Compound index for power quality evaluation and benchmarking

DOI:
10.1049/iet-gtd.2018.5391

Document Version
Accepted author manuscript

Citation for published version (APA):
Milanovi, J. V., Abdelrahman, S., & Liao, H. (2018). Compound index for power quality evaluation and benchmarking. *IET Generation, Transmission & Distribution*, *12*(19), 4269-4275. https://doi.org/10.1049/iet-gtd.2018.5391

Published in:
IET Generation, Transmission & Distribution

ACCEPTED VERSION OF THE PAPER

Compound Index for Power Quality Evaluation and Benchmarking

Jovica V. Milanović [1*], Sami Abdelrahman [2], Huilian Liao [3]

[1] School of Electrical and Electronic Engineering, The University of Manchester, Manchester, M13 9PL, UK
[2] National Grid, Warwick, CV34 6DA, UK
[3] Power, Electrical and Control Engineering Group, Sheffield Hallam University, Sheffield, S1 1WB, UK
[*] milanovic@ manchester.ac.uk

Abstract: High level of delivered Power Quality (PQ) is becoming one of the key performance indicators for both contemporary and future power networks. The increased proliferation of converter connected generation and load in power networks, increased sensitivity to network disturbances of some of these new types of devices and requirements for more flexible operation of power networks led to the revision of some of PQ standards and introduction of modified or in some cases new requirements for PQ compliance. Although almost all PQ phenomena, with exception of voltage transients, are well defined and appropriate thresholds for individual phenomena are set in international standards, there is no standardized nor commonly accepted way to describe and evaluate the overall PQ performance at buses. This paper presents an analytic hierarchy process (AHP) inspired methodology for assessing the overall PQ performance at a bus based on several different PQ phenomena considered simultaneously. Compound Bus PQ Index (CBPQI) is defined using AHP to present the overall PQ performance at the bus with respect to voltage sag, harmonics and voltage unbalance. The application of the methodology is illustrated on a 295 bus generic distribution network.

1. Introduction

Since the late 1980s different voltage and current disturbances and variations, previously dealt with separately and under different names, were brought together under the common name Power Quality (PQ). PQ has become one of the most talked about and analysed performance indicator of power networks. Even though the common name PQ existed different phenomena continued to be addressed individually by the utilities and customers. Many customers, ones having very sensitive industrial processes in particular, tried to tackle the disturbances they were exposed to locally without much interest in how their equipment or solutions impact the system [1].

More recently, an agreement, at least in principle, among all the parties involved, from the producers and suppliers of electricity to the end users, seems to be that the PQ in general can be addressed using system level approaches rather than individual solutions. Nevertheless PQ is still considered as a consumer-driven issue, and the main concerns are the compatibility between the customers' equipment and PQ disturbances originating in the network. The compatibility levels defined in international standards serve as a guideline for the network operators to deliver PQ below these limits, and for the equipment producer to ensure immunity limits higher than these levels.

In spite of all the past work and efforts in this area, there is still no standard way to describe the performance of a bus or a network in terms of overall PQ performance. Since different parts of the network exhibit different types and levels of PQ disturbances and have different customers (with equipment having different immunity levels) connected to it, the process of comprehensive PQ evaluation is challenging. The ability to assess global PQ performance of the bus/network, however, would not only help with benchmarking studies but would also greatly contribute to development of cost effective PQ mitigating solutions.

2. Global PQ indices

Since early 2000s several publications addressed the issue of unified PQ assessment and proposed various mathematical models. One of the earliest publication discussing the global PQ index is [2], which presents a computationally demanding methodology based on calculation of the missing RMS voltage throughout a study period using time domain analysis. Then the calculated RMS error (RMSE) is used as an index to compare different PQ solutions.

With the increasing amount of the monitoring data in modern networks [3], data mining approach was suggested in [4] for structuring and classifying the recorded data before calculating a global PQ index. A multi-level structured framework for PQ data analysis involving time and space compression was proposed in [5, 6]. In the time compression stage of this framework the raw recorded data are first classified, normalized and numerically consolidated into single number/index for each disturbance. The unification of the consolidated indices is then performed based on the exceedance of the specified thresholds. The space compression is performed by the weighted averaging/summation of the unified index for a number of locations, e.g. sites, feeders, substations, or parts of the network [5].

A global PQ index is proposed in [7] based on the available "reserve" for a PQ phenomenon at a certain bus. The consolidation of this methodology was performed by taking the minimum reserve as the bus overall score in case of no PQ limits violation, or taking the sum of negative reserves in case of PQ limits violations. Recent applications of similar, global PQ indices using real life PQ monitoring data can be found in [8, 9]. An illustration of distribution network PQ performance using global PQ index is given in [8]. A commercial PQ management system installed in German industrial park that reports continuously the global

PQ index to the system operator is presented in [9]. A number of suggested global PQ indices are based on application of fuzzy logic [10-11]. A power-quality index is proposed to calculate weighted sum of the effects of voltage unbalance and harmonic distortions in [12]. In [13], a quantitative global index was proposed from the perspective of pricing in competitive electricity market using artificial neural network (ANN) and fuzzy logic. In [14], a unified power quality index is proposed by converting all PQ interruptions to their financial cost and using the overall cost as the global PQ index. References [15-16] presented two methodologies to evaluate the overall PQ performance, considering the costs of the disturbances in the evaluation. Reference [17] introduced a new application of the PQ global indices to study the variation in PQ due to the connection of distributed generation (DG).

It is inevitable to lose some information while describing different phenomena using a single index and even describing a single phenomenon using a single index will introduce some level of ambiguity [18]. However, considering global drive towards standardised measurements in power networks and increasing availability of measurement data, global PQ indices will provide useful and efficient tool for benchmarking network performance and identification of sub-standard performing parts of the network that could guide decision making about network maintenance and investment in network.

This paper presents a new flexible methodology to evaluate and illustrate the overall PQ performance of the network.

