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Assessment of Power Quality Performance in Distribution Networks

Part II – Performance Indices and ranking of network buses

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***Abstract*— Power Quality has become one of the main measures of distribution network operation evaluation. Utilities and customers monitor the different PQ aspects for benchmarking and compatibility check. This is a second part of a paper that investigates a long term PQ measurement campaign. In this part, global PQ indices are applied to combine a number of PQ phenomena indices into one number that represents the PQ performance of a site. Two global PQ indices are applied on 64-week PQ measurements of 8 sites. The indices are compared in terms of the final rank of sites. Different levels of flexibility are introduced to the indices to consider a variable importance or priority of the phenomena and sites.**

***Index Terms*—Power Quality, Measurement Campaign, Indices**

I. INTRODUCTION

In 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). Since then, it has become one of the most talked about and analysed performance indicator of power networks. This can be broadly attributed to re-regulation of electric power industry and introduction of competition in electricity generation and supply business. Moreover, customers became fully aware about PQ issues, especially the ones that lead to industrial process interruptions, and consequential financial losses. Introduction of highly sensitive equipment in customer plants has also led to increased attention to PQ issues. Therefore, both utilities and customers started to pay much more attention to PQ.

Even though the common name 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, it has been agreed between all the parties involved that the PQ in general can be addressed using system approaches as well as individual solutions. Nevertheless, PQ is still considered a consumer-driven issue and the main concerns of the utilities, when studying this issue, the compatibility between the customers' equipment and PQ disturbances originating in the network. These disturbances can lead to equipment and process/customer activity misoperation or even complete interruption resulting in very high financial losses. All the main PQ phenomena are well defined in the international standards, the compatibility levels defined in some of them serve as a guideline for the network operators to deliver PQ below these limits, and for the equipment producers to ensure appropriate immunity levels.

Since early 2000s several publications addressed the issue of unified PQ assessment, adopting various mathematical models. Reference [2] is one of the earliest, the methodology presented there is based on calculation of the missing RMS voltage, i.e. comparing the sampled voltage to the ideal voltage and the RMS error (RMSE) was used as an index to compare different PQ solutions. The methodology considers both event-type and continuous-type PQ disturbances, however it can be computationally extensive, as it involves time domain analysis.

Due to the increased concerns about network performance in the future, utilities started to deploy more PQ (and other) monitors in their networks which will lead to huge amount of recorded data. This abundance of data unless properly structured and processed to yield useful information about network performance will not be useful to the users [3]. Reference [4] suggests a data mining method for structuring and classifying the recorded data, before calculating a global PQ index. References [5, 6] suggest a multi-level structured framework for PQ data analysis and compression and propose Unified Power Quality Index (UPQI) for overall PQ assessment. In [5, 6] the UPQI is applied to combine continuous-type phenomena only and in [7, 8] to include the event-type phenomena.

A number of suggested global PQ indices are based on application of fuzzy logic [9-12]. The other group [13-15] proposes methodologies to evaluate the overall PQ performance, considering the costs of the disturbances in the evaluation.

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Examples of recent applications of global PQ indices using real life PQ monitoring data in Switzerland and Germany can be found in [16, 17].

In spite of all the very good 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. 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. They can also be used in the identification of sub-standard performing parts of the network and in the decision making about network maintenance and investment.

This paper presents and compares two global PQ indices based on monitoring data from a long term PQ measurement campaign presented in Part I of the paper. The application of the Compound Bus PQ Index (CBPQI) [18] and the Aggregated PQ Index (APQI), which is based on [19], for overall PQ performance ranking of network buses is illustrated and discussed. The indices limitations and strengths are highlighted.

II. THEORY OF ASSESSMENT INDICES

A. CBPQI – Compound Bus Power Quality Index

The CBPQI is an index calculated based on the Analytic Hierarchy Process (AHP) mathematical model. It can be considered as an average index, where all considered PQ phenomena are weighted and averaged to present the final index. The final index is a ratio between the site performance compared to a reference performance. Different phenomena can have different priorities in the overall evaluation (phenomena's' importance) and the sites can have different reference performance (sites' importance). The main motive of introducing flexibility to the PQ index is to analyse the feasibility of proposing differentiated PQ provision at future distribution networks, as different sites have different PQ requirements and have different types of equipment with different immunity levels. To give an example, domestic and industrial sites will have different priorities with regard to the voltage unbalance and flicker phenomena, furthermore different types of industrial sites can have different levels of acceptable voltage unbalance levels based on the equipment types operating. Nevertheless, it is also possible to set equal weights, as first approximation, for simple comparison between sites, especially when there is not enough information to decide the different priorities of different PQ phenomena.

