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Techno-Economic Analysis of Global Power Quality Mitigation Strategy for Provision of Differentiated Quality of Supply

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Abstract

This paper presents a comprehensive methodology for techno-economic assessment of power quality (PQ) mitigation solutions, both network-based and device-based, and proposes an optimisation-based PQ mitigation strategy for delivering differentiated PQ in networks integrated with renewable generation. The proposed strategy is based on the evaluation of financial losses due to several critical PQ phenomena, the cost of different mitigation solutions and the payback due to the adoption of particular solution. Furthermore, it accounts for different customers' requirements and provides differentiated levels of PQ across the network. The simulation results present both the financial and technical benefits of the optimal mitigation scheme.

Keywords: Power quality, mitigation strategy, techno-economic analysis, FACTS devices.

1. Introduction

Power quality (PQ) has been for a number of years one of the most important areas of research encompassing the whole chain of electricity supply from generation and transmission of electricity to its distribution and utilization. The most attention though is received from distribution companies and end users. Typical PQ phenomena in distribution networks include voltage sags, unbalances and harmonics [1, 2]. Insufficient PQ performance results in substantial financial losses to both utilities and customers. The productivity and competitiveness of manufacturing of the industrial customers suffer the most from the interruptions caused by PQ phenomena. The PQ requirements, however, vary from area to area, depending on the customers' line of business (commercial, industrial or residential) as well as the sensitivity of their processes and equipment to the PQ phenomena. Different groups of customers also may have different requirement for the quality of supply and consequently their willingness to invest in improvement of PQ or to pay premium price for better quality of supply may be different. Therefore it is appropriate to consider

possibility of providing differentiated levels of PQ to different zones (large geographical areas of the network or collocated groups of customers with similar PQ requirements) of the network while the PQ threshold of each zone is set based on customers' requirements in that zone. This approach requires less mitigation effort on the part of the utility while the important customers or those requiring premium PQ may still receive the service that they need. It also improves the efficiency of electricity/energy distribution by only ensuring the PQ performance as required, it reduces the investment cost, and helps utilities to price the electricity accordingly. In this way the utilities can get additional revenue from offering a differentiated and guaranteed PQ levels, and ultimately plan mitigation solutions based on customers' willingness to pay in different areas. This provides a fair way to subsidize the mitigation activity. Therefore, in PQ mitigation planning, it is necessary to address the difference in PQ requirements among different zones [3].

To ensure adequate PQ performance at point of delivery, a variety of mitigation techniques have been proposed in the past at different levels of system hierarchy. At equipment and process level, the equipment can be made more immune to quality of power supply, and the process design can incorporate more redundancy and fail proof approach. PQ mitigation can also be handled at plant level and network level. The overall

improvement of PQ levels in demarcated zones of the network has wider scope of application and offers higher overall benefit when the mitigation activity is performed at network level. Network wide mitigation can be implemented by adopting various preventive strategies including appropriate design, planning, operating and maintaining different aspects of networks. Although these strategies yield good results, they are still not sufficient to offer a guaranteed quality of supply at all time. Alternatively, real-time compensation strategy can be applied to provide network level mitigation solution using custom power devices based on flexible ac transmission system (FACTS) devices. With the fast development of smart grid technologies and the enhanced features and functionality of the latest generation of power-electronic-based devices, FACTS devices become even more feasible global mitigation option. They have been thoroughly studied over the years considering their application in power systems for various purposes [4], including PQ mitigation, [5-8] and there are a number of examples around the world of successful practical applications of different FACTS devices for this purpose. However, in vast majority of cases, if not exclusively, FACTS devices have been considered and applied for mitigation of one particular PQ phenomenon or for mitigating a few PQ issues at a single bus. Typically the FACTS devices can affect more than one PQ phenomenon and contribute to PQ improvement to more than one bus at the same time. From the perspective of efficiency and economy, it is necessary to consider the critical and other related PQ phenomena simultaneously as well as potential contribution to PQ improvement to more than one bus while planning the placement of FACTS devices for PQ mitigation.