1) The Analytic Hierarchy Process (AHP) based approach, an approach which has been widely used for multi criteria decision making, is proposed to evaluate and enumerate different aspects of individual PQ phenomenon as well as overall bus performance with respect to multiple PQ phenomena at the same time. This allows easy comparison and identification of poorly performing areas of the network either with respect to standard set thresholds or based on customer's process sensitivity to PQ phenomena. This approach allows different thresholds to be set spatially for different PQ phenomena in the network and the introduction of differentiated PQ delivery based on needs and requirements of the end users.

2) For this purpose, a new index, Compound Bus PQ index (CBPQI), is proposed to enumerate the overall PQ performance of the bus. The proposed compound index has added flexibility to consider different levels of detail, depending on the network operator or end user needs, in the overall PQ evaluation as well as evaluation of single PQ phenomenon.

The application of the proposed CBPQI is illustrated on a generic 295-bus distribution network focusing on simultaneous global evaluation of network performance with respect to three critical PQ phenomena namely, voltage sags, harmonics and voltage unbalance.

3. CBPQI via analytic hierarchy process

Analytic Hierarchy Process (AHP) is one of the common mathematical models for multi criteria decision making problems. It solves the problem of selecting a goal from a number of alternatives based on a number of selecting criteria. Different selection criteria will have different weights on the final decision. Also, each selecting criterion can have a number of sub-criteria, which again can have different weights in the main selecting criterion. Based on the different weights, each criterion has a different priority on the final decision. The alternatives have different scores for each selecting criteria, then based on the criteria relative priorities the final score will be given to the alternatives and the final decision will be made. Further details and mathematical modelling can be found in [19].

3.1. Harmonics

The evaluation of the harmonic performance of the bus is based on the total voltage harmonic distortion (THD) and the harmonic distortion based on individual voltages V_h. Monte Carlo harmonic load flow was performed taking samples of the harmonic voltages every 100 cycles (instead of every 10 cycles as recommended by the standards, to reduce the computational burden) and averaged every 10 minutes to calculate $V_{h,}$ [20]. One year was taken as the evaluation period considering hourly load variation, hence different harmonic injection every hour. The 95th percentiles of the worst phase V_h and THD were taken as the harmonic evaluation indices and the IEEE 519-2014 harmonics limits were taken as the thresholds (3% for individual harmonic voltages, 5% for THD at the 11 kV level) [21]. The harmonic injections used for illustrations in the paper are based on measurements at the LV commercial loads comprising personal computers, TV sets, fluorescent lamps etc. and dominated by the 3rd, 5th, 7th and 9th harmonic currents as reported in [22] and broadly, qualitatively, illustrated in Fig. 1.

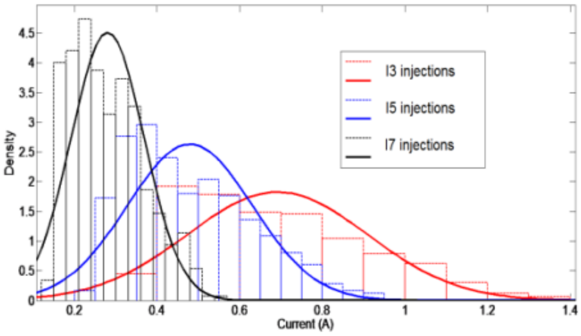

Fig. 1. *Example of harmonic current injection ranges*

3.2. Voltage Unbalance

The voltage unbalance is simulated by modelling buses with unequal apparent power in each phase, either by having single phase real power injections from DG, or unequal reactive power consumptions for selected loads. Monte Carlo simulation based three phase load flow was performed for the same evaluating hours as in the harmonic evaluation and the positive and negative sequence of voltages were calculated for each bus. Following this the 95th percentile of the voltage unbalance factor VUF, given by (1), was taken as the evaluation index.

$$VUF = \frac{V_2}{V_1} \times 100\,\%, \tag{2}$$

where V_2 and V_1 are the negative and positive sequences voltages respectively. VUF threshold of 2% was adopted as recommended by EN 50160 [23]. Further details about unbalance modelling and simulation can be found in [24].

3.3. Voltage Sag

The voltage sag performance of a bus is based on the number of sag events it experiences during the year, and the severity of each event. The severity evaluation is based on sag magnitude and duration in comparison with thresholds defined by SEMI F47 curve. The uncertainty of the sag severity is introduced to the evaluation by considering probabilistic SEMI F47 curve, as shown in Fig. 2, and sag severity index, bus performance index (BPI), was calculated probabilistically for all sags recorded at a bus. BPI is calculated by the sum of the severity for all recorded sag events at the bus, divided by a constant coefficient. The sags at each bus are calculated by simulating different types of faults at all network buses considering historical data about fault types and fault rates. In the study, the threshold for the BPI was set based on the worst performing bus. The threshold fault statistics provided in [25] was used and the critical operating condition was adopted for assessing the BPI throughout the study period. Further details about calculation of BPI can be found in [25].

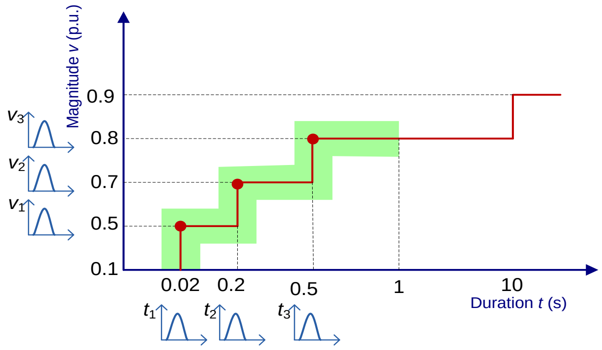

Fig. 2. Probabilistic SEMI F47 curve thresholds adopted from [24].

