Zonal Mitigation of Power Quality Using FACTS Devices for Provision of Differentiated Quality of Electricity Supply in Networks with Renewable Generation

DOI:
10.1109/TPWRD.2016.2585882

Document Version
Accepted author manuscript

Citation for published version (APA):
Liao, H., Abdelrahman, S., & Milanovic, J. V. (2017). Zonal Mitigation of Power Quality Using FACTS Devices for Provision of Differentiated Quality of Electricity Supply in Networks with Renewable Generation. *IEEE Transactions on Power Delivery*, *32*(4), 1975-1985. https://doi.org/10.1109/TPWRD.2016.2585882

Published in:
IEEE Transactions on Power Delivery

Zonal Mitigation of Power Quality Using FACTS Devices for Provision of Differentiated Quality of Electricity Supply in Networks with Renewable Generation

Huilian Liao, *Member, IEEE*, Sami Abdelrahman, *Graduate Student Member, IEEE*, and Jovica V. Milanović, *Fellow, IEEE*

***Abstract*--This paper presents the concept of provision of differentiated quality of electricity supply based on customers' requirements in distribution networks. To fulfill this concept, five new gap indices are proposed to reflect the satisfaction of the received power quality (PQ) performance compared to the thresholds which are set based on customers' requirements regarding the performance of individual PQ phenomenon or the aggregated PQ performance. Using these new indices as objective functions, an optimisation based mitigation strategy is proposed to carry out the strategic placement of different FACTS devices based on the analysis of PQ performance and sensitivity analysis. In this methodology, greedy algorithm is applied to search the optimal mitigation scheme in order to enable the provision of differentiated PQ levels. The feasibility of the proposed mitigation methodology is demonstrated using large scale generic distribution network. The advantages and disadvantages of using the proposed indices as the optimisation objective functions are also analysed in the paper.**

***Index Terms*—Quality of supply, power quality, mitigation strategy, FACTS devices.**

I. INTRODUCTION

Power quality (PQ) issues continue to attract significant attention from both utilities and customers. Among PQ phenomena that attract the most attention are voltage sags, voltage unbalance and harmonics. Voltage sags cause frequent disruptions to industrial processes and malfunction of electronic equipment; voltage unbalance issues cause overheating, accelerated thermal ageing of equipment and reduction of efficiency of the load and overall network [1]; and harmonics (voltage distortion) cause thermal stress, insulation stress and load disruption to both power system equipment and customer's equipment [2]. These PQ phenomena result in substantial financial losses to both utilities and industries. Furthermore, the increasing level of penetration of intermittent, power electronics connected renewable resources, electric vehicles and other power electronics interfaced loads results in increasing variability of PQ in power systems. With more sensitive equipment/devices connected to the grids, it is essential to provide acceptable quality of supply as required by customers. To ensure this, a number of international PQ standards, e.g., EN 50160 and IEC 61000 series, have been set up to provide guidelines to utilities regarding the acceptable levels of PQ supply.

In reality, requirements on PQ performance vary from area to area (e.g., commercial, residential and industrial areas), depending on the sensitivity of customers' processes and equipment to specific PQ phenomena. Considering different PQ requirements by different parties involved in electricity supply chain, costs associated with PQ mitigation and willingness to contribute to PQ mitigation by different market players, the idea of provision of differentiated levels of quality of supply to different customers in different zones is becoming more and more acceptable. This approach will improve the efficiency of electricity/energy distribution by only offering the PQ performance as required. In this way, less mitigation effort is required, and the cost of investment is reduced, compared to the case when the PQ performance is improved over the whole network and all customers benefit from better PQ performance even though they may not need it. Besides, the provision of differentiated PQ performance helps utilities to price the electricity and plan the mitigation strategy based on customers' willingness to pay in different areas, which provides a fair way to subsidize the mitigation activity. The need for electrical services with different levels of quality of supply was identified as early as 1989 [3]. In spite of this, the concept of providing differentiated services was only addressed in limited areas of power systems such as reliability options [4] and some non-price attributes for customers [5]. Though the power supply with differentiated PQ levels was recommended as one of the characteristics of the future model of power supply in the past [6, 7], no clear definition and feasible solution have been provided yet. This was mainly due to the challenges associated with technology development, the technical constraints of monitoring and the lack of control flexibility [7], though classification and grouping of customers according to quality demands have been comprehensively investigated [8]. It is therefore timely to investigate the feasibility of the concept of provision of differentiated PQ levels, especially for the development of future grids where service flexibility is highly valued. To implement this novel

This work was supported by SuSTAINABLE Project under Grant 308755.
H. Liao, S. Abdelrahman and J.V. Milanović are with the School of Electrical and Electronic Engineering, The University of Manchester, PO Box 88, Manchester, M60 1QD, UK. (email: milanovic@ manchester.ac.uk).

concept in practice, advanced techniques and proper mitigation strategy are required.

With the fast development of smart grid technologies in power systems and the enhanced features and functionality of the latest generation of power electronic devices, the provision of differentiated levels of quality of supply becomes possible nowadays with the help of flexible ac transmission system (FACTS) devices. FACTS can control network parameters including current, voltage and impedance flexibly. They have been already reasonably well and widely studied for implementation in power systems for various purposes [9]. Their application has been also widely investigated in power systems for mitigating PQ issues [10-12]. So far, the application of FACTS devices for PQ mitigation was mainly focused on the mitigation of one particular PQ phenomenon even though they can contribute to more than one PQ phenomenon simultaneously. Therefore, from the perspective of efficiency and reducing investment cost, it is very important to consider the critical and related PQ phenomena simultaneously when planning the placement of FACTS devices for PQ mitigation. Placing FACTS devices for PQ mitigation is proved to be beneficial in the long run, as the financial benefits will cover the initial capital investment within a few years after installation [13, 14].

In this paper, a mitigation strategy is proposed to facilitate the concept of provision of differentiated PQ across the network. Within the developed methodology, five new gap indices are proposed to describe the gap between the customer specified PQ thresholds and the actual PQ performance received by the customers. These indices cover various scenarios with respect to different PQ requirement settings, e.g. the requirement can be either set based on the performance of individual PQ phenomenon or the aggregated PQ performance. Based on the analysis of PQ performance of the network and the sensitivity of PQ performance to the injection of active/reactive power, a set of potential locations is selected globally and zonally, and made available initially for the placement of various FACTS devices. Given the objective function based on gap indices, greedy algorithm is applied to search the optimal mitigation scheme from the potential FACTS device placement. The feasibility of the proposed methodology and the comparison among the proposed gap indices in terms of their characteristics and benefits are analysed on a case study of a large, 295-bus, generic distribution network (GDN).

In this paper, Section II introduces the problem description with the proposed gap indices and optimisation methodology for the provision of differentiated PQ levels based on zonal requirement. In Section III, the proposed methodology was implemented on 295-bus GDN. Comparison and analysis of the simulation results were carried out using six case studies representing different scenarios of PQ requirements. Section IV concludes the paper.

II. METHODOLOGY

A. Problem Description

To provide differentiated levels of PQ supply, PQ zones and the associated PQ thresholds should be defined based on customers' requirements. As described in Fig. 1, PQ zones can be obtained by demarcating a network based on three steps: 1) customers are classified according to pre-defined customer classes. Customers can be broadly classified as residential, commercial and residential loads based on customers' activities. Alternatively, the customers can also be classified into more detailed classes based on the analysis of the sensitivity of customers' process to inadequate quality as well as the financial vulnerability of it on customer profits [8]; 2) zones can be formed based on the distribution of customer classes in the network, however, the decision regarding the number of zones and geographical coverage of each zone can be made based on other commercial or geographical reasons; 3) With the network divided in zones, zonal thresholds can be obtained based on the range of customer requirements and the percentage of the customers whose requirements are aimed at during PQ planning or other commercial arrangements between the network operator and customers. Further details regarding demarcating the network into zones can be found in [8, 15]. This paper focuses on the description of the provision of differentiated PQ levels via the construction of tailored optimisation objectives and the development of mitigation strategy/solution which is to facilitate the provision of differentiated PQ levels for given zones and zonal thresholds. The zones and zonal thresholds per se are irrelevant for the methodology itself and it can work with any number of zones and different zonal thresholds.