1) Theory and Calculation

Analytic Hierarchy Process (AHP) is one of the common mathematical models for multi criteria decision making (mcdm) problems. It solves the problem of selecting a goal from a number of alternatives based on a number of selecting criteria considered simultaneously. 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 [20].

2) Aggregation of indices

The AHP model is adjusted to accommodate the CBPQI calculation as shown in Fig. 1. At the Alternatives Level, the score of the site under evaluation Site_i in a certain phenomenon compared to the score of a reference performance Site_{ref} is an indication of how 'far' the site is from the limit. For example $\text{score}_i=\text{score}_{ref}=0.5$ indicates site performance at the limit, while $\text{score}_i \approx 1$ and $\text{score}_{ref} \approx 0$ indicates very high exceedance of the limit. At the Criteria Level, the priorities of different phenomena for a certain site are calculated based on a pairwise predefined weighting matrix, as shown in Table I for three phenomena, the priorities are calculated from the absolute normalized principle eigenvector [20]. Similarly for phenomena that are evaluated based on more than one index, a sub-criteria level can be defined, as in the harmonics case (see Fig. 1). The final step is to calculate the CBPQI_i based on Site_i total weighted score compared to the adopted reference Site_{ref} total weighted score as shown in equation (1), where N is the total number of considered PQ phenomena. CBPQI can range from 0 (best performance) to higher than 1 pu in case of threshold exceedances.

$$CBPQI_i = \frac{\sum_{n=1}^{N} score_{i,n} \times p_n}{\sum_{n=1}^{N} score_{ref,n} \times p_n} \tag{1}$$

TABLE I: PAIRWISE WEIGHTING MATRIX

	Flicker	Harmonics	Unbalance	Priorities (Eigenvector)
Flicker	1	w_{flk}/w_{har}	w_{flk}/w_{unb}	p_{flk}
Harmonics	w_{har}/w_{flk}	1	w_{har}/w_{unb}	p_{har}
Unbalance	w_{unb}/w_{flk}	w_{unb}/w_{har}	1	p_{unb}

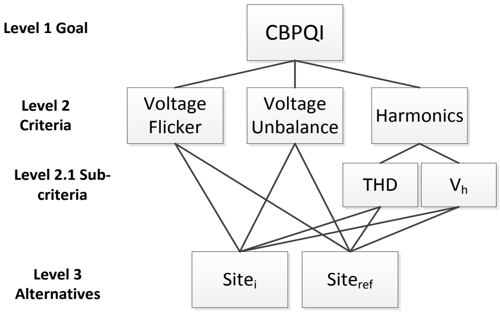


Figure 1. AHP model for calculating the CBPQI

B. APQI – Aggregated Power Quality Index

The APQI is based on the assessment of the existing reserve of an individual PQ phenomenon to a specified limit within a given time interval (e.g. according to EN 50160) [21]. Starting from these individual indices a flexible aggregation with different levels of detail is possible. Two different approaches can be used for the aggregation:

minimum or average (see also section V in Part I [22]). The individual indices are aggregated in several stages. Typical aggregation levels are the individual site (site index) or a network area (network index). The network index (top level index at highest aggregation) represents the PQ performance of all considered sites (e.g. a whole network) and all considered time intervals (e.g. all weeks of one year) as one single number. The concept is illustrated in Fig. 2.

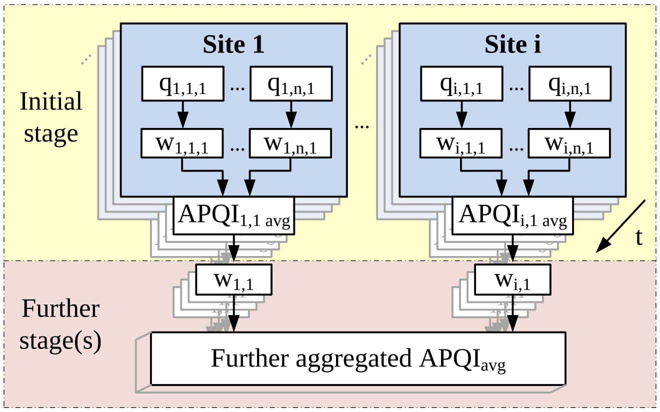


Figure 2. General concept of $APQI_{avg}$

1) Theory and Calculation

The general equation for calculating an individual Power Quality Index $q_{i,n,t}$ for a site *i*, PQ phenomenon *n* and time interval *t* is given by

$$q_{i,n,t} = \left(1 - \frac{m_{i,n,t}}{g_n}\right) \cdot 100\% \tag{2}$$

where $m_{i,n,t}$ represents the measured value and g_n the limit for the PQ phenomenon *n*. For this part of the paper the analysis follows also EN 50160, where the 95th percentile of the 10-minute-mean r.m.s. values of one week corresponds to the measured value *m*, while *g* represents the limits according to EN 50160. The individual indices are usually aggregated as described in the next section.