Financial compensation for poor PQ is still not widely spread, partly due to the insufficient awareness among customers/end-users regarding the financial loss due to inadequate PQ supply, as well as the insufficient studies of the benefits resulting from applying PQ mitigation solutions. From an economic and efficiency point of view, the utilities will have incentive to improve service quality up to the point where the cost of doing so equals the willingness to pay value of the quality [9]. If PQ mitigation is handled by utilities at network level, individual customers do not have to make huge upfront investments in capital costs for insulating themselves against PQ problems. Instead, they only need to pay a relatively small amount of tariff to utilities for performing the network-level mitigation activities. With the increase in reported financial losses caused by PQ phenomena (which may be also a consequence of more appropriate accounting for these losses), and a drive and regulatory pressure to improve global PQ performance of the network, the economic benefits of PQ mitigation should be studied more thoroughly. PQ mitigation should be planned based on proper techno-economic assessment of the mitigation solutions and the economic quantification of financial losses due to various PQ phenomena in power systems and end users. Various methods and techniques have been proposed for the quantification of the financial impact of different PQ phenomena [9-11], and a number of methods have been provided in the past for the

economic quantification of various mitigation techniques [12, 13]. However, comprehensive assessment of financial benefits of a range of PQ mitigation solutions for a number of PQ phenomena simultaneously while considering both financial impact of PQ phenomena and financial investment in various mitigation techniques is still missing in available literature.

This paper presents for the first time the methodology for comprehensive techno-economic assessment of both range of PQ phenomena (voltage sags, unbalance and harmonics) and mitigation techniques (network-based and device-based mitigation solutions), as well as the methodology for assessing technical PQ performance with respect to different customers' requirements across the network. It focuses on: i) definition of a global (several PQ phenomena are taken into account simultaneously) PQ planning problem by considering both technical and economic perspectives; ii) proposal of an objective function that incorporates both, technical and economic, aspects into optimisation for development of global solution; 3) and development of an optimisation-based global PQ planning approach to mitigate a range of critical PQ phenomena to different required levels across the network simultaneously. This paper builds on and extends the work presented in [3] by introducing comprehensive, rigorous economic analysis into the problem of provision of differentiated PQ which assesses the financial losses due to several critical PQ phenomena simultaneously, the cost of different mitigation solutions, both device and network based (only device based solutions were used in [3]) and the payback due to the adoption of particular solution over the lifetime of the solution. A new objective function is therefore developed and used for optimisation in this paper, compared to [3], to incorporate both technical and economic aspects together. The global mitigation strategy is determined/selected based on the comprehensive techno-economic analysis, rather than purely based on technical aspect of the problem. The proposed mitigation strategy facilitates more informed decision-making as it takes into account the cost of critical PQ issues and the cost of various mitigation approaches. The long-term financial benefits of applying the proposed mitigation scheme are demonstrated on the representative 295-bus distribution network.

2. Methodology

2.1. Mitigation approaches

In this study, three PQ phenomena, voltage sags, harmonics and unbalance, are considered simultaneously as they are generally acknowledged to be the most likely cause of equipment failure or malfunction and interruption of industrial processes and thus direct cause of massive financial loss to customers and distribution network as a whole. Both device-based and network-based solutions introduced below are considered for PQ mitigation in the study.

1) *Device-based solutions*: FACTS devices including Static VAR Compensator (SVC), Static Compensator (STATCOM) and Dynamic Voltage Restorers (DVR) are investigated for PQ mitigation [5, 6]. Passive filters (PF)

are also selected as the potential device based solution for mitigation of harmonics, as they have been, and are still widely used to mitigate harmonics in power networks and industrial facilities.

2) *Network-based solutions*: Voltage disturbance including voltage sags and interruption observed in distribution networks originate typically from short circuit faults in the transmission and distribution networks. Thus voltage disturbance of this type can be mitigated by reducing the possibility of fault occurrence. The mitigating solutions that can be implemented at critical locations (ones with higher fault rates) is provided in Table 1 [15, 16]. Instead of reducing fault rates, the phenomena of voltage sags can be also mitigated by reducing the fault severity. The severity of faults can be reduced by reducing fault clearing time, i.e., the response time of circuit breakers, or by placing fault current limiters around the network. Apart from filters, harmonics can also be mitigated by placement of line reactors [17], by the selection of appropriate transformer winding connections [2], using zigzag and grounding connected or transformers phase shifting transformers (quasi 12-pulse methods) [17].