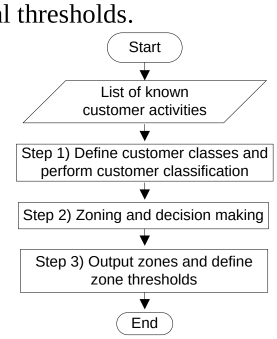


Fig. 1 Flowchart of zone division.

In this study, three critical phenomena, including voltage sags, harmonic and unbalance, are considered, as these phenomena would most likely result in PQ interruption to equipment and industrial processes. To accurately evaluate the PQ performance from the perspective of utilities and customers, appropriate indices should be adopted. The severity of voltage sags is assessed using Bus Performance Index (BPI), which takes into account various sag characteristics simultaneously as well as sensitivity of equipment to voltage sags, and reflects to a good approximation the practical consequence of voltage sags from the point of view of system/equipment operation [16]. Harmonics and unbalance phenomena are evaluated using Total Harmonic Distortion (THD) and voltage unbalance factor (VUF) respectively, which are widely used in practice [1]. For each PQ zone, the threshold with respect to each PQ phenomenon is determined based on the sensitivity of customers' equipment/process to the specific phenomenon in that zone. Given the PQ zones and specified zonal PQ thresholds, this paper investigates the mitigation strategy to ensure the provision of differentiated PQ levels in zones.

This problem is defined as an optimisation problem, which is to minimise the gap between the received PQ performance and the zonal thresholds. To facilitate the concept of provision of differentiated PQ levels, five new indices are proposed here to present the PQ gaps with respect to different forms of customer requirements. The thresholds with respect to voltage sags, harmonics and unbalance phenomena in PQ zone *i* are denoted as $BPI_{\mathrm{TH},i}$, $THD_{\mathrm{TH},i}$ and $VUF_{\mathrm{TH},i}$ respectively. If the PQ phenomena are considered individually, three gap indices can be derived. Sag Gap Index (SGI), which presents the gap between the received voltage sag performance and the imposed zonal sag requirements, can be defined as:

$$SGI=\sum_{i=1}^{N}\left(\sum_{j=1}^{B_i}\left|BPI_{i,j}-BPI_{\mathrm{TH},i}\right|_{BPI_{i,j}>BPI_{\mathrm{TH},i}}\right) \quad (1)$$

where B_j denotes the total number of buses within PQ zone *i*; and $BPI_{i,j}$ denotes BPI of the j^{th} bus in zone *i*. The same principle is applied to the phenomena of harmonics and unbalance respectively, Harmonic Gap Index (HGI) and Unbalance Gap Index (UGI) can be derived as below:

$$HGI=\sum_{i=1}^{N}\left(\sum_{j=1}^{B_i}\left|THD_{i,j}-\mathrm{THD}_{\mathrm{TH},i}\right|_{BPI_{i,j}>BPI_{\mathrm{TH},i}}\right) \quad (2)$$

$$UGI=\sum_{i=1}^{N}\left(\sum_{j=1}^{B_i}\left|VUF_{i,j}-VUF_{\mathrm{TH},i}\right|_{BPI_{i,j}>BPI_{\mathrm{TH},i}}\right) \quad (3)$$

where $THD=\sqrt{\frac{\sum_{h=2}^{H}(U_h)^2}{U_1}}$ and $VUF=\frac{U_2}{U_1}\times 100\ \%$ [1].

From the perspective of mitigation efficiency, the three PQ phenomena should be considered simultaneously, as generally one mitigation device can affect more than one PQ phenomenon. Therefore, the performance of the concerned phenomena should be suitably aggregated. Various approaches have been proposed in the past to represent the aggregate PQ performance at the bus, including artificial neural network, fuzzy logic, weighting functions and analytic hierarchy process (AHP) method [17-19]. In this paper, PQ performance is aggregated using a revised AHP [20], which consists of four steps:

1) Assess performance index of each PQ phenomenon denoted as I_k; identify the performance of its critical state denoted as IC_k. The critical state, threshold, can be set based on standards or experts opinion in which case it can vary from bus to bus depending on expert's perception of importance of particular phenomenon for customers connected at given bus.

2) For each PQ phenomenon *k*, the comparison between I_k and IC_k is performed by building pair-wise comparison matrix, whose derived principle eigenvectors will be taken as the scores for I_k and IC_k respectively (denoted as S_k and SC_k), which is to measure how 'far' the received PQ performance is from the standard/expert specified state.

3) The priorities among different phenomena are calculated from pair-wise comparison among three PQ phenomena with weights assigned by a number of decision-makers/experts and they can vary from bus to bus depending on expert's perception of importance of particular phenomenon for customers connected at given bus. The principle eigenvectors of the pair-wise comparison are taken as the priority for each phenomenon (p_k).

4) Aggregate PQ performance based on:

$$PQ_{\mathrm{A}}\ (I_1,\dots,I_K)=\frac{\sum_{k=1}^{K}s_k\times p_k}{\sum_{k=1}^{K}sc_k\times p_k} \quad (4)$$

where K=3, the total number of considered PQ phenomena,

For convenience, the aforementioned procedure of deriving the aggregated PQ performance is denoted as AHP, and the Unified Bus Performance Index (UBPI) can be obtained by

$$UBPI_{i,j}=\mathrm{AHP}\ (BPI_{i,j}, THD_{i,j}, VUF_{i,j}) \quad (5)$$

Further details can be found in [20]. Different from other aggregated indices, standard specified critical PQ performance state is integrated in the aggregation procedure by (4), as it is believed that the inclusion of standard specified thresholds is essential to keep the methodology as relevant to industrial practice as possible. Furthermore, it greatly simplifies normalisation procedure and particularly suits optimisation problems, which will be further discussed later.

In (5), zonal PQ thresholds are not included yet. Given the aggregated PQ performance and zonal PQ thresholds (denoted as $UBPI_{\mathrm{TH}}$), the gap between the received UBPI and the zonal PQ thresholds can be defined as:

$$PQGI_{\mathrm{UBPI}}=\sum_{i=1}^{N}\left(\sum_{j=1}^{B_i}\left|UBPI_{i,j}-UBPI_{\mathrm{TH},i}\right|_{\mathrm{UBPI}_{i,j}>UBPI_{\mathrm{TH},i}}\right) \quad (6)$$

In (6), the performance of each PQ phenomenon in comparison to its threshold is not reflected, and the performance of different PQ phenomena can cancel each other. For instance, assume there exists a bus with poor performance with respect to sags (low BPI) and good performance with respect to harmonics (low THD) and unbalance (low VUF). In this case, the low BPI will be compensated by the good performance of the other two PQ phenomena when they are integrated in $PQGI_{\mathrm{UBPI}}$, and the contribution of each PQ phenomenon on the aggregated performance will not be reflected in the gap index. If the performance of each PQ phenomenon is expected to meet the threshold that is individually specified for this PQ phenomenon, (6) is not appropriate. Therefore, another PQ gap index, defined as (7), should be used for this purpose:

$$PQGI_{\mathrm{IND}}=\sum_{i=1}^{N}\left(\sum_{j=1}^{B_i}\mathrm{AHP}\left(\left|BPI_{i,j}-BPI_{\mathrm{TH},i}\right|_{\mathrm{BPI}_{i,j}>BPI_{\mathrm{TH},i}},\left|THD_{i,j}-THD_{\mathrm{TH},i}\right|_{THD_{i,j}>THD_{\mathrm{TH},i}},\left|VUF_{i,j}-VUF_{\mathrm{TH},i}\right|_{\mathrm{VUF}_{i,j}>VUF_{\mathrm{TH},i}}\right)\right) \quad (7)$$

The difference between (6) and (7) is that the former aggregates the performance of the three PQ phenomena first and then compares it with the zonal threshold presented as aggregated PQ performance, while the latter compares the performance of each PQ phenomenon with its corresponding zonal threshold first, and then aggregates the gaps of these three PQ phenomena together. It should be mentioned that among the five newly proposed gap indices, the study mainly focuses on (6) and (7). The aggregated PQ gap indices are used as optimisation objectives while (1)-(3) are provided for the convenience of comparing/analysing the performance of each PQ phenomenon individually.