2) Aggregation of indices

The methodology of aggregation of multiple individual indices *q* depends on the objective of the analysis and can follow different ways. In case a compliance assessment according to standards is required, the minimum of all indices *q*, which are going to be aggregated, is used ($APQI_{min}$). This approach is discussed and applied in the first part of the paper [22].

In order to assess the average performance, e.g. of a site or network, the $APQI_{avg}$ is applied, which consists according to Fig. 2 of an initial stage that aggregates individual indices *q* to a site index $APQI_{i,t\ avg}$ and further stages that aggregate multiple site indices in terms of sites and/or time intervals (e.g. all sites of a network for a specific week, all weeks of a year for a specific site). In order to set priorities for different individual indices or aggregated indices, additional weighting factors are introduced in analogy to the CBPQI. If desired, these factors can even differ between sites and time intervals. The general equation to calculate the $APQI_{i,t\ avg}$ in the initial stage for a set of N individual indices at a specific site *i* and time interval *t* is given by:

$$APQI_{i,t\ avg} = \frac{\sum_{n=1}^{N}\left[w_{i,n,t} \cdot q_{i,n,t}\right]}{\sum_{n=1}^{N} w_{i,n,t}} \tag{3}$$

The weighting factors $w_{i,n,t}$ can be any positive value. If $w_{i,n,t} = 0$, the respective individual index is excluded from the analysis. In case no weighting shall be applied, all weighting factors have to be set to $w_{i,n,t} = 1$. For aggregating multiple site indices (further stages), the calculation according to (3) can be applied but *q* has to be replaced by $APQI_{i,t\ avg}$.

III. APPLICATION OF ASSESSMENT INDICES

A. Results using CBPQI

1) Evaluation of one measurement site

The 8 different type LV sites under PQ evaluation are R1, R2, R3, R4 (residential sites), C1, C2 (commercial sites) and M1, M2 (mixed sites). The considered phenomena from the 64 weeks measurement campaign (see Part I) are the RMS voltage, voltage unbalance (UNB), total harmonic distortion (THD), long term flicker (PLT) and the individual odd harmonic voltages up to the 25th harmonic. All performances (except for unbalance) are considered per phase and the worst performing phase is taken as the site performance. In the case of the RMS voltage performance the phase with the highest absolute deviation RMS_{dev} from nominal voltage (230 V) determines the site index. The PQ performance variation for site R1 is shown in Fig. 3 with the aid of box plots. The CBPQI was calculated for each measurement week based on the 95th percentile of the different phenomena performances with equal weights. To facilitate the comparisons, the phenomena were normalized based on their respective limits from EN 50160 (the RMS_{dev} is normalized based on 23 V limit, i.e. 10% of the nominal voltage) and are shown as colour matrix in pu in Fig. 4. The CBPQI, which is already normalized in the calculation process (see equation (1)) is shown in the top row.

2) Non-weighted evaluation of multiple measurement sites

The ranking based on CBPQI for site performances is presented in Fig. 5. The ranking was performed for each week and an average rank is calculated as shown in the figure. The dark red represents the worst site and the dark blue represents the best site, while black boxes in the figure represent missing measurement weeks. From Fig. 4, the final rank, from the worst site, is C2, R3, R1, M1, R2, M2, C1 and R4.