3.4. Development of CBPQI by applying AHP

The AHP structure for calculating CBPQI is shown in Fig. 3. The CBPQI calculation is based on a comparison of PQ performance at bus *i*, denoted as $PQ_i=\{VUF_i, Har_i, BPI_i\}$ (performance indices evaluated for unbalance, harmonics and sag respectively) and the PQ performance reference/thresholds $PQ_{Ref}=\{VUF_{thr}, Har_{thr}, BPI_{thr}\}$ (thresholds for the three PQ phenomena respectively) in the alternative level. The comparison is performed using pair-wise comparison matrix for each phenomenon, and taking the principle eigenvector as the score. Table 1 shows the construction of the comparison matrix for the unbalance, where $Score_i$ and $Score_{Thr}$ are the measures of how 'far' (above or below) performance PQ_i at bus *i* is from the threshold. If actual PQ performance is the same as the threshold levels, $Score_i$ and $Score_{Thr}$ are both equal to 0.5, while in case of limit violation $Score_i$ will be greater than $Score_{Thr}$. In this way, the critical states derived from the thresholds specified by standards, or user requirements, are included in the evaluation and contribute to the final comparative scores. It is believed that the inclusion of standard specified thresholds in PQ evaluation is essential to keep the methodology as relevant to industrial practice as possible.

The score calculated in the first step for each phenomenon at the bus will be multiplied by the priority of the phenomenon from the criteria level. In the criteria level, the priority of each phenomenon is calculated based on weighting factors assigned to each phenomenon. Again, the different phenomenon priorities are calculated from the principle eigenvector of the pair-wise comparison matrix. Table 2 shows the comparison of priorities where w_{sag}, w_{har} and w_{unb} are the weighting factors of the voltage sag, harmonics and unbalance respectively.

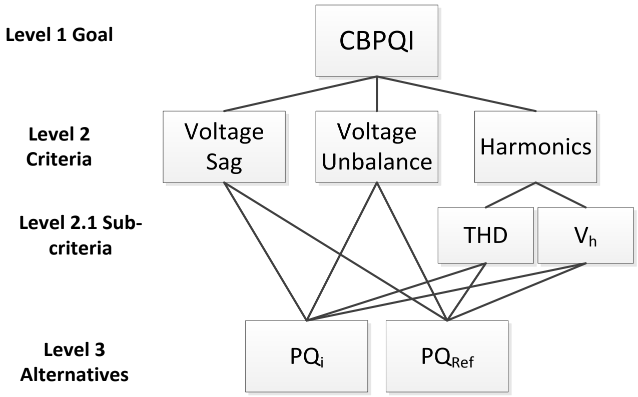

Fig. 3. AHP model for calculating CBPQI.

Table 1 Comparison of alternatives using comparison matrix

Sag			
	Actual perfor.	Thresholds	Eigenvector
Actual perfor.	1	BPI_i / BPI_{Thr}	**$Score_{i,1}$**
Thresholds	BPI_{Thr} / BPI_i	1	**$Score_{Thr,1}$**
Harmonics			
	Actual perfor.	Thresholds	Eigenvector
Actual perfor.	1	HAR_i / HAR_{Thr}	**$Score_{i,2}$**
Thresholds	HAR_{Thr} / HAR_i	1	**$Score_{Thr,2}$**
Unbalance			
	Actual perfor.	Thresholds	Eigenvector
Actual perfor.	1	VUF_i / VUF_{Thr}	**$Score_{i,3}$**
Thresholds	VUF_{Thr} / VUF_i	1	**$Score_{Thr,3}$**

Table 2 Comparison of priorities using comparison matrix

	Sag	Harmonics	Unbalance	Priorities (Eigenvector)
Sag	1	w_{sag}/w_{har}	w_{sag}/w_{unb}	***Pri_1***
Harmonics	w_{har}/w_{sag}	1	w_{har}/w_{unb}	***Pri_2***
Unbalance	w_{unb}/w_{sag}	w_{unb}/w_{har}	1	***Pri3***

The total score for PQ_i at Bus *i* is calculated as the sum of the multiplications of the scores of the bus in each criterion by the priorities of the phenomenon, i.e., $\sum_{n=1}^{N} score_{i,n} \times pri_n$. With the same approach, the score for PQ_{Ref} can be estimated by $\sum_{n=1}^{N} score_{Thr,n} \times pri_n$. Then, the $CBPQI_i$ is calculated by comparing the score of actual PQ_i to the score of reference PQ_{Ref}, as shown in (2) where *N* is the total number of considered phenomena.

$$CBPQI_i = \frac{\sum_{n=1}^{N} score_{i,n} \times pri_n}{\sum_{n=1}^{N} score_{Thr,n} \times pri_n} \tag{2}$$

In (2), if one of the phenomena has sub-criteria levels, the corresponding scores (i.e., $\text{score}_{\text{i},n}$ and $\text{score}_{\text{Thr},n}$) will be calculated by combining the sub-criterion scores weighted by the sub-priorities, which can be obtained using the same procedure that calculates the total scores for PQ_i and PQ_{Ref}. Taking Harmonics as example, at the sub-criteria level, different weights are assigned to different sub-criteria. For example, the different harmonic voltage characteristics (e.g. negative/positive sequence, high/low frequencies, near/far from resonance, crest factor, zero-crossings) will have different impact on the sensitive loads, even if they have equal THD [18]. Therefore, if two buses have similar THD, but one of them, for example, contains harmonic orders close to the system resonance frequencies, it should be ranked as more critical in terms of harmonic performance as it is more likely to have more severe impact. Similarly different weights can be considered for other harmonic indices that are more relative to certain load, e.g. zero crossing for electronic clocks and contactors, the Crest Factor ($V_{\text{peak}}/V_{\text{rms}}$) for considering the impact on insulation or Voltage Telephone Interference Factor for the impact on telecommunication equipment [1, 21]. Table 3 shows an example of calculation of the sub-priorities for harmonics. After obtaining the scores and the sub-priority for each sub-criteria, the overall score (weighting) of the harmonics can be calculated in (3) by integrating the sub-criteria THD, V5 and V7. The same way can be used to calculate the $\text{Score}_{\text{Thr},2}$. Then the $\text{Score}_{i,2}$ and $\text{Score}_{\text{Thr},2}$ can be used in (2) as harmonic scores in order to calculate the overall performance CBPQI.