The reasons for adopting AHP procedure in (5) and (7) are discussed below from the perspective of optimisation. The ranges of the evaluated severity indices of various PQ phenomena vary across the network and with time. Furthermore, even for one particular PQ phenomenon, the range of the evaluated severity indices varies greatly at different iterations as the optimisation process proceeds. In this case normalisation is required for each PQ phenomenon before aggregating the performance of different PQ phenomena together. In general normalisation can be completed by setting weights to the evaluated indices of different PQ phenomena. However, from the perspective of optimisation, the varying ranges of the severity indices during the optimisation process cannot be addressed by changing the weights when optimisation proceeds, as the objective function should adopt the fixed reference in order to enable the optimisation algorithm to evaluate whether the PQ performance is improved or not at different iterations. Proper weight settings require the prior knowledge of the range of each PQ index obtained with and without the application of mitigation solution. With this knowledge, the trade-off between the two ranges of severity indices (obtained with and without the application of mitigation) can be and should be considered when setting the weights. However, usually the ranges of the indices evaluated for various PQ phenomena are not known in advance, especially the ones obtained with the application of mitigation. In (5) and (7), the dilemma of setting weights can be avoided by using the normalisation approach of AHP, which aggregates the PQ performance by comparing the actual performance with the industrial standards which are used as fixed references. In this way, the step of setting weights for normalisation is not required, and the influence of each phenomenon on the aggregated PQ performance is incorporated via standards. The methodology of using AHP aggregation is suitable for the cases where the PQ performance is expected to follow preset standards and requirements, and it is particularly useful for constructing objective functions for optimisation purpose.

The impact of the adopted objective functions on the selection of the mitigation scheme and ultimately their impact on the final mitigated PQ performance are investigated through different scenarios. Six scenarios are introduced here:

Case 1: Optimisation based on *SGI*.

Case 2: Optimisation based on *HGI*.

Case 3: Optimisation based on *UGI*.

Case 4: Optimisation based on $PQGI_{\mathrm{UBPI}}$.

Case 5: Optimisation based on $PQGI_{\mathrm{IND}}$.

Case 6: Optimisation based on *UBPI* (the optimisation procedure terminates when *UBPI* reaches $UBPI_{\mathrm{TH}}$).

Among these six cases, the first five cases are based on gap indices in which zonal thresholds are included. In case 6 the zonal thresholds are not included in the optimisation process and they only serve as termination criteria. Besides, cases 1-3 are based on individual PQ phenomenon while cases 4-6 are based on aggregated PQ performance.

B. Initialising Allocation of FACTS Devices and Optimisation

In the study, passive filters (PF) and FACTS devices including Static VAR Compensator (SVC), Static Compensator (STATCOM) and Dynamic Voltage Restorer (DVR) are investigated for PQ mitigation [21]. SVC is a shunt device that regulates the voltage by controlling the reactive power generated into or absorbed from the power system. STATCOM regulates the voltage by adjusting the amount of reactive and active power transmitted between the power system and the Voltage Source Converter (VSC). DVR connected in series with the grid is capable of protecting sensitive loads against the voltage variations or disturbances via a VSC that injects a dynamically controlled voltage in series with the supply voltage through three single-phase transformers for correcting the load voltage. Passive filters, though, strictly speaking, not a FACTS device, are also considered as the potential solution for harmonic mitigation, as they have been, and are still most widely used for this purpose by utilities and industrial installations due to their cost- effectiveness.

The proposed methodology includes three parts, global selection, zonal selection and optimisation, as illustrated in Fig. 2. In order to place available devices optimally, potentially effective locations for their placement are selected based on the analysis of PQ performance and sensitivity analysis. The potential locations are chosen globally (i.e., based on the whole network) and zonally (i.e., based on zonal information) respectively. These locations form a pool of available locations for optimisation algorithm to select the optimal device placement.

1) Global selection. Buses are sorted according to performance indices *BPI*, *VUF*, *THD*, $\sum_{j=1}^{N_B}\left|\frac{\partial V_j}{\partial Q}\right|$ and $\sum_{j=1}^{N_B}\left|\frac{\partial V_j}{\partial P}\right|$ in descending order, respectively (step 1 in Fig. 2). The ranking index of bus B_i with respect to BPI is denoted as $R_{\mathrm{BPI}}(B_i)$, and the same applies to other variables. Then $R_{\mathrm{BPI}}(B_i)$=1 suggests that bus B_i is experiencing the worst sag performance, and $R_{\partial V/\partial Q}(B_i) = 1$ that the bus voltage in the network is the most sensitive to the injection of reactive power at bus B_i. The buses having R_{BPI}=1, R_{VUF}=1, the smallest $R_{\mathrm{BPI}} + R_{\partial V/\partial Q}$, the smallest $R_{\mathrm{VUF}} + R_{\partial V/\partial Q}$ and the smallest R_{BPI}+R_{VUF} are selected as the potential locations for installing SVC (step 2 in Fig. 2). The same procedure is applied to select the potential locations for installing STATCOM (step 3 in Fig. 2) and DVR (step 4 in Fig. 2), while in this case the selection is based on R_{BPI}=1, R_{VUF}=1, the smallest $R_{\mathrm{BPI}} + \frac{R_{\partial V/\partial P} + R_{\partial V/\partial Q}}{2}$, the smallest $R_{\mathrm{VUF}} + \frac{R_{\partial V/\partial P} + R_{\partial V/\partial Q}}{2}$ and the smallest R_{BPI}+R_{VUF}. It can be seen that instead of using $R_{\partial V/\partial Q}$, the $\frac{R_{\partial V/\partial P} + R_{\partial V/\partial Q}}{2}$ is used in this case as both STATCOM and DVR can transmit both active and reactive power between the devices and the grid. To initialise the placement of PF, the same selection procedure mentioned above is performed to select the potential locations, while the buses are ranked based on R_{THD} (steps 1 and 5 in Fig. 2). For each type of devices, following the selected devices of the same type are preliminarily placed at the selected potential locations, the selection procedure introduced above is then performed again to select the second set of potential locations (step 7 in Fig. 2). Besides, the intersections of two branches which have more than three buses in the downstream branches are also initially made available for placement of PF (step 6 in Fig. 2), as the PF located at the intersections can prevent the harmonic current flowing from one branch to another.

2) Zonal selection. To ensure the capability of providing certain PQ levels required in different zones, the potential locations should also be selected zonally (step 8 in Fig. 2). For zonal selection, the procedure is the same as the global selection, except that the ranking procedure is performed within the zones rather than within the whole network. Geography feasibility could be also taken into account during the process of selecting potential locations.