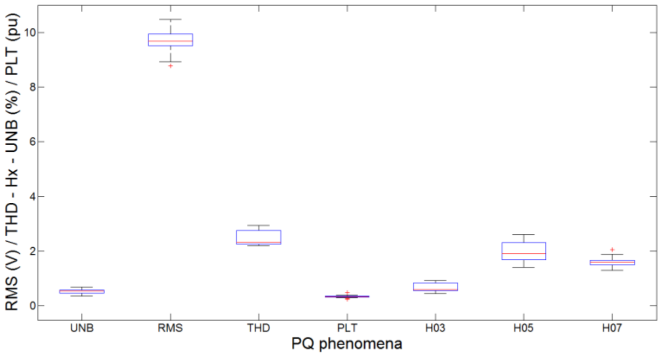


Figure 3. Some PQ phenomena variation for site R1

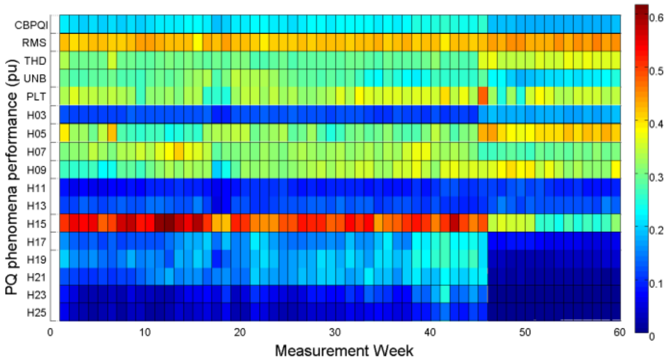


Figure 4. R1 PQ pu performances

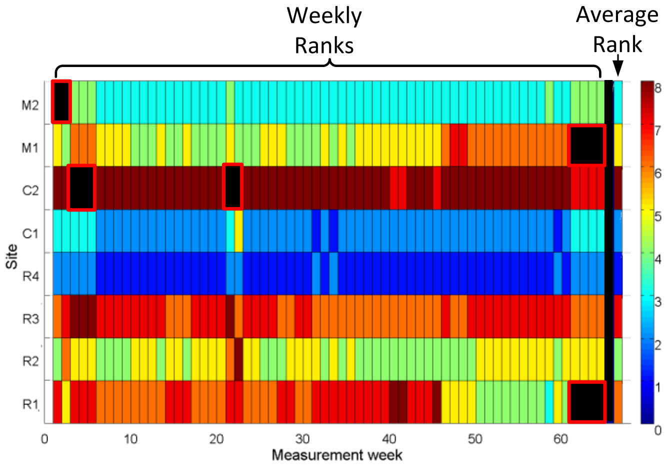
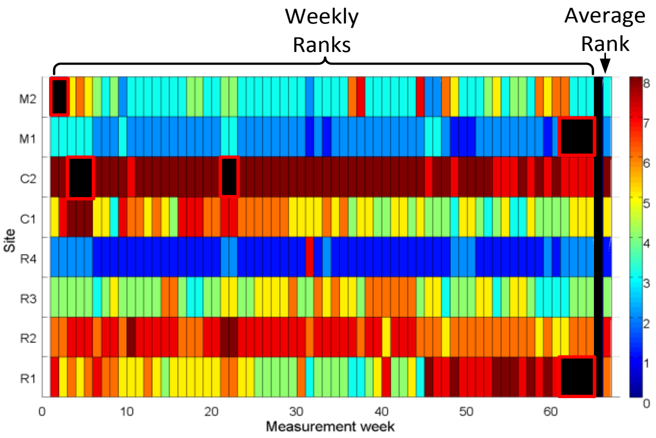


Figure 5. Average and weekly sites rank (original case CBPQI)

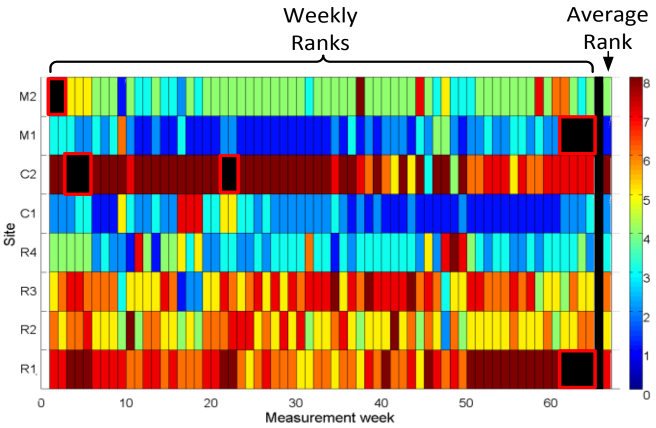
3) *Weighted evaluation of multiple measurement sites*

To introduce flexibility in the evaluation, a phenomenon can be weighted in the CBPQI to be more or less pronounced in the final index. To perform simplified analysis, only three phenomena are considered in the overall evaluation, total harmonic distortion (THD), unbalance (UNB) and flicker (PLT). The selection of weights is based on segments of a normal distribution function *f*(x). For high probability of failure due to a certain phenomenon, this phenomenon is assigned a weight of 0.68 which is the probability in the range of μ ± σ for normal distribution, the moderate important phenomenon is assigned a weighting of 0.27 which is the probability calculated by $2 \times \int_{\sigma}^{2\sigma} f(x).dx$ and the least important phenomenon assigned a weight of 0.05 which is the remaining probability. The flexibility analysis was performed in two case studies, the first was weighting the considered phenomena with constant weights for all the sites and the second was considering site types in the analysis.