$$\text{Score}_{\text{i},2} = (score_i^{THD} \times subpriority_{THD} + score_i^{V5} \times subpriority_{V5} + score_i^{V7} \times subpriority_{V7}) \qquad (3)$$

Table 3 Comparison of sub-priorities using comparison matrix

	THD	V_5	V_7	Eigenvector
THD	1	w_{THD}/w_{V5}	w_{THD}/w_{V7}	$subpriority_{\text{THD}}$
V_5	w_{V5}/w_{THD}	1	w_{V5}/w_{V7}	$subpriority_{\text{V5}}$
V_7	w_{V7}/w_{THD}	w_{V7}/w_{V5}	1	$subpriority_{\text{V7}}$

For conventional AHP methodology, the scores calculated by $\sum_{n=1}^{N} score_{i,n} \times pri_n$ are taken as the final results and used to compare PQ performance among different buses/alternatives, which is acceptable if only one set of thresholds is used as the reference for all alternatives. However, if the critical thresholds are set to different values based on spatial requirements, conventional AHP methodology will be insufficient. Equation (2) provides a way to solve this issue. It incorporates the comparative results of two states, i.e. critical state and standard state, into one numerical index which represents how good the actual PQ performance is compared to the corresponding critical state that is obtained from the thresholds specified by standards or user requirements locally.

The CBPQI is primarily intended for ranking purposes considering global PQ performance (i.e., identifying weak areas of the network) and is based on weighted averaging of different indices. In some cases therefore it could mask violation of particular threshold by a certain phenomenon that was originally assigned with low weight. If the exceedance of thresholds however, is to be given higher priority rather than average performance, higher weights can be assigned to exceeding phenomena in the calculations. This will ensure CBPQI>1 for any exceedance of threshold.

The framework for the overall methodology is summarized in Fig. 4. As shown in the figure, designated PQ thresholds at certain buses can be used as inputs to the model in lieu of the standards compatibility levels. This is to consider the types of customers for which the common compatibility levels specified in standards are not adequate due to their highly sensitive equipment/processes which would still underperform in spite of bus meeting standard specified PQ thresholds for different phenomena. The economic losses incurred by these customers, for example, could be used to inform setting of weighting factors for different phenomena when calculating the compound index.

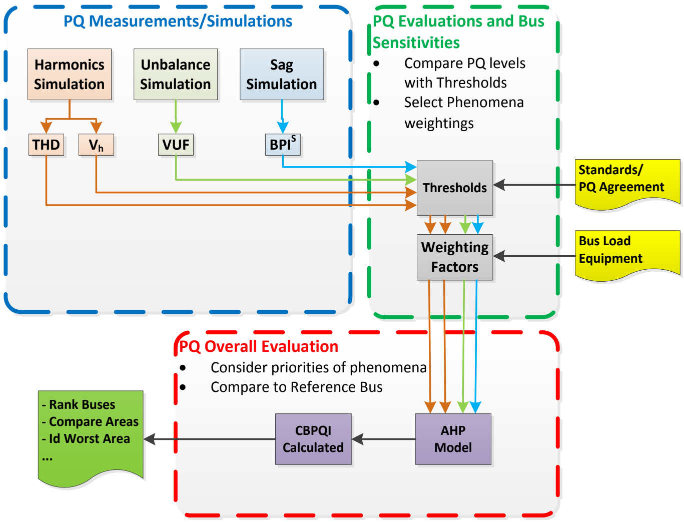

Fig.4. *General frame work for overall PQ evaluation*

3.5. Comparison with other Global Indices

The proposed index CBPQI is compared with several other recently proposed global PQ indices. In this paper, due to space limitation, only the comparison with the unified power-quality index (UPQI) [17] and combined PQ index (CPQI) [12] is presented. Further comparison with the most recently proposed global PQ index is available in [26] and [27]. For all three indices, compared here, higher PQ index suggests worse PQ performance. For comparison, assume that the threshold and PQ index for each phenomenon are given in Table 4. It can be seen that in Scenario 1 BPI exceeds its threshold by 1 while HAR and VUF are the same as their thresholds; in Scenario 2 HAR exceeds its threshold by 1, while other two PQ indices are the same as their thresholds. However, when comparing the exceedance against the thresholds, it can be seen that in Scenario 1 BPI exceeds its threshold by $\frac{2-1}{1}\% = 100\%$, and HAR exceeds its threshold by $\frac{1.5-0.5}{0.5}\% = 200\%$. Assume now that the three PQ phenomena are of the same importance in the global index. It is obvious that Scenario 2 has worse PQ performance than Scenario 1, and it is expected that the global index obtained from Scenario 2 is higher than that in Scenario 1.

Table 4: Thresholds and PQ indices for individual PQ phenomenon

PQ index	Thresholds	Scenario 1	Scenario 2
BPI	1	2	1
HAR	0.5	0.5	1.5
VUF	1.5	1.5	1.5

With the assumption given above (i.e., same importance among various PQ phenomena), the same weights (for simplicity weight 1 is used) are assigned to various phenomena in calculating CBPQI and CPQI, as these two indices require weights. As for UPQI, weights are not required, but it needs the possible maximum index value for individual PQ phenomenon (due to normalization). For UPQI, two sets of maximum individual PQ indices are used, $MI_1=\{2.5, 5, 2\}$, where 2.5, 5 and 2 are the maximum possible BPI, HAR and VUF obtained in the network respectively, and $MI_2=\{5, 2.5, 2\}$. The PQ evaluation results are given in Table 5. It can be seen that CBPQI evaluates the global PQ performance accurately as expected, i.e., PQ performance in Scenario 2 (CBPQI=1.4) is worse than that in Scenario 1 (CBPQI=1.2501). As for UBPQI, its PQ evaluation is highly dependent on the settings of maximum possible individual PQ indices. Between the two different sets of maximum PQ indices, UPQI provides completely the opposite results. It can be seen from Table 5 that UPQI with setting MI_1 yields 1.4 and 1.2 for Scenarios 1 and 2 respectively, while UPQI with MI_2 generates the reverse results. As for CPQI, it does not take into account the thresholds, and the global indices obtained from both scenarios are the same, i.e., 4. It suggests that CPQI cannot distinguish the PQ performance between these two scenarios.