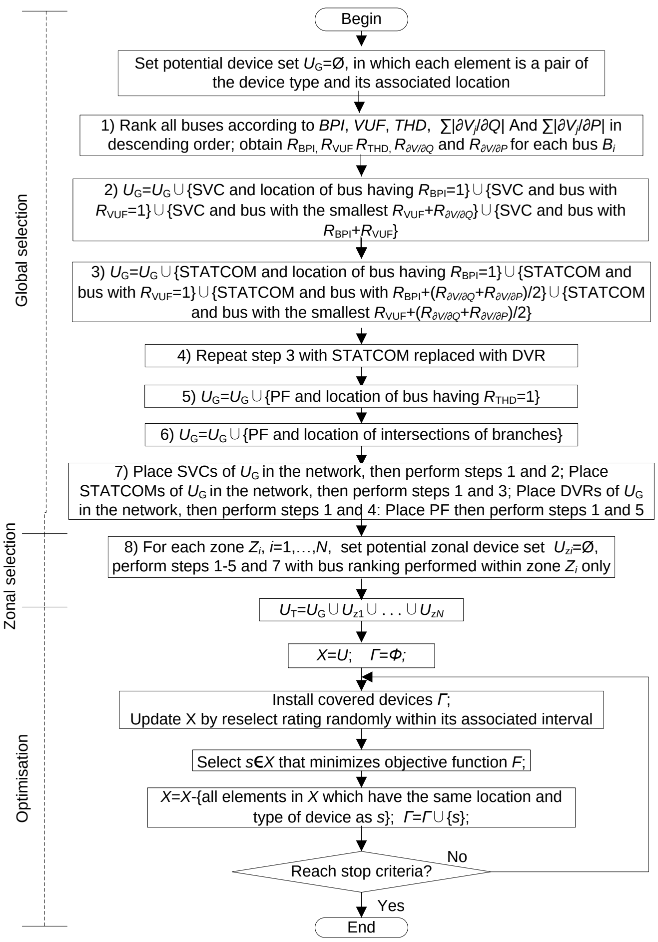


Fig. 2 Flowchart of the proposed methodology.

3) Optimisation using greedy algorithm. With these pre-selected locations, greedy algorithm [22] is used to search the optimal placement of FACTS devices and their optimal rating settings. Greedy algorithm is chosen due to its simplicity of implementation. It divides the problem into different consecutive stages and solves the problem heuristically by making the local optimal choice 'greedily' at each stage. The optimisation problem presented here belongs to a class of a combinatorial problems with independence property, i.e.: the considered mitigation devices have their respective control regions and two devices located far apart have typically limited influence on each other; two different devices located at the same bus, or at electrically close buses, may have conflicting control requirements and interfere with each other's operation. Greedy algorithm is particularly suitable for solving this class of optimisation problems and it has been successfully applied for device placement in large power systems in the past [23]. Further comparison between greedy algorithm and Genetic Algorithms will be given in Section III.

The optimisation procedure is provided in Fig. 2. A pool of potential solutions, denoted as set U_T, including types of the devices and the installation locations have been decided. Assume there are M_D potential devices. For each potential device, an extra variable needs to be determined, i.e. rating. The rating range of each device is divided into M_I intervals, and for each interval, a rating is chosen by randomly selecting a value within the interval. Thus, a pool of $M_D \times M_I$ potential solutions (i.e., U) which consists of locations, types of devices and ratings, are made available initially for optimisation.

With set U, the greedy algorithm is applied to select the optimal mitigation solution, as given in Fig. 2, where s is the chosen solution which is corresponding to the minimum objective value evaluated at each stage; Γ denotes the devices selected so far; and X is the updated pool of potential solutions at each stage. At each stage, X is updated by removing its elements which have the same location and type of devise as the selected s. The optimisation procedure can be terminated if the size of Γ reaches the preset maximum number of allowed devices, or if the improvement of PQ performance between two sequential stages is smaller than a preset threshold. Set Γ is selected as the final optimal mitigation solution. As the number of intervals M_I increases and reaches the resolution allowed in industrial practice, the optimisation procedure is approximately deterministic. For example, given one type of device and the rating range between 1-3MVA and assuming that the devices can be only manufactured with rating resolution of 1MVA, the potential ratings for selection will be 0, 1, 2 and 3MVA, so the greedy algorithm will select the best among the four ratings, i.e., the selection procedure is deterministic.

III. Case Study

A. Network Settings

In the study, a 295-bus generic distribution network (GDN), as shown in Fig. 3, is used [15, 16]. It comprises 275 kV transmission in-feeds, 132 kV and 33 kV predominantly meshed sub-transmission networks, and 11 kV predominantly radial distribution network. The network consists of 276 lines including overhead lines and underground cables, 37 transformers with various winding connections, 297 loads (including 10 unbalance loads) representing industrial, commercial and domestic loads, and 26 distributed generators (including 5 wind turbines, 9 fuel cells and 12 photovoltaic) connected to 11 kV distribution network. The wind generators were modeled as three phase asynchronous generators of DFIG type with the max output of 0.6 p.u. based on their full capacity. The fuel cells were connected as single phase static generators. As for the 12 photovoltaics, three photovoltaic generators are connected in three-phase, while the rest are connected in single-phase. Different types of DGs with different levels of harmonic injection were modeled using the embedded components in DIgSILENT. The locations of the unbalanced loads, fixed non-linear loads and different types of distributed generators are marked by different labels in Fig. 3.

The network is divided into three zones circled by solid red

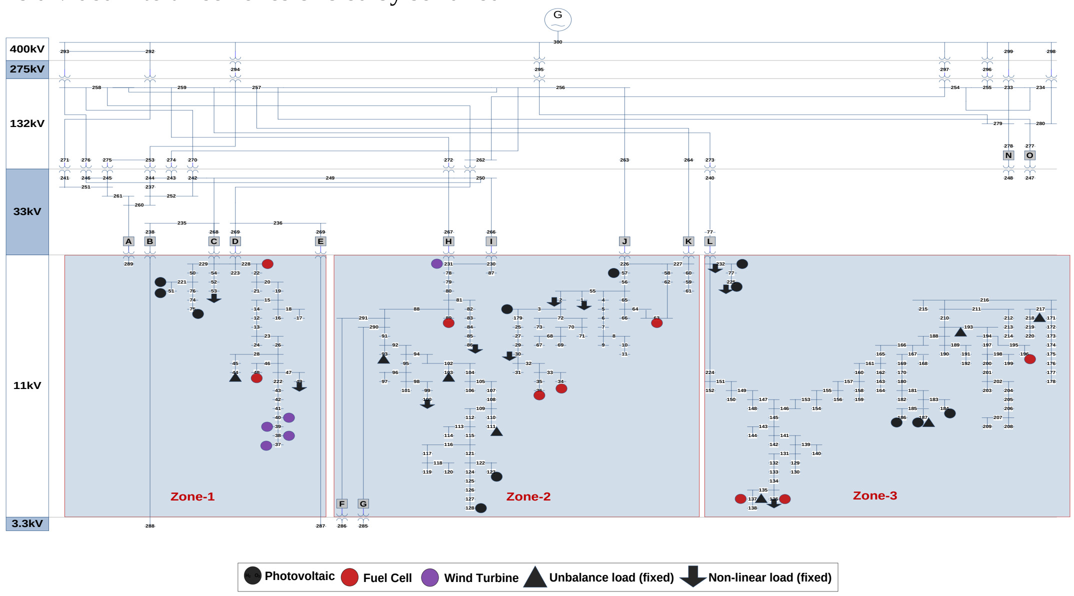


Fig. 3 Single line diagram of 295-bus generic distribution network.

lines. The zone division and zonal PQ requirements are set here for illustrative purposes only. They are based on the distribution of different classes of customers and the assumed sensitivities of different classes of customers to PQ disturbances. The industrial loads are mainly located in zone 2, thus zone 2 is assigned the most rigorous PQ requirement in the study, with $UBPI_{TH}$ set to 0.1724. $UBPI_{TH}$ in zones 1 and 3 are set to 0.2492 and 0.4628 respectively, to represent the differentiated levels of PQ requirements. All types of faults are considered. All simulations related to PQ phenomena are implemented in commercially available DIgSILENT/PowerFactory.