Table 1

| Effectiveness and cost of various network based solutions [15,16] | | |
|---|---|-----------------|
| Techniques | Effect on improved feeder | Assumed cost/km |
| undergrounding | Dig-in faults remains | £100,000.00 |
| Shield wire | 78% reduction in lightning faults | £22,800.00 |
| Surge arrester | 78% reduction in lightning faults | £8,150.00 |
| Animal guard | 50% reduction in animal caused faults | £200.00 |
| Tree trimming | 20% reduction in tree caused faults for every year earlier than 5 years | £200.00 /trim |
| Insulated line | 75% reduction in lightning faults, 100% reduction in contact faults | £10,000.00 |
| Communication | Assume 50% less dig-ins | £100.00 |

2.2. Financial Assessment

When financially assessing PQ mitigation at planning level, it is important to consider the benefits during the entire life span of the deployed solution. The upfront investment made for a mitigation solution pays back its returns only during the life span duration. This makes it important to consider the net present value of future benefits, as well as the net present value of future maintenance. This brings the investment cost and its future benefit to a common ground/level of comparison with planning or deployment year as the reference. The net present value approach accounts for the factors like inflation (denoted as i), discount rate (denoted as r) and escalation rate (denoted as e) required for the assessment of time value of money. Net present value (NPV) can be calculated using the following equation [14]:

$$NPV = CI + \frac{\sum_{t=0}^n (C_{tb} + C_{tc}) \times (1+e)^t}{(1+r)(1+i)^t} \quad (1)$$

where CI denotes the initial capital investment (usually expressed as a negative amount), C_{tb} denotes the benefit component (difference between original cost and remaining cost after the installation of the solution) occurring at the beginning of time period t ; and C_{tc} denotes the cost component (annual maintenance cost)

occurring at beginning of time period (usually expressed as a negative amount).

1) Assessment of financial consequence of PQ phenomena

Detailed analysis of economic impact due to voltage sags, unbalance and harmonics are very important while considering the investment in PQ mitigation. Economic impact can be assessed by identifying losses to different types of business due to various PQ phenomena. Considering the diversity of business types that exists, customers can be categorized based on their previous history of economic losses due to inadequate PQ performance, similarities in their business process and the sensitivity of their equipment/devices. This categorization enables the evaluation of the economic impact of a group of customers using a common model, thus each category has a unique model for analysis. This economic impact provides an estimate of financial losses for that particular customer at a given level of PQ in the network. Since losses caused by voltage sags, unbalance and harmonics are due to different reasons, it requires separate financial assessment models for each of them.

The financial losses to industrial customers due to voltage sags are mainly caused by the subsequent process trips. When assessing the probability of having process trips the main elements/parameters that should be considered include sag characteristics, frequency of sags at the customer busbars, equipment sensitivity, customer plant sensitivity, process operational cycle and the plant's load profile [18]. With realistic modelling of process cycle and proper probabilistic modelling of uncertainties associated with each of the influential parameters, risk-based analysis approach is applied to assess the possibility of having industrial process trips by modeling the industrial process and performing risk analysis with the consideration of process immunity time [19]. The financial loss due to a sag event can be assessed by:

$$\left(\text{Financial loss} \right) = \left(\text{Process failure risk} \right) \times \left(\text{Loss due to process trip} \right) \quad (2)$$

where the loss due to process trip can be obtained through survey or from customers directly.

According to the general classification of unbalance cost proposed by CIGRE/CIREN C4.107 report in the context of customers [9], economic losses due to unbalance phenomena are mainly caused by power and energy losses and the shortened life of equipment. NEMA recommends the use of de-rating curves for calculating power loss in induction motors [20]. The loss of power can be converted to financial cost using the rate of unit cost of energy over a period of time. By applying the NPV method it is possible to identify the accumulated cost of energy losses over the period of system study. These costs are considered as operating costs since this gets accounted into the operating expense incurred from payment of electricity charges by a business.