Table 5 The global PQ evaluation obtained with different indices

	CBPQI	UPQI with MI_1	UPQI with MI_2	CPQI
Scenario 1	1.2501	1.4	1.2	4
Scenario 2	1.4	1.2	1.4	4

4. Case study and results

4.1. Test System

The test network used to illustrate the proposed approach is the 295 bus Generic Distribution Network (GDN). The network parameters and topology are based on realistic UK distribution network [28, 29]. Detailed description and parameters of the network can be found on [30]. Three types of loads are modelled in the network (domestic, commercial and industrial) and three types of Distributed Generators (fuel cells, photovoltaic and three phase DFIG based wind turbines), with maximum penetration not exceeding 30% of the total load at the feeder throughout the year. The whole system is three phase balanced system, except for some DG units which are connected via single phase 4-pulse PWM inverters, and a number of selected unbalanced loads (three phase loads with unequal apparent power consumption per phase).

The annual PQ evaluation of the test network was performed for 16 representing hours during the year, the selection of the hours was based on load clustering and some extreme cases, e.g. peak load, industrial peak load, maximum DG outputs, maximum PV outputs and maximum wind generation output. For the illustration of the methodology, the 95th percentiles of the considered PQ indices throughout the year were adopted as relevant measure in the paper. It is recommended though to perform studies over shorter periods of time (e.g. weeks or seasonal) to facilitate continuous PQ assessment in the network. The evaluation was performed for the 11 kV level.

4.2. Harmonic Evaluation

The harmonic injections were sampled from normally distributed injection ranges (Fig. 1). Injection ranges of ±20% of the averages covering 3σ were adopted based on average injection values adopted from [31-33]. Different types of composite load injections based on measurements reported in [31] are used. The DFIG type wind turbines injections were adopted from [32] and the inverters injections for the commercial inverters were adopted from [33]. Based on these reported harmonic injections, harmonic load flow studies were performed in the network considering all harmonics up to the 13th harmonic.

Monte Carlo simulations were performed and the 95th percentile of the voltage *THD* was recorded considering results for all simulation hours of the study period. In the study the sub-criteria level for the harmonics was not used to simplify illustration of the methodology. Fig. 5(a) shows a heat map of the *THD* performance of the buses under evaluation, with the calculated 95th percentiles *THD* values, for all simulation hours, ranging from 0.21% to 7.13%.

4.3. Unbalance Evaluation

The unbalanced sources in the network are the single phase connected DG units (PV and fuel cells) and a number of three phase loads with unequal apparent power injections per phase. The unbalanced loads have three ranges of power factors with average values of 0.8, 0.95 and 1. Normally distributed ranges of ±20% covering 3σ around the average power factor of each phase of the load were adopted (no leading power factors were considered at this stage and in case of unity power factor only -20% range was adopted). The load unbalance is created by varying the reactive power only in accordance with the sampled power factor. The unbalance performance of the buses under study is shown by the heat map in Fig. 5(b), where the 95th percentile of VUF, for all simulation hours of the study period, ranged between 0.12% and 2.17%. The adopted methodology and its validation against measured unbalance levels are presented and discussed in [23].

4.4. Sag Evaluation

The sag evaluation was based on all possible fault locations in the network using DIgSILENT sag table calculation function, with the assumption that protective actions are coordinated by two types of protective relays, i.e. primary and backup protection systems. The fault rates and fault statistics are shown in Table 6. The severity of each sag is calculated based on probabilistic SEMI F47 curves (Fig. 2) and the bus sag performance is calculated based on the severity of recorded sags at the bus. The sag bus performance index BPI ranged from 0.1 p.u. to 2.7 p.u. In the study, the threshold for sag performance is set to BPI_{Thr}=3 p.u., which is subject to modification and here it is chosen based on the worst bus performance when critical operating condition is applied, as discussed in Section 3.3. The voltage sag was selected as the most important phenomenon (highest weights in the AHP model). Selecting the same sag performance threshold at all the buses helps to analyse the representativeness of the CBPQI when the very influential PQ phenomenon is well performing and less influential phenomena violates the limits. Fig. 5(c) shows the sag performance of the network.