For voltage sag assessment, the components at different voltage levels have different fault rates. The detailed system fault statistics, the failure probability of primary protection relays and the mean and standard deviation of the distribution of fault clearing time applied for voltage sag assessment can be found in [16]. To model the unbalanced operation of a network, a number of loads are selected as potential sources of unbalance in the network. For these unbalance loads, real power demand at each phase is set according to the true load profile, while the reactive power is set based on power factors which are generated randomly based on a preset normal distribution. In the study, 10 unbalance loads are considered. The mean of the normally distributed power factors is set to 0.95 representing a general load [24], and their standard deviation is set to 0.053. Furthermore, 30 loads in total are selected as non-linear loads. Ten of these are fixed non-linear loads, which inject harmonic current into the grid at fixed locations. Further 20 loads are randomly selected (their location varies with different operating points) from the rest of the load buses and taken as non-linear loads. The ratio of the magnitude of the injected harmonic current to that of the fundamental component (used to model harmonic injection by nonlinear loads and generation) follows pre-set normal distributions. The mean values of the normal distribution used for different types of non-linear loads and various DGs (including PV and wind generators), not listed here due to space limitations, can be found in [25]. The standard deviation of the aforementioned normal distributions is set to 10% of the mean. 500 sets of weights were adopted to calculate priorities among different PQ phenomena in AHP, and the average of the 500 obtained aggregated indices is taken as the final aggregated index.

To reflect the PQ performance accurately, the variation of load profiles and network parameters are taken into account. Probabilistic modelling of residential and commercial loads based on the yearly load profile was proposed in [26, 27]. In this paper, annual hourly loading curves were extracted from 2010 survey of different types of loads (including commercial, industrial and residential loads), and 8760 operating points are obtained [28]. The wind and photovoltaic generators have annual hourly output curves which are extracted from the realistic outputs data based on the UK weather [29, 30]. The fuel cells are assumed to have a constant output. Since there exist similar patterns of load demand variation among loads of the same types (e.g., industrial, commercial and domestic loads) and similar variation trends of the outputs of certain DGs (i.e., PV) in terms of day and season, similar operating condition re-occurs throughout the whole year. Similar to the modelling approaches in [26], the representative operating points are selected through the process of clustering and evaluation. The industrial load, commercial load, domestic load and PV output are taken as the input to the classification approaches here. In the study, Cluster Evaluation of Statistics Toolbox in Matlab is used to find the representative operating condition. Various clustering approaches (K-means, fuzzy c-means, agglomerative clustering algorithm and Gaussian mixture distribution algorithm) and clustering criteria were tested, and the approach yielding the best results during evaluation is adopted here. The appropriateness of the obtained clusters is validated using the method of Silhouette [31]. It was found that the K-means with the clustering criterions of Calinski-Harabasz [32], which defines the ratio between the overall between-cluster variance and the overall within-cluster variance, yields the best results [33]. Using this approach, 9 representative operating points are obtained. Additionally, further 7 operating points corresponding to the maximum load, the maximum DG output, the maximum wind output, the maximum PV output, the maximum industrial load, the maximum commercial load, and the maximum domestic load are also accounted for in the simulation. In total there are 16 characteristic operating points taken into account. The average of the 16 indices evaluated from the 16 operating points respectively is taken as the objective function for optimisation.

B. Simulation Results

1) Compared with Genetic Algorithm (GA)

Genetic Algorithm has also been used to find the optimal solution (with the maximum number of allowed devices equal to 10) for two cases, one based on individual PQ performance (case 2) and the other based on aggregated PQ performance (case 5). Optimisation procedure is terminated if the improvement of the objective function among five continuous generations is <0.2%. For case 2, with 214 function evaluations, the objective function reaches zero with the solution involving 10 devices. For more complicated case, however, i.e., case 5, the final value of the objective function with GA is 1.691, while it is 0.132 with the greedy algorithm, i.e., the solution with the greedy algorithm is superior in this case. Therefore, greedy algorithms are used in the rest of the studies.

2) Optimisation based on individual PQ phenomenon

In cases 1-3 introduced in Section II-A, each PQ phenomenon is tackled individually. For these three cases, the optimisation procedure terminates if the evaluated gap index reaches zeros. In case 1, SGI reaches zero with the installation of 4 devices; in case 2, HGI reaches zero with 7 devices; and in case 3, 4 devices are required to reduce the UGI to zero. If all of these devices mentioned above are enabled simultaneously during the simulation, the load flow calculation cannot converge. It suggests that in PQ mitigation planning, it is more appropriate to consider the related critical phenomena simultaneously. Otherwise, the solution which directly combines the optimal schemes obtained from individual PQ phenomenon respectively could be infeasible.

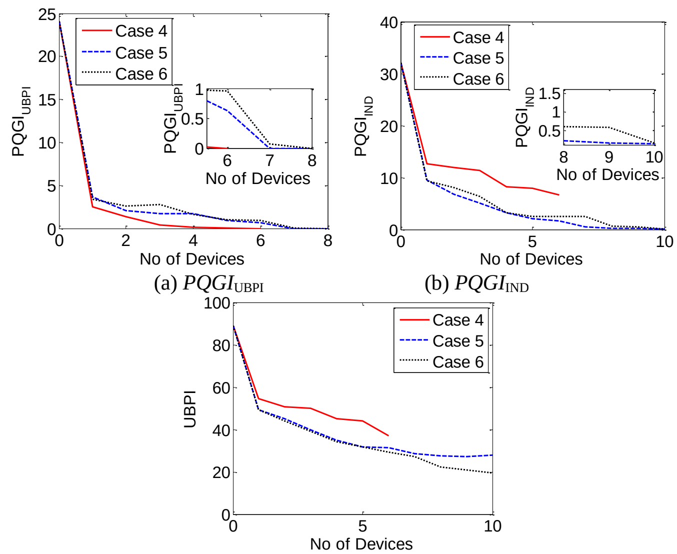
3) Optimisation based on aggregated PQ performance

In cases 4-6, the performance of the three PQ phenomena is aggregated in different ways, as introduced in Section II-A. In case 4, the thresholds are presented as $UBPI_{\mathrm{TH}}$, while in case 5 the thresholds are given individually for each PQ phenomenon. For the convenience of comparison, $UBPI_{\mathrm{TH}}$ adopted in case 4 is derived from the thresholds of individual PQ phenomenon used in case 5:

$$UBPI_{\mathrm{TH},i}=\mathrm{AHP}\ (BPI_{\mathrm{TH},i}, THD_{\mathrm{TH},i}, VUF_{\mathrm{TH},i}) \qquad (5)$$

In cases 4-5, the optimisation procedure terminates when the improvement of the associated index is <0.2%; in case 6, the optimisation procedure terminates when the improvement is <2%, as in this case thresholds are not included in the index and the evaluated values are relatively larger than those obtained in cases 4-5. For each case, three indices, including *UBPI*, $PQGI_{\mathrm{UBPI}}$ and $PQGI_{\mathrm{IND}}$, are evaluated against the number of devices installed. The convergence curves of these indices are provided in Fig. 4. It can be seen from Fig. 4 that the index being targeted at during optimisation converges faster than other indices. For instance, in Fig. 4(a), $PQGI_{\mathrm{UBPI}}$ obtained in case 4 converges faster than that in cases 5-6, as $PQGI_{\mathrm{UBPI}}$ is used as the objective function in case 4. To reduce $PQGI_{\mathrm{UBPI}}$ to zero, 6 devices are required in case 4, 7 devices in case 5, and 8 devices in case 6. In Fig. 4(b), $PQGI_{\mathrm{IND}}$ obtained in case 5 converges faster. $PQGI_{\mathrm{IND}}$ reaches 0.14 when 10 devices obtained from case 5 are installed, and $PQGI_{\mathrm{IND}}$ reaches 0.56 when 10 devices obtained from case 6 are installed. In Fig. 4(c), *UBPI* converges faster in case 6 compared to that obtained from cases 4-5.

