (equal to planning levels) for all considered phenomena at all buses. As it can be seen from the figure some 'pockets' of negative reserves are dispersed all over the network, due to the randomness of the selected variable thresholds.

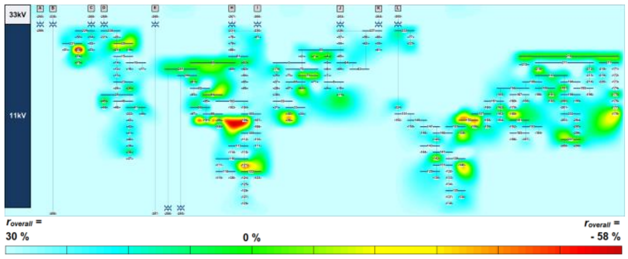
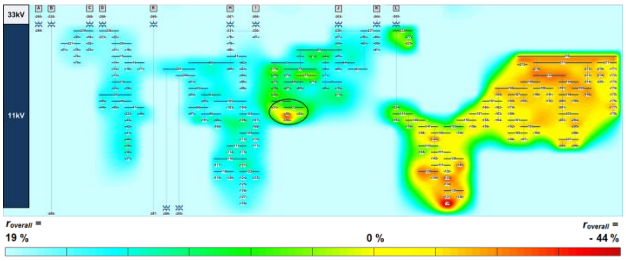
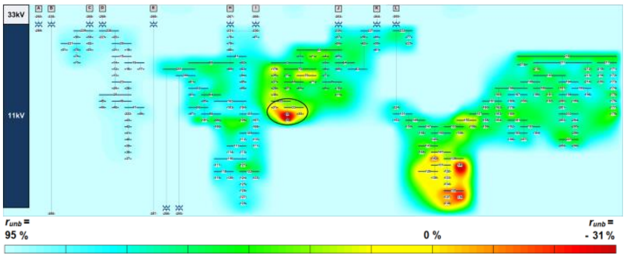


Fig. 4 Sensitive buses

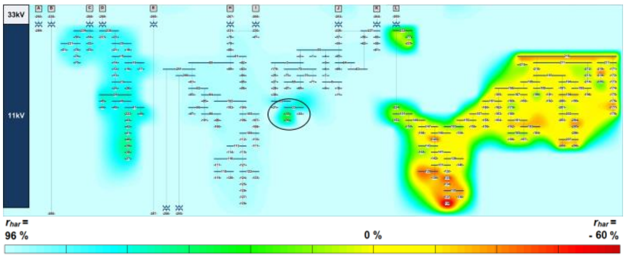
Fig. 5 (a), (b) and (c) show the overall PQ, unbalance and harmonic performances respectively. It can be clearly seen that the overall performance follows the trend of the harmonic performance, as a result of high weight of the phenomenon. Furthermore, the circled group of buses shows good example of the performance of the index, and its capability of considering both utility and the customers' perspectives. Due to high weight of the harmonics but relatively good performance, and the low weight of unbalance but very poor performance and high customers' requirements (buses B_35 and B_36, see Tab 1 (a)), the average overall index was recorded in the yellow zone. While some buses with moderate unbalance performance when averaged with good harmonic performing areas were totally masked and pushed up to the green areas, i.e., acceptable overall PQ performance.



(a) Overall PQ performance



(b) Unbalance performance



(c) Harmonic performance

Fig. 5 Heat maps for unified and separate PQ performance (Note: The heat bars have different ranges and color for 0% reserve)

Tab. 1 Worst performing buses

(a) Separate Evaluation

Harmonics		Flicker		Unbalance	
Bus	r_{har}	**Bus**	r_{flk}	**Bus**	r_{unb}
B_138	-0.6	B_193	-0.33	B_140	-0.31
B_133	-0.38	B_210	0.3	B_35	-0.27
B_145	-0.36	B_195	-0.27	B_36	-0.22
B_129	-0.31	B_196	-0.27	B_136	-0.21
B_137	-0.27	B_194	-0.27	B_135	-0.1

(b) Overall Evaluation

	Harmonics			Flicker		
	THD	**Comp.**	r_{har}	P_{lt}	**Comp.**	r_{flk}
B_138	7.133	4.4	-0.604	0.303	1	0.697
B_135	6.608	5.3	-0.256	0.335	1	0.665
B_219	5.294	4.2	-0.260	1.119	1	-0.119
B_136	6.616	5.5	-0.198	0.335	1	0.665
B_193	5.221	4.7	-0.119	1.335	1	-0.335

	Unbalance			Overall PQ $r_{overall}$ (weighted average)
	VUF	**Comp.**	r_{unb}	
B_138	2.166	2.1	-0.034	-0.4413
B_135	2.05	1.9	-0.1	-0.2113
B_219	0.707	2.0	0.651	-0.2074
B_136	2.081	1.7	-0.214	-0.2027
B_193	0.706	1.6	0.551	-0.2003

Numerical results are shown in Tab 1 (a) and (b). The worst performing buses with the recorded reserves (in p.u.) are ranked when evaluated separately and overall. In the overall ranking, Bus 219 appeared third worst, although it has not been recorded as one of the worst performing buses in the separate evaluation. This is due to its average performance in the two important phenomena, harmonics and flicker.

The main application of the index is the comparison between buses and areas based on the overall PQ performance considering different phenomena with different levels of importance from the utility's and customers' perspectives, sometimes conflicting perspectives. The utility might be interested in planning high reserves for certain phenomena to meet expected levels of disturbances, e.g., having high reserves on harmonics and unbalance will allow higher penetration of single phase, converter based DG units without standards violations. On the other hand, the sensitive equipment at end user facilities determines the customers' perspectives. Due to averaging and weighting the index does not describe the exact reserve level of the worst phenomenon at individual buses and cannot be used for this purpose.

Another application of the unified index is the optimization of PQ solution. The selection of a single index to optimize PQ performance in the network will significantly reduce the complexity of the optimization problem. Also, by pinpointing the areas where higher PQ requirements coincide with poor PQ performance, the reinforcement optimization problem size can be reduced. Fig. 6 shows a comparison between the sensitive areas map (Fig. 4) and the overall performance map (Fig. 5-a), indicating the areas which most probably will suffer from PQ disturbances.

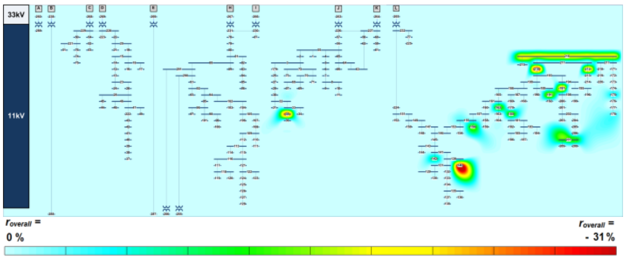


Fig. 6 Sensitivity and poor PQ overlapped areas

CONCLUSIONS

The paper presents a methodology to evaluate the overall PQ at a site or a bus, using single index, for the purpose of benchmarking and network reinforcement planning. The index is calculated based on the concept of PQ reserves, and it considers different level of importance of different phenomena in the evaluation, based on utilities' and customers' perspectives, trying to find the balance between both parties' requirements in the overall calculated index. The index considers the expected variable PQ requirements between different customers in different areas of the network. These PQ requirements may also vary with time. The temporal variation can be easily captured by the proposed methodology and such further enhance its applicability to PQ evaluation in future power networks with spatial and temporal variation of generation and loads. .

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