Customers with economic activities as specified in NACE (e.g., manufacture of motor vehicles, food products, electronic products, etc.) [21] have substantial installation of induction motors and suffer the most from equipment ageing issues. Equipment ageing due to

thermal stress can be modeled as [22, 23]:

$$L = L'_0 e^{-(Bc\theta)} \quad (3)$$

where L'_0 refers to the reference life of the equipment for reference temperature θ_0 ; B is a constant for a material represented as $B = E/K$, where E is the activation energy of the aging reaction in Joule/mol and K is the gas constant in $\text{JK}^{-1}\text{mol}^{-1}$; θ is the operating temperature in the presence of unbalance.

As per NEMA guidelines the approximate increase in winding temperature $\Delta\theta$ in induction motors due to percentage voltage unbalance V_{as} can be calculated using $\Delta\theta = 2V_{as}^2$. A decrease in useful life of the motors results in economic loss due to equipment replacement and process disruption caused by the equipment damage. The financial cost due to equipment ageing can be calculated to a good approximation by $(L'_0 - L)/L'_0 \times C_{re}$, where C_{re} denotes the cost of replacing the motors [9, 21].

Financial losses due to voltage/current harmonics can be classified into the categories of energy losses, losses due to premature ageing and losses due to equipment malfunction. CIGRE/CIREC C4.107 report suggests the methodologies for evaluating economic losses arising from wave form distortion caused by harmonics [9]. The losses in electrical motors caused by harmonics can be calculated with [9]:

$$P_M = 3 \sum_{h=h_1}^{h_{\max}} \left(\frac{V^h}{Z_M^h}\right)^2 R_M^h + P_{co}^1 \sum_{h=h_1}^{h_{\max}} \left(\frac{V^h}{Z_M^h}\right)^{m_M} \frac{1}{h^{0.6}} \quad (4)$$

where V^h represents the voltage harmonic of order h ; Z_M^h and R_M^h denote the equivalent impedance and resistance of the motor at the harmonic of order h respectively; P_{co}^1 denotes the core loss at the fundamental frequency; and m_M is the numerical coefficient.

Harmonic distortions also cause additional electric and thermal stresses in the insulating materials of electric equipment. A simple electro thermal life model recommended by CIGRE/CIREC C4.107 can be represented by [22, 23]:

$$L = L'_0 (K_p)^{-n_p} e^{-(Bc\theta)} \quad (5)$$

where K_p is the peak factor of the voltage waveform, represented by $K_p = V_p/V_{1p}^*$ where V_p is the value of the distorted voltage and V_{1p}^* is the peak value of the fundamental voltage; n_p is the coefficient related to the shape of the distorted waveform; $c\theta = 1/\theta_0 - 1/\theta$.

The aforementioned financial losses due to various PQ phenomena can be summed up and their NPV is calculated to identify the present worth of future economic PQ losses, by applying $\sum_{t=0}^n C_{PQt} \times (1+e)^t / ((1+r)(1+i))^t$ where C_{PQt} denotes the sum of costs due to different PQ phenomena at time period t , and e , i and r are, as before, escalation rate, inflation and discount rate, respectively.

The assessed financial cost may vary in practical depending on the accuracy of the data collected from customers. Generally with more accurate information used for assessment, the financial analysis will provide more valuable reference. The data accuracy can be evaluated by the nature of customers and data source etc. If the cost information is not provided by certain customers, it can be estimated from customers with similar nature but assigned with larger uncertainty for probabilistic financial

assessment.