UBPI, *BPI*, *THD* and *VUF* evaluated at all buses in various cases are provided in Fig. 5 (a)-(d) respectively. The results obtained in cases 1-3 are also provided in Fig. 5(b)-(d) to illustrate the difference between the performance of *BPI*, *THD* and *VUF* obtained based on the aggregated PQ performance and that obtained based on individual PQ phenomenon. The results of cases 1-3 in Fig. 5(b)-(d) present the feasibility of using FACTS devices for the purpose of mitigating individual PQ phenomenon, as the evaluated performance indices are well below their thresholds.

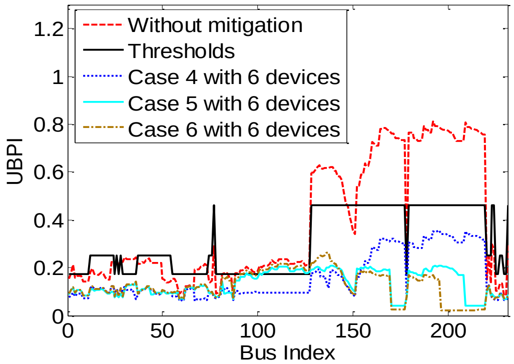


(a) $PQGI_{\mathrm{UBPI}}$ (b) $PQGI_{\mathrm{IND}}$

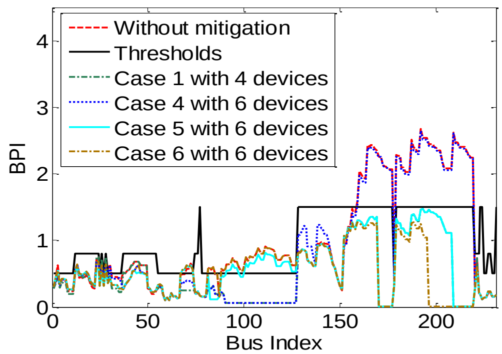
(c) *UBPI*

Fig. 4. The convergence curves of *UBPI*, $PQGI_{\mathrm{UBPI}}$ and $PQGI_{\mathrm{IND}}$ against the number of devices installed.

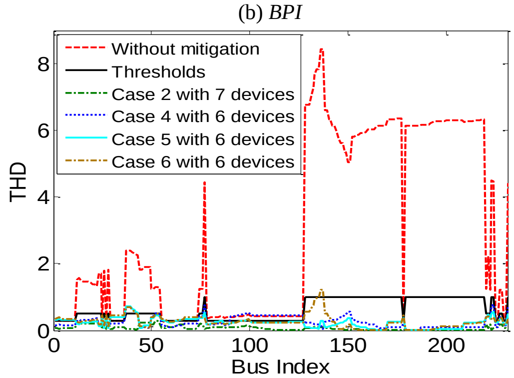
In Fig. 5 (a), *UBPI* at all buses obtained in case 4 meats the thresholds $UBPI_{\mathrm{TH}}$ as expected. However, as shown in Fig. 5 (b), the *BPI*s obtained at buses 159-219 in case 4, which contribute to the well-performed *UBPI*, i.e., UBPI obtained in case 4 in Fig. 5(a), are almost the same as those obtained without mitigation. They do not meet the customers' requirement if the BPI_{TH} is considered. However, the aggregated *UBPI* obtained in this case still meets threshold $UBPI_{\mathrm{TH}}$, due to *THD* and *VUF* (obtained at buses 159-219 in case 4) are well performed and they compensate/cancel the poor performance of *BPI* in *UBPI*. It can be seen that the simulation results presented here are in line with the discussion given in Section II-A, i.e., in case 4, the performance of various PQ phenomena can cancel each other, and the performance of individual phenomenon is not reflected in the aggregated gap index. In this case, the optimisation favours the devices which can easily improve one of the PQ phenomena that require less mitigation effort, such that the performance of this PQ phenomenon will compensate the performance of other PQ phenomena which requires more effort to be mitigated.



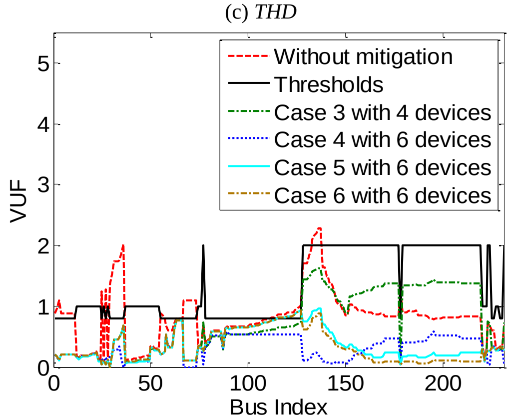
(a) *UBPI*



(b) *BPI*



(c) *THD*

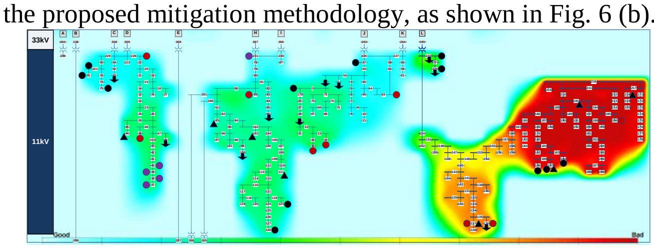


(d) *VUF*

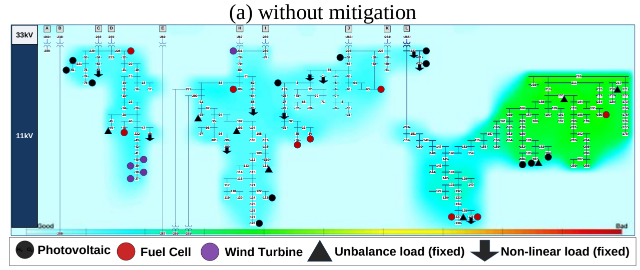
Fig. 5. *UBPI*, *BPI*, *THD* and *VUF* obtained with 6 devices in various cases.

In case 5, with the threshold of each phenomenon included in the gap index, the performance of each phenomenon (i.e., *BPI*, *THD* and *VUF*) together with the aggregated PQ performance (i.e., *UBPI*) can meet the expected thresholds with 6 devices, except at buses 100-157 where the evaluated *UBPI*s and *BPI*s are slightly above the thresholds, as shown in Fig. 5. Compared with cases 5-6, case 4 provides better mitigation solution if the PQ requirements/thresholds are given as aggregated PQ performance like $UBPI_{TH}$, as *UBPI* is the targeted objective in this case. If each PQ phenomenon has its own specific threshold that should be complied with, $PQGI_{IND}$ is more suitable to be used as objective function than considering overall PQ performance simultaneously.

To present the aggregated performance visually, and for the convenience of comparing the aggregated *UBPI*s obtained without and with mitigation, the heatmaps of *UBPI*s obtained with 6 devices from case 4 are plotted in Fig. 6. The critical area marked in red is exposed to severe PQ disruption, and it is greatly improved with the mitigation scheme obtained using the proposed mitigation methodology, as shown in Fig. 6 (b).