For the first case study the phenomena were weighted in the following criterion, harmonics with high importance (0.68), flicker with moderate importance (0.27) and unbalance with the least importance (0.05). In the second case study, based on the site type the weights of the phenomena were varied. For domestic sites flicker is selected as most important, then harmonic and finally unbalance, while for commercial sites harmonics got the highest weighting, then unbalance and at the least weighting flicker. For mixed sites, based on the ratio between types the weights were averaged, for example for a 70:30 domestic to commercial site the weights are w_{THD}=0.39, $w_{\mathrm{PLT}k}$=0.49 and w_{UNB}=0.12 based on the same weighting values discussed above. Fig. 6 (a) and (b) show the weekly and average ranks for the two cases of weightings considered.



(a) Constant weighting of phenomena



(b) Weightings based on site type

Figure 6. Average and weekly sites rank (flexible cases CBPQI)

By comparing Fig. 5 and Fig. 6 it can be noted that there is high discrepancy between average ranks. Furthermore, the weekly ranks for the weighted cases are not as consistent as the original case. This is mainly due to considering fewer phenomena which variations are now more pronounced in the averaging process. It is clear that adding different types of flexibility in PQ evaluation shifts the attention from some sites to another (except for extreme cases, e.g. C2 remains the worst performing in all cases).

Nevertheless, this is only performed to retune the index to focus in certain PQ disturbances or types of customers when evaluating PQ, while it is always possible to adopt the original case index to benchmark performance with the

TABLE II. SITE RANKING BASED ON CBPQI

Average performance ranking	No weighting	Constant weighting	Site-type dependent weighting
1 (best)	R4	R4	M1
2	C1	M1	C1
3	M2	M2	R4
4	R2	R3	M2
5	M1	C1	R2
6	R1	R1	R3
7	R3	R2	R1
8 (worst)	C2	C2	C2

standards. Table II presents the comparison between the three case studies rankings.

B. Results using APQI

1) Evaluation of one measurement site

The estimated performance of one measurement site is illustrated in Fig. 7 in a similar way and for the same site (R1), time (54 weeks) and PQ phenomena as in Fig. 4. For each PQ phenomenon except UNB the non-weighted average of all phases and each week is calculated. The $\mathrm{APQI}_{i,t\ \mathrm{avg}}$ of the site (first row) is calculated using (3), but also without weighting ($w_{i,n,t} = 1$). It can be seen that e.g. the 3rd harmonic voltage (H03) for this site has an average reserve compared to the EN 50160 limit of more than 80%, while the RMS has an average reserve of about 60%. A sudden change in the reserve occurs for the 15th harmonic (H15) from below 60% to about 75% in week 46, which is easy to identify by the colour matrix representation.

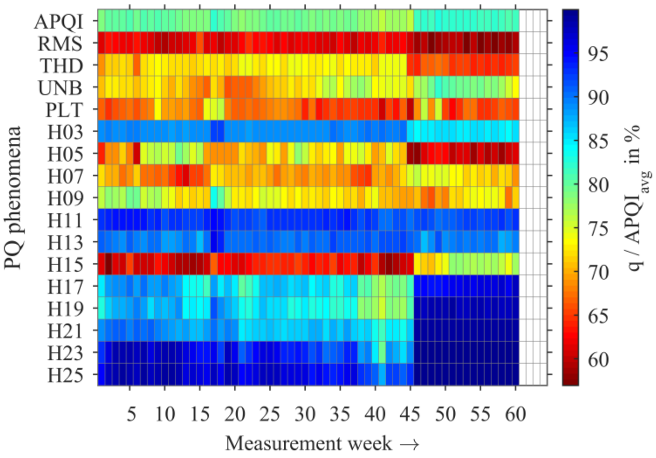


Figure 7. Non-weighted $\mathrm{APQI}_{\mathrm{avg}}$ for all PQ phenomena at site R1

2) Non-weighted evaluation of multiple measurement sites

Similar to section II.A.2) the non-weighted evaluation of multiple sites has been applied to all sites using exemplarily the PQ phenomena THD, PLT and UNB. The results are illustrated in Fig. 8 for each week and site. It can be seen that the site R4 is the best performing site with an average reserve of $\mathrm{APQI}_{\mathrm{avg}} > 70\%$ while the site C2 is the worst performing site with average reserve of $\mathrm{APQI}_{\mathrm{avg}} < 60$. These results are the same as ones obtained using CBPQI.