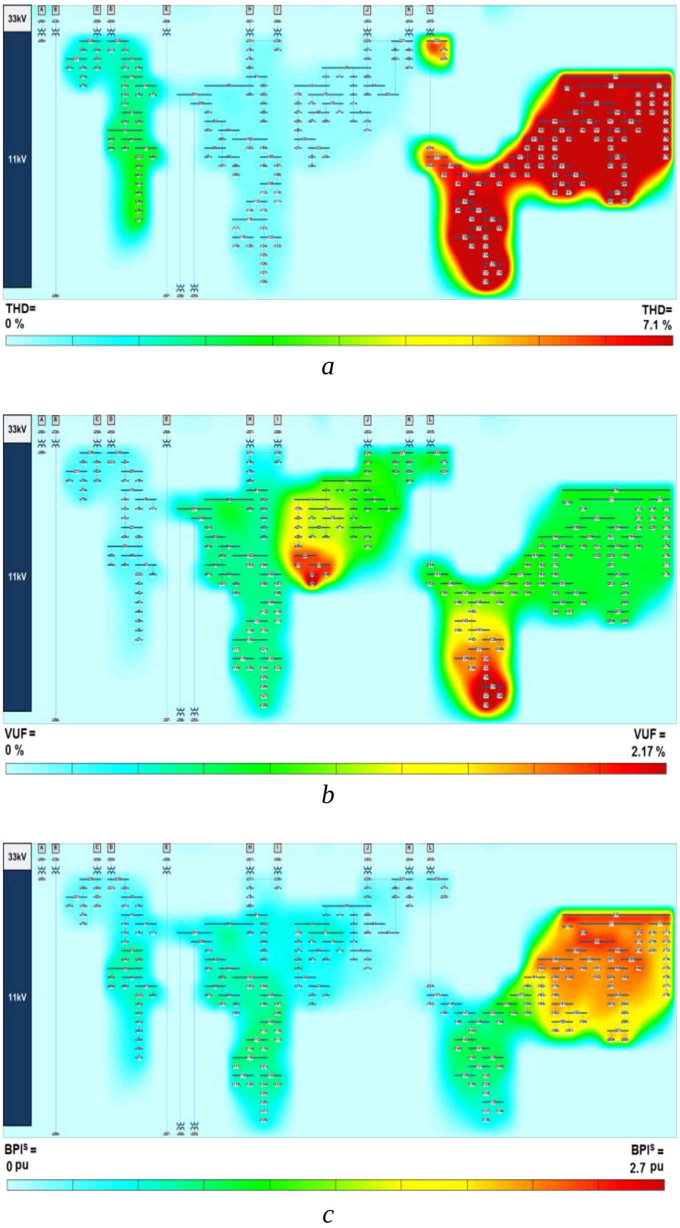

Fig. 5. *Performance for individual PQ phenomenon*
(a) The harmonic performance, **(b)** The unbalance performance, **(c)** The sag performance

Table 6 Fault rates and distribution of fault types

	Buses	Overhead lines	Cables
Fault rate (/year)	0.08	8.699	4.9
Single phase to ground (%)	73	73	73
Double phase to ground (%)	17	17	17
Phase to phase fault (%)	6	6	6
Three phase fault (%)	4	4	4

4.5. Overall PQ Evaluation

The overall PQ performance of each bus is based on calculation of CBPQI of the bus following methodology illustrated in Fig. 3. The weights for three different phenomena considered were sampled from uniformly distributed ranges. These ranges are overlapped to cater for the different sensitivities to different phenomena at different times for the bus. Five hundred Monte Carlo simulations are performed to calculate the CBPQI by sampling different weights from the pre-defined ranges and applying the AHP model. The input to the AHP model (Fig. 4) are the 95th percentiles values of THD, VUF and BPI from annual performances calculated by separate probabilistic evaluation for each phenomenon. The probability density function of the CBPQI is obtained by the Monte Carlo simulations and the most probable value is taken as the final CBPQI. The calculated CBPQI for the buses under evaluation ranged from 0.07 p.u. to 0.76 p.u., Fig. 6.

The weight ranges for different phenomena were selected arbitrarily to illustrate the methodology and to have the sags as the most important (weights 15-20), harmonics second most important (weights 10-15) and the unbalance the least important (weights 6–10). In practical applications the immunity levels of different loads connected to different buses to different phenomena should be considered to determine the relative thresholds of the phenomena for the bus. The selection/assignment of the possible sets of weights to different phenomena can be obtained by either surveys or PQ loss analysis: 1) Surveys in the format of questionnaires can be given to experts (or engineers), and the experts' opinion or the operator's experience about relative importance of different phenomena in general or at specific location can be used to determine possible sets of weights; 2) The selection of weights can be obtained by assessing PQ losses (technical or economical) caused by different phenomena at different location, and the ratio of financial cost or sensitive loads can be used as reference to determine the weights. To address the possibility of having multiple sets of weights obtained from different sources, Monte Carlo simulations for selections of weights from different ranges are adopted in the study to cater for the uncertainty and temporal variation of the types of sensitive loads connected at the bus throughout the study period.

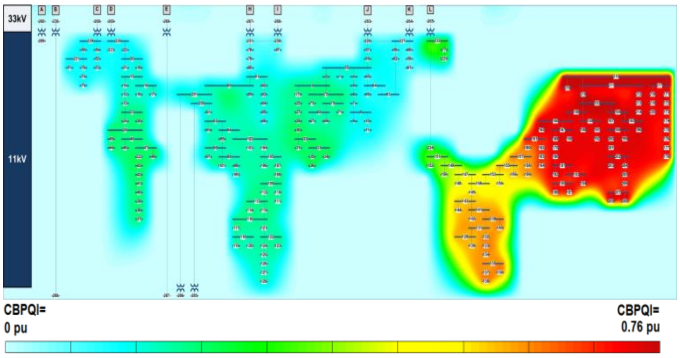

Fig. 6. *Overall PQ performance based on CBPQI*

The CBPQI, calculated in this way, is an approximate measure of how close are the relevant PQ phenomena levels at a certain bus to chosen thresholds (thresholds can be adjusted based on standards or some other criteria defined by the user). Table 7 shows the performance of the five worst performing buses based on each phenomenon separately and the corresponding CBPQI calculated for each bus (4 buses were among the worst performing in both harmonics and unbalance, therefore only 11 buses are shown).

Table 7 Worst performing buses for all phenomena together (in p.u.)