(a) without mitigation



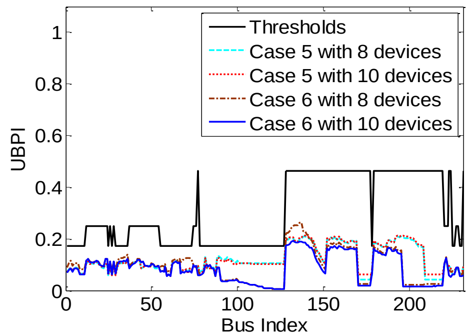
(b) with mitigation

Fig. 6. Heatmaps of *UBPI* obtained with 6 devices in case 4 with and without mitigation

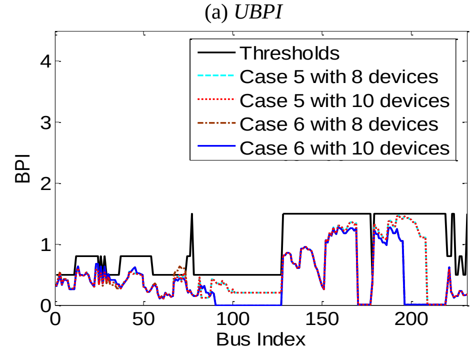
To present the PQ performance when more devices are allowed to be installed in the network, *UBPI*, *BPI*, *THD* and *VUF* at all buses obtained with 8 and 10 devices in cases 5-6 are provided in Fig. 7 (a)-(d) respectively. It can be seen that with more devices installed in the network, *UBPI*, *BPI* and *VUF* obtained in case 5 are well below the thresholds. If the performance of individual phenomenon compared to its threshold is concerned, case 5 provides better results than case 6. It presents the advantage of using $PQGI_{IND}$ as optimisation objective if individual PQ requirement is of concern.

4) Comparison of optimal solutions for different cases

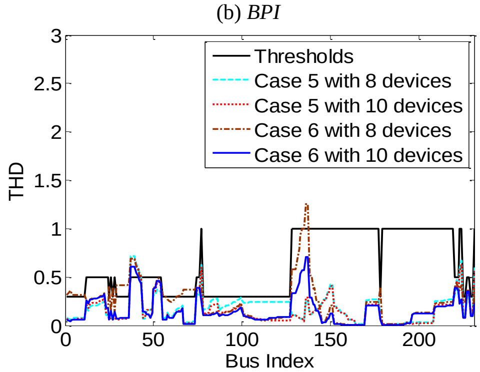
The optimal solutions obtained using previously defined optimisation-based selection rules for different cases are listed in Table I. For cases 1-3, the devices are selected to ensure that the corresponding indices are zeros; for cases 4-6, although the devices are selected based on different objective functions, the number of selected devices is determined based on the same criteria, i.e., when $PQGI_{UBPI}$ reaches zero. The optimal solution obtained for case 1 consists of three DVR and one SVC, which shows the preference of DVR for sag mitigation. It can be seen from case 2 that harmonic mitigation solution favours STATCOM. Apart from the harmonic mitigation, PF, working along with other active devices, also contribute to compensation of reactive power and ultimately voltage regulation. It can be seen from Table I that for cases 4-6, the optimal mitigation solution consists of different types of devices, including STATCOM, SVC, DVR and PF, as all three PQ phenomena are considered simultaneously in these cases. The investment costs for different cases are provided in Table I based on [34]. It can be seen that if the three PQ phenomena are tackled separately, to meet the requirements of all three PQ phenomena, it costs £790,000.00 (sum of the investment cost in cases 1-3), which is much higher than the cost when considering three phenomena simultaneously (e.g., cases 5 in which $PQGI_{\mathrm{IND}}$ is used).



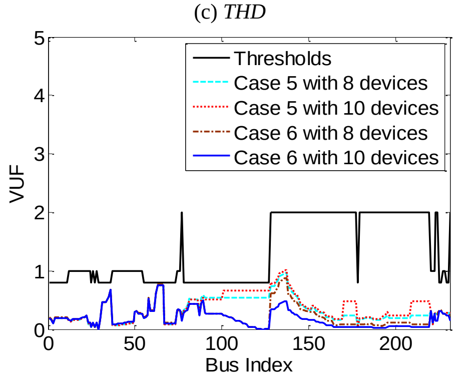
(a) *UBPI*



(b) *BPI*



(c) *THD*



(d) *VUF*

Fig. 7. *UBPI*, *BPI*, *THD* and *VUF* obtained with 8 and 10 devices in cases 5 and 6 respectively.

TABLE I
Optimal Solutions for Different Cases

Cases	type (size MVA) location	Costs
Case 1	DVR(4.40) at B72; DVR(7.71) at B210; DVR(6.01) at B291; SVC (6.42) at B165	£270,000.00
Case 2	STATCOM (1.34) at B29; STATCOM (4.38) at B42; STATCOM (7.27) at B124; STATCOM (7.18) at B210; SVC (6.66) at B196; PF (6.50) at B116; PF (4.52) at B232	£358,000.00
Case 3	SVC (6.98) at B29; STATCOM (4.20) at B28; PF (7.77) at B102; PF (5.59) at B136	£162,000.00
Case 4	STATCOM (7.85) at B48; STATCOM (6.88) at B138; SVC (5.47) at B36; SVC (6.55) at B72; PF (3.62) at B181; DVR (6.01) at B291	£347,000.00
Case 5	STATCOM (7.67) at B28; STATCOM (7.77) at B165; SVC (1.65) at B29; PF (5.68) at B136; DVR (7.4) at B82; DVR (3.30) at B102; DVR (2.55) at B210	£415,000.00
Case 6	STATCOM (4.40) at B48; STATCOM (7.10) at B165; SVC (3.26) at B29; SVC (7.13) at B124; PF (5.08) at B146; DVR (2.37) at B197; DVR (2.15) at B210; DVR (6.01) at B291	£483,000.00

IV. CONCLUSIONS

This paper presents the concept of provision of differentiated PQ based on customers' requirement. To facilitate this concept, five gap indices are proposed to present satisfaction levels of the received PQ performance compared to the PQ thresholds which are set based on either individual PQ phenomenon or the aggregated PQ performance. Based on the newly proposed gap indices, a mitigation methodology is proposed to search the optimal mitigation scheme. In this methodology, a set of potential locations are selected by globally and zonally ranking the buses according to their PQ performance, as well as the sensitivity of the PQ performance to the injection of active/reactive power at these buses. Given the potential set of FACTS devices, greedy algorithm is adopted to search the optimal mitigation scheme in order to minimize the gap between the actual received PQ performance and the imposed PQ thresholds.

The feasibility of the proposed methodology is presented in a 295-bus GDN while accounting for a number of uncertainty factors. The simulation results demonstrate that the proposed methodology yields promising mitigation scheme which ensures the received PQ performance meets the imposed thresholds as expected. The characteristics and benefits of the proposed gap indices are also analysed and compared in the paper. The results show that $PQGI_{\mathrm{UBPI}}$ can be chosen if the PQ thresholds are given in the form of aggregated PQ performance. However, in this case, the performance of different PQ phenomena can compensate/cancel each other, and the optimisation tends to select the mitigation scheme which targets the PQ phenomenon that is easier to be mitigated (i.e., requiring less mitigation effort), as long as the overall aggregated PQ performance meets the thresholds. $PQGI_{\mathrm{IND}}$ is preferred if the thresholds of various PQ phenomena are given individually. Unlike the case of adopting $PQGI_{\mathrm{UBPI}}$ as the objective function, when $PQGI_{\mathrm{IND}}$ is used, the performance of the multiple PQ phenomena is considered at the same time as well as the aggregated PQ performance, and the performance of each PQ phenomenon compared to its specific threshold is reflected in the gap index.

The proposed methodology particularly suits the distribution networks which have the characteristic of zonal centralization of customers of the same type. The presented methodology has been applied in practice on a small (35-bus) real distribution network as part of the work on the EU FP7 project. The methodology is flexible and can be easily modified for different networks, allowing the variation of the component modelling and data profiles. The main challenges of implementing the methodology is the requirement for substantial data (including customer profiles) and sufficient observability of the network in terms of factors that contribute to various PQ phenomena. If this information is not fully available, proper stochastic modelling of the critical components and PQ phenomena is required, as it has been and still is done in many studies. Considering rapid development in network monitoring (e.g., Advanced Metering Infrastructure) and deployment of advanced information and communication technologies, and the enhanced ability of collecting required data from the network, the amount of collected data is constantly increasing, hence the aforementioned challenges are constantly been reducing. Further analysis regarding scalability, repeatability, modelling flexibility and financial assessment (cost minimisation) in particular will be essential parts of the future work. The viability of different solutions will however strongly depend on the cost inquired and assessment of this cost, which is an extremely challenging topic in its own right.