3) Weighted evaluation of multiple measurement sites

TABLE III. SITE RANKING BASED ON $\mathrm{APQI}_{\mathrm{AVG}}$

Average performance ranking	No weighting	Constant weighting
1 (best)	R4	R4
2	M2	M1
3	R2	M2
4	M1	R3
5	R3	C1
6	R1	R1
7	C1	R2
8 (worst)	C2	C2

Similar to Section III.A.3) only THD, PLT and UNB are analysed. Same weights are applied, namely $w = 0.68$ for THD (high importance), $w = 0.27$ for PLT (medium importance) and $w = 0.05$ for UNB (low importance). The respective plot is shown in Fig. 9. In comparison with Fig. 8 the performance of site C2 improves significantly because RMS is not considered, but it remains the worst performing site due the high THD values. The other sites change their average performance as well. The ranking based on the average $\mathrm{APQI}_{\mathrm{avg}}$ over all weeks for the non-weighted and the weighted evaluation is listed in Table III. Only three sites remain constant, including sites R4 and C2 as best and worst performing sites. Site R2 is downgraded from rank 3 to rank 7, whereas site M1 improves from rank 4 to rank 2.

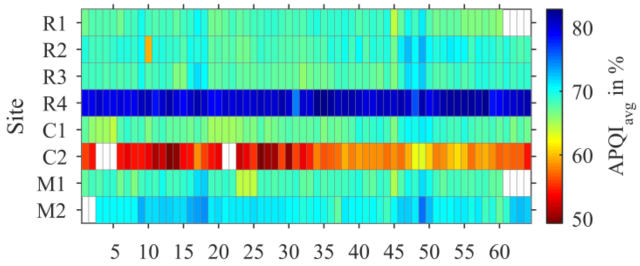


Figure 8. Non-weighted $\mathrm{APQI}_{\mathrm{avg}}$ for sites: R1-M2 and PQ phenomena: THD, PLT, UNB and RMS

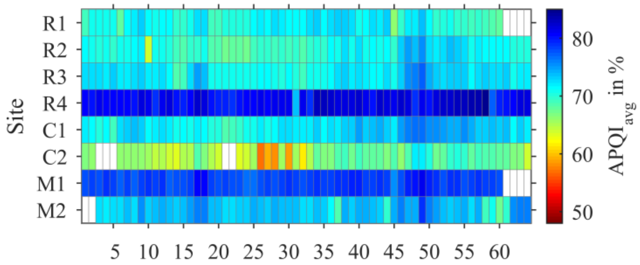


Figure 9. Weighted $\mathrm{APQI}_{\mathrm{avg}}$ for sites: R1-M2 and PQ phenomena: THD ($w = 0.68$), PLT ($w = 0.27$), UNB ($w = 0.05$)

Comparing Table II and Table III shows that at least worst and best performing site are equal identified by both indices, even if the calculation methodology is very different. Furthermore the ranking by using constant weighting are completely similar for both methods. This confirms the significant impact of weights to the result and underlines that weighting values should be determined very carefully.

IV. CONCLUSION

This is the second part of a paper analysing a long-term PQ measurement campaign. While Part I describes the details of the campaign itself, this part presents two global PQ indices which are used to compress the large amount of data into single indices of different aggregation (e.g. each site and week) as basis for comparing of sites average PQ performance. The raw data of each PQ phenomenon is statistically processed first and the resulting weekly 95th percentiles of the PQ individual indices are combined into the global indices, namely the compound bus PQ index CBPQI and the aggregated PQ index APQI. Both indices are intended to be used for assessing the average performance of different network sites. Even if the methodology differs, both indices show good correlation, particular in case of similar weights are applied. Without weighting the indices are more discrepant. This paper has also shown that, regardless the calculation methodology, global indices can provide consistent evaluation of PQ performance of sites. Global PQ indices also provide simpler and easier to visualize tool for sites performance comparison. Even if weighting enables higher flexibility it can complicate the application of the PQ indices, as setting suitable weights requires care and a lot of knowledge about network and connected customer including their equipment. Furthermore clear guidance on how a PQ index has to be interpreted is crucial for its successful application.

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