	Sags	Harmonics	Unbalance	CBPQI
Bus 193	0.890	1.044	0.353	1
Bus 210	0.872	1.048	0.353	0.992
Bus 196	0.848	1.053	0.347	0.977
Bus 194	0.848	1.050	0.346	0.976
Bus 195	0.848	1.051	0.345	0.976
Bus 136	0.223	1.323	1.040	0.796
Bus 137	0.202	1.427	1.083	0.795
Bus 138	0.202	1.427	1.083	0.795
Bus 134	0.236	1.294	0.997	0.793
Bus 135	0.223	1.322	1.025	0.792
Bus 36	0.135	0.048	1.001	0.315

The normalized values in the table are normalized based on the thresholds adopted for each index and the CBPQI is normalized based on the performance of the worst performing bus in the network. The values from Table 7 are depicted in Fig. 7. The effect of the weighting factors can be clearly seen by comparing the individual phenomenon heat maps (Fig. 5) with the overall performance shown in heat map in Fig. 6. The worst performing areas in terms of sag are the worst areas after unifying the indices. Also, some of the worst performing areas in terms of unbalance are completely masked in the overall heat map showing average overall performance. This impact can also be noticed in Fig. 7, where the CBPQI bars (striped) follow the trend of the sag bars (black). The first five buses (193, 210, 196, 194 and 195) which show poor performances for both sag and harmonics and good performances for unbalance scored very high CBPQI, while the next five buses (136, 138, 137, 134 and 135) which show good performances in sag but poor performances in both unbalance and harmonics still scored relatively high in the CBPQI. When it came to Bus 36, the fifth worst bus in terms of unbalance but with good performances in both sag and harmonics, the CBPQI was low indicating good overall performance.

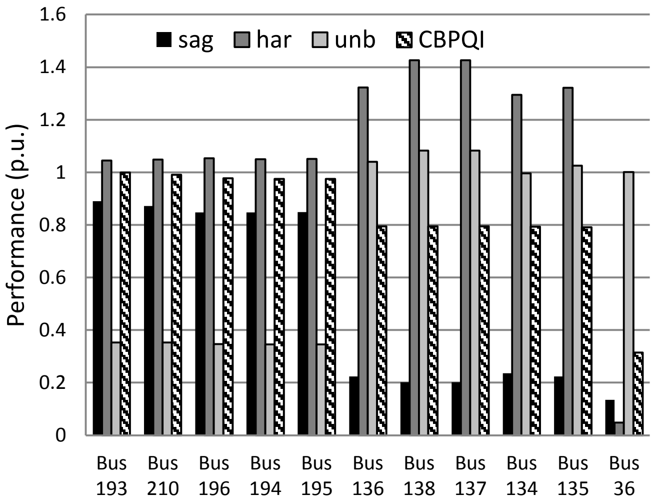

Fig. 7. *Worst performing buses (normalized)*

Another important aspect can be noticed from the results in Table 7, the PQ performance varies slightly (second or third decimal place) between some buses; this is intuitive because the geographical and electrical proximities between some buses cause them to experience the same types and levels of PQ disturbances, unless a certain bus has special operating conditions (e.g. DG connected and/or capacitors bank connected). This fact can be used for zonal or area based PQ evaluation rather than bus by bus evaluation, especially if the evaluation is performed to identify the weak areas of the network for the purpose of PQ mitigation as the mitigation solutions will also have zonal effects rather than affecting the connection buses only. Considering this “zonal behavior” of different PQ phenomena and consequently overall PQ in the network as well as all the uncertainties involved in assessment the feasible practical approach would be to identify ranges of CBPQI and group the buses into classes, e.g. 1-0.9 very poor performance, 0.6-0.5 acceptable performance and 0.1-0.3 good performance, rather than insisting on individual ranking of buses. Heat maps used for illustration of the results in this paper are a good example of identifying critical areas of the network rather than critical buses per se.

5. Conclusion

The paper proposed a new index for overall PQ evaluation at network buses. It evaluates the PQ performance comprehensively based on both event-type (voltage sags) and continuous-type phenomena (unbalance and harmonics), considering different weight for each phenomenon in the overall evaluation. The methodology can include sub-level evaluations for the phenomena considered, e.g. the harmonics can be evaluated based on THD and selected harmonic voltages or any other relevant index like the Crest Factor or zero crossing, depending on the sensitive equipment and the more relevant evaluation indices. The index can be used to identify the weak areas of the network in terms of overall PQ, to provide useful comparison tool between the buses and to give indicative information about how far a PQ performance of a certain bus is from the PQ limits. The proposed CBPQI is compared with two other recently introduced global PQ indices and the results show that it can both evaluate the global PQ performance of the bus and assess the performance of individual PQ phenomenon against its threshold more accurately than the other two. To increase further the robustness of CBPQI in future practical applications, probabilistic approach should be used to assess the performance of individual phenomena instead of combining statistical measures of indices (95th, average).

6. Acknowledgments

This work was supported by SuSTAINABLE Project under Grant 308755. The authors wish to acknowledge contributions of Dr Tingyan Guo, Dr Yizheng Xu, Miss Xiaoxue Wang, Mr Yunling Li, D. Yue Guo, and Mr Yichi Zhang who participated over the years at different stages of development of the methodology.

7. References

[1] Dugan, R.C., McGranaghan, M.F., Santoso, S., Beaty, H. W.: 'Electrical power systems quality' (New York: McGraw-Hill, 2002, 2nd ed)

[2] Watson, N.R., Ying, C.K., Arnold, C.P.: 'A global power quality index for aperiodic waveforms'. Proc. Int. Conf. Har. and Quality of Power, Orlando, USA, 2000, pp. 1029-1034

[3] Kilter, J., Meyer, J., Howe, B., Zavoda, F. et al.: 'Current practice and future challenges for power quality monitoring - CIGRE WG C4.112 perspective'. Proc. Int. Conf. Har. and Quality of Power, Hong Kong, China, 2012, pp. 390-397

[4] Nourollah, S., Moallem, M.: 'A data mining method for obtaining global power quality index'. Proc. Electric Power and Energy Conv. Syst., Sharjah, United Arab Emirates, 2011, pp. 1-7.