V. References

[1] R. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality (2 Ed.)*. New York: McGraw-Hill, 2002.

[2] Spec. Semicon. Process, Equipment Voltage Sag Immunity, SEMI-F47-0706. Available: www. Semi.org.

[3] G. L. Hamm, G. Briggs, J. Burke, J. Waterman, C. Herig, S. Johnston, and H. Chao, "Marketing quality differentiated power," *IEEE Trans. on Power Syst.*, vol. 4, pp. 856-861, 1989.

[4] S. Junlakarn and M. Ilic, "Toward implementation of the reconfiguration for providing differentiated reliability options in distribution systems," in *Proc. 2014 IEEE PES General Meeting*, 2014, pp. 1-5.

[5] C. K. Woo, P. Sreedharan, J. Hargreaves, F. Kahrl, J. Wang, and I. Horowitz, "A review of electricity product differentiation," *Applied Energy*, vol. 114, pp. 262-272, 2014.

[6] J. Szkutnik, "The future European electric power system," in *Symposium ELEKTROENERGETIKA*, Stara Lesna, 2007, pp. 28-30.

[7] R. Yokoyama and K. Nara, "New concept of energy delivery network for practical use of distributed generations and customer services - committee report of IEE Japan," in *Proc. IFAC Symposium Power Plants and Power Systems Control*, South Korea, 2003.

[8] J. Thomas, "Development of methodology for online provision of differentiated quality of electricity supply," MSc. Electrical Power Systems, Fac. of Eng. and Phys. Sciences, The University of Manchester, 2012.

[9] E. Ghahremani and I. Kamwa, "Optimal placement of multiple-type FACTS devices to maximize power system loadability using a generic graphical user interface," *IEEE Trans Power Syst.*, vol. 28, pp. 764-778, 2013.

[10] J. V. Milanović and Y. Zhang, "Modeling of FACTS devices for voltage sag mitigation studies in large power systems," *IEEE Trans. Power Del.*, vol. 25, pp. 3044-3052, 2010.

[11] M. M. El Metwally, A. A. El Emary, F. M. El Bendary, and M. I. Mosaad, "Using FACTS controllers to balance distribution systems based ANN," in *Proc. Int. Mid. East Power Syst. Conf.*, 2006, pp. 81-86.

[12] R. Grunbaum, "FACTS for voltage control and power quality improvement in distribution grids," in *Proc. CIRED Semi. Smart Grids for Dist.*, 2008, pp. 1-4.

[13] J. V. Milanović and Z. Yan, "Global minimization of financial losses due to voltage sags with FACTS based devices," *IEEE Trans. on Power Del.*, vol. 25, pp. 298-306, 2010.

[14] F. B. Alhasawi and J. V. Milanović, "Techno-economic contribution of FACTS devices to the operation of power systems with high level of wind power integration," *IEEE Trans. Power Syst.*, vol. 27, pp. 1414-1421, 2012.

[15] J. Y. Chan, "Framework for assessment of economic feasibility of voltage sag mitigation solutions," Ph.D., Ph.D. thesis, Dep. Electr. And Electro. Eng., University of Manchester, Manchester, U.K., 2010.

[16] H. L. Liao, S. Abdelrahman, Y. Guo, and J. V. Milanović, "Identification of weak areas of power network based on exposure to voltage sags—Part II: assessment of network performance using sag severity index," *IEEE Trans. Power Del.* , vol. 30, pp. 2401 - 2409, 2015.

[17] A. Salarvand, B. Mirzaeian, and M. Moallem, "Obtaining a quantitative index for power quality evaluation in competitive electricity market," *IET Gen., Trans. & Dist.*, vol. 4, pp. 810-823, 2010.

[18] A. Bracale, P. Caramia, G. Carpinelli, A. Russo, and P. Verde, "Site and System Indices for Power-Quality Characterization of Distribution Networks With Distributed Generation," *IEEE Trans. on Power Del.*, vol. 26, pp. 1304-1316, 2011.

[19] S. A. Farghal, M. S. Kandil, and A. Elmitwally, "Quantifying electric power quality via fuzzy modelling and analytic hierarchy processing," *IEE Prc. - Gen., Trans. and Dist.*, vol. 149, pp. 44-49, 2002.

[20] S. Abdelrahman, H. Liao, T. Guo, Y. Guo, and J. V. Milanović, "Global assessment of power quality performance of networks using the analytic hierarchy process model," in *Proc. IEEE PowerTech*, Eindhoven, 2015, pp. 1-6.

[21] R. Asati and N. R. Kulkarni, "A review on the control strategies used for DSTATCOM and DVR," *Int. J. of Elec., Electr. Comp. Eng.*, vol. 2, pp. 59-64, 2013.

[22] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, *Introduction to Algorithms, 3rd ed.*: MIT press, 2009.

[23] J. M. A. Mora, "Monitor Placement for Estimaton of Voltage Sags in Power Systems," Ph.D. dissertation, Sch. of Electr. and Electro. Eng., University of Manchester, 2012.

[24] Z. Liu and J. V. Milanovi, "Probabilistic Estimation of Voltage Unbalance in MV Distribution Networks With Unbalanced Load," *IEEE Trans. on Power Del.*, vol. 30, pp. 693-703, 2015.

[25] S. Abdelrahman, H. Liao, J. Yu, and J. V. Milanović, "Probabilistic assessment of the impact of distributed generation and non-linear load on harmonic propagation in power systems," in *Proc. 18th Pow. Syst. Com. Conf.* , Wroclaw, Poland, 2014.

[26] M. K. Gray and W. G. Morsi, "Power Quality Assessment in Distribution Systems Embedded With Plug-In Hybrid and Battery Electric Vehicles," *IEEE Trans Power Syst.*, vol. 30, pp. 663-671, 2015.

[27] M. S. ElNozahy and M. M. A. Salama, "A Comprehensive Study of the Impacts of PHEVs on Residential Distribution Networks," *IEEE Trans on Sust Energy*, vol. 5, pp. 332-342, 2014.

[28] S. Hesmondhalgh, "GB energy demand-2010 and 2025. Initial brattle electricity demand-side model-scope for demand reduction and flexible response," 2012.

[29] CM SAF JRC EUROPEAN COMMISSION. Photovoltaic Geographical Information System - Interactive Maps [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.

[30] "The Renewable Energy Review," Committee on Climate Change, 2011.

[31] L. Kaufman and P. J. Rousseeuw, *Finding Groups in Data: An Introduction to Cluster Analysis*. Hoboken, NJ: John Wiley & Sons, Inc., 1990.

[32] T. Calinski and J. Harabasz, "A dendrite method for cluster analysis," *Comm. in Statist.*, vol. 3, pp. 1–27, 1974.

[33] S. Lloyd, "Least squares quantization in PCM," *IEEE Trans. Infor. Theory*, vol. 28, pp. 129-137, 1982.

[34] Y. Zhang, "Techno-economic Assessment of Voltage Sag Performance and Mitigation," Ph.D., Ph.D. dissertation, Dep. Electr. And Electro. Eng., University of Manchester, Manchester, U.K., 2008.

Huilian Liao (M'13) is currently working as a Research Associate at the University of Manchester, UK, investigating power quality.

Sami Abdelrahman (S'13) is completing his PhD degree at the University of Manchester, Manchester, UK.
Jovica V. Milanović (M'95, SM'98, F'10) is a Professor of electrical power engineering and Deputy Head of the School of Electrical and Electronic Engineering a at The University of Manchester, UK.