[5] Gosbell, V.J., Perera, B.S.P., Herath, H.M.S.C.: 'New framework for utility power quality (PQ) data analysis'. Proc. IEEE Power & Energy Society Innovative Smart Grid Tech., Australia, 2001, pp. 577-582

[6] Gosbell, V. J., Perera, B. S. P., Herath, H.M.S.C.: 'Unified power quality index (UPQI) for continuous disturbances'. Proc. Int. Conf. Har. and Quality of Power, Rio de Janeiro, Brazil, 2002, pp. 316-321

[7] Meyer, J., Schegner. P., Winkler, G., Stadtwerke, M.M.D., Schulze, L.: 'Efficient method for power quality surveying in distribution networks'. Proc. Int. Conf. Elec. Dist., Turin, Italy, 2005, pp. 1-4

[8] Meyer, J., Holenstein, H., Egger S.: 'NEQUAL web based voltage quality monitoring in Switzerland'. Proc. Int. Conf. Elec. Dist., Lyon, France, 2015, pp. 1-4

[9] Kraft, M.: 'Power quality recording and evaluation in an industerial area (chemical park)'. Proc. Int. Conf. Elec. Dist., Lyon, France, 2015, pp. 1-4

[10] Morsi, W., El-Hawary, M.: 'Fuzzy-wavelet-based electric power quality assessment of distribution systems under stationary and nonstationary disturbances', Proc. IEEE General Meeting Power and Energy Society, RI, USA, 2010

[11] Vokas, G. A., Kaminaris, S. D., Kontaxis, P. A., et al.: 'Electric network power quality assessment using fuzzy expert system methodology', Proc. Power Gen., Trans., Dist. and Energy Conv., Cagliari, Italy, 2012, pp. 1-6

[12] Duarte S.,and Kagan N.: 'A power-quality index to assess the impact of voltage harmonic distortions and unbalance to three-phase induction motors', IEEE Trans. Power Del., 2010, 25, (3), pp. 1846-1854

[13] Salarvand, A., Mirzaeian, B., Moallem, M.: 'Obtaining a quantitative index for power quality evaluation in competitive electricity market', IET Gen., Trans. & Dist., 2010, 4, (7), pp. 810-823

[14] Buhm, L., Min, K.K.: 'Unified power quality index based on value-based methodology', Proc. Power & Energy Society General Meeting, Calgary, Canada, 2009, pp. 1-8

[15] Buhm, L., Min K.K.: 'Development of ideal analytic hierarchy process-application of power quality', Proc. Fuzzy Systems, South Korea, 2009, pp. 64-67

[16] Buhm, L., Min, K.K., Yeongjin G.: 'Unified power quality index using ideal AHP', Proc. Har. and Quality of Power, Australia, 2008, pp. 1-5

[17] Bracale, A., Caramia, P., Carpinelli, G. et al.: 'Site and system indices for power-quality characterization of distribution networks with distributed generation', IEEE Trans. on Power Del., 2011, 26, (3), pp. 1304-1316

[18] Heydt, G.T., Jewell, W.T.: 'Pitfalls of electric power quality indices', IEEE Trans. on Power Del., 1998, 13, (2), pp. 570-578

[19] Vargas, L.G., Saaty, T.L.: 'Models, methods, concepts & applications of the analytic hierarchy process' (New York: Springer Science and Business Media, 2012)

[20] IEC, 'IEC 61000-3-6:1996 – Assessment of emission limits for distorting loads in MV and HV power systems', 1996

[21] IEEE, 'IEEE 519:2014. IEEE recommended practices and requirements for harmonic control in electrical power systems', 2014

[22] Sami Abdelrahman: 'Estimation and Provision of Differentiated Quality of Supply in Distribution Networks', PhD thesis, University of Manchester, Manchester, 2016

[23] CENELEC, 'EN 50160:1999 voltage characteristic of electricity supplied by public distribution systems', 1999

[24] Liu, Z., Milanovic, J.V.: 'Probabilistic estimation of voltage unbalance in MV distribution networks with unbalanced load', IEEE Trans. on Power Del., 2015, 30, (99), pp. 693-703

[25] Liao, H., Abdelrahman, S., Guo, Y., Milanovic, J.V.: 'Identification of weak areas of network based on exposure to voltage sags - Part II: Assessment of Network Performance Using Sag Severity Index', IEEE Trans. on Power Del., 2015, 30, (6), pp. 2401-2409

[26] Gasch, E., Domagk, M., Meyer, J., Abdelrahman, S., Liao, H., Milanović, J.V.: 'Assessment of power quality performance in distribution networks: Part I – Measurement campaign and initial analysis'. Proc. 17th IEEE PES International Conference on Harmonics and Quality of Power, Belo Horizonte, Brazil, October 2016

[27] Abdelrahman, S., Liao, H., Milanović, J.V., Gasch, E., Domagk, M., Meyer, J.: 'Assessment of power quality performance in distribution networks: Part II – Performance indices and ranking of network busses'. Proc. 17th IEEE PES International Conference on Harmonics and Quality of Power, Belo Horizonte, Brazil, October 2016

[28] Bahadoorsingh, S., Milanovic, J.V., Zhang, Y. et al: 'Minimization of voltage sag costs by optimal reconfiguration of distribution network using genetic algorithms', IEEE Trans. on Power Del., 2007, 22, (4), pp. 2271-2278

[29] Milanovic, J.V., Lu, J.: 'Application of artificial immune system for detecting overloaded lines and voltage collapse prone buses in distribution network'. Proc. PowerTech, Bucharest, 2009, pp. 1-7

[30] Zhang, Y.: 'Techno-economic assessment of voltage sag performance and mitigation'. PhD, University of Manchester, Manchester, 2008

[31] Teng, A.M., Milanovic, J.V.: 'Establishing harmonic distortion level of distribution network based on stochastic aggregate harmonic load models', IEEE Trans. on Power Del., 2007, 22, (2), pp. 1086-1092

[32] Patel, D., Varma, R.K., Seethapathy, R., Dang, M.: 'Impact of wind turbine generators on network resonance and harmonic distortion'. Proc. Electrical and Comp. Eng., Calgary, Canada, 2010, pp. 1-6

[33] SMA Solar Technology, 'EN 50438 Type certification test result sheet’,
http://files.sma.de/dl/1366/TR50438_SBWBTL-ZEEN113310.pdf