2) Financial assessment of mitigation techniques

The capital costs of SVC, DVR and PF can be obtained based on curve fitting approach using available cost records. The costs of DVR and STATCOM are considered to be the same. The capital cost including construction cost of these devices can be defined as [12]:

$$C_{STAT+con} = 553(-0.0008S_{STAT}^2 + 0.155S_{STAT} + 120) \left(\frac{E}{MVAr}\right) \quad (6)$$

$$C_{DVR+con} = 553(-0.0008S_{DVR}^2 + 0.155S_{DVR} + 120) \left(\frac{E}{MVAr}\right) \quad (7)$$

$$C_{SVC+con} = 553(0.0003S_{SVC}^2 - 0.3051S_{SVC} + 127.38) \left(\frac{E}{MVAr}\right) \quad (8)$$

where S_{STAT} , S_{DVR} and S_{SVC} denote the sizes of STATCOM, DVR and SVC respectively. Continuous maintenance costs incurred every year during the life time are assumed to be 5% for SVC, and 10% for STATCOM and DVR, of their capital cost.

A conservative reactance of 0.1p.u. is used for each Fault Current Limiter (FCL), and the cost of owning and installing FCL is based on the cost model with the ten-year owning costs based on ABB products [24], with annual operation and maintenance costs at 5% of initial cost. The cost of passive filters is based on [25], with the continuous maintenance costs incurred every year assumed to be 5%. The cost of placing phase shifting transformers are based on [17], with annual maintenance costs at 5% of initial cost. The transformer connection related cost is calculated based on [26], assuming that the copper wire is 3% of the weight of the distribution transformers, and the weight of distribution transformers is based on ABB oil distribution transformer catalogue. The investment costs of other network-based mitigation techniques are given in Table 1, with annual maintenance costs at 5% of the initial cost. Tree trimming is scheduled to be carried out every 5 years.

2.3. Provision of Differentiated PQ levels

Generally customers with similar types locate in the same area. Based on the types of customer groups and sensitivity of their equipment/process to PQ phenomena, a network can be divided into zones that have various PQ requirements. Three critical PQ phenomena, voltage sags, unbalance and harmonics, are mainly considered in the study. For each PQ phenomenon, an appropriate PQ severity index is selected to present the main concern from the perspective of utilities and customers. To present the practical consequence of voltage sags from the system/equipment operation's point of view, Bus Performance Index (BPI) [18] is selected to evaluate the severity of voltage sags, as it takes various sag characteristics into account while simultaneously considering the sensitivity of equipment to voltage sags. Widely used evaluation indices Total Harmonic Distortion (THD) and voltage unbalance factor (VUF) are adopted to evaluate harmonics and unbalance phenomena respectively [2]. The threshold of the PQ phenomenon can be decided based on the impact of the PQ phenomenon on customers' equipment/process. Since in general one mitigation device can affect more than one PQ phenomenon, the three aforementioned PQ phenomena

should be considered simultaneously when searching for the optimal mitigation solution. In this paper, Unified Bus Performance Index (UBPI) defined as (9) is adopted to represent the aggregated performance of the three PQ phenomena [3]:

$$UBPI_{i,j} = AHP(BPI_{i,j}, THD_{i,j}, VUF_{i,j}) \quad (9)$$

where AHP (Analytic Hierarchy Process) is the aggregation procedure introduced in [27] and applied in [3] for assessment of aggregate PQ performance. With this aggregation approach, the gap between the actual PQ performance $UBPI$ and the aggregated thresholds $UBPI_{TH}$ as given in (10) is adopted to reflect the customers' satisfaction level on the PQ performance received.

$$PQGI_{UBPI} = \sum_{i=1}^N \left(\sum_{j=1}^{B_i} |UBPI_{i,j} - UBPI_{TH,i}|_{UBPI_{i,j} > UBPI_{TH,i}} \right) \quad (10)$$

Further details regarding the aggregation index and the provision of differentiated PQ levels can be found in [3].

2.4. Problem Definition and Optimisation

In the study, the problem is defined as an optimisation problem, which applies the mitigation solutions in the network optimally in order to minimise the overall financial cost that includes the investment cost, operation/maintenance cost and the cost caused by various PQ phenomena, and to maximise the benefits as a result of the application of mitigation solution. Simultaneously, in planning PQ mitigation, the provision of differentiated PQ levels should be facilitated among different zones of the network based on customers' requirements. The provision of differentiated PQ levels is considered as the technical requirement, and treated as a constraint to be imposed during the optimisation process. In the study, the technical requirement is included in the objective function using Lagrangian relaxation [28]. The present value of annual operation/maintenance cost and cost due to various PQ phenomena during the entire life span of the deployed solution is calculated using NPV method. To achieve the aforementioned objectives, an objective function (F) to be minimised in the optimisation problem is proposed and defined as:

$$F = C_m - C_b + \beta \times PQGI_{UBPI} \quad (11)$$

$$C_m = C_{ICI} + \frac{\sum_{t=0}^n (C_{AnnOpeMai}^t) \times (1+e)^t}{((1+r)(1+i))^t} \quad (12)$$

$$C_b = \frac{\sum_{t=0}^n (C_{PQ}^{1t} - C_{PQ}^{2t}) \times (1+e)^t}{((1+r)(1+i))^t} \quad (13)$$

where C_{PQ}^{1t} and C_{PQ}^{2t} denote the costs of PQ phenomena without and with mitigation, respectively at time period t and β is a Lagrange multiplier which imposes the penalty to the selected mitigation scheme if the technical constraints are violated. The total period for evaluation is 40 years. To avoid confusion, all cost variables in (11)-(13) are expressed as positive values (€). It can be seen that the smaller C_m is, the less investment cost is required. The financial benefit of placing the mitigation techniques, denoted as C_b , is calculated by $(C_{PQ}^{1t} - C_{PQ}^{2t})$, as shown in (13). In (11), negative sign is applied to $C_{benefit}$ so that the optimisation procedure will attempt to maximise the benefit. $\Delta C = (C_m - C_b) < 0$ suggests that the subsequent financial benefits resulting from the application of mitigation techniques will cover the initial capital

investment and maintenance cost of these mitigation techniques, and placing the selected mitigation scheme is beneficial in the long run.

2.5. Optimisation Methodology

In order to optimally place the mitigation techniques introduced in Section 2.1, potential and effective locations are selected based on evaluated PQ performance together with sensitivity analysis, and will be made initially available for optimisation search. Geography feasibility of the potential mitigation location should be also considered during selecting the potential mitigation techniques. Locations are selected based on rankings of buses, which are ranked based on BPI , VUF and THD , and the sensitivity of the voltages on the injection of reactive and active power, i.e., $\sum_{j=1}^{N_B} \left| \frac{\partial V_j}{\partial Q} \right|$ and $\sum_{j=1}^{N_B} \left| \frac{\partial V_j}{\partial P} \right|$. With these rankings, global and zonal selection of the potential locations are carried out based on the whole network and zonal information respectively [3]. Given the pool of pre-selected locations and the applied mitigation techniques, greedy algorithm is applied to find out the optimal mitigation solution (i.e., the optimal locations for the implementation of mitigation techniques and the optimal settings for the applied techniques if exist) to minimise the objective function F as defined in (11), which incorporates both financial assessment (including PQ cost and cost of PQ mitigation) introduced in Section 2.2 and technical requirement provided in Section 2.3. The search procedure in optimisation is terminated if either of the following requirements is met: 1) the number of iterations reaches the predefined maximum number; 2) the improvement of PQ performance between two continuous iterations is negligible by being smaller than a preset value.

3. Case Study

3.1. Test Network

The proposed approach is demonstrated on a 295-bus generic distribution network (GDN) [18], shown in Fig. 1. It comprises different types of sub-networks such as transmission in-feeds, predominantly meshed sub-transmission networks and predominantly radial distribution network at four different voltage levels (275 kV, 132 kV, 33 kV and 11 kV). The network consists of 37 transformers with various winding connections and 276 lines with different line types (e.g., overhead lines and underground cables). There are in total 297 loads with different types of customers, e.g., industrial, commercial and domestic customers. Among these loads, 10 loads are unbalanced and 30 loads are non-linear. 26 distributed generators (DGs) are connected in 11 kV distribution network, including 12 photovoltaic, 9 fuel cells and 5 wind turbines. The photovoltaics have either three-phase or single-phase connection. The fuel cells are connected in single-phase, and the wind generators are connected in three-phase with a model of asynchronous generators of DFIG type. Using the embedded components in DlgSILENT, different types of DGs have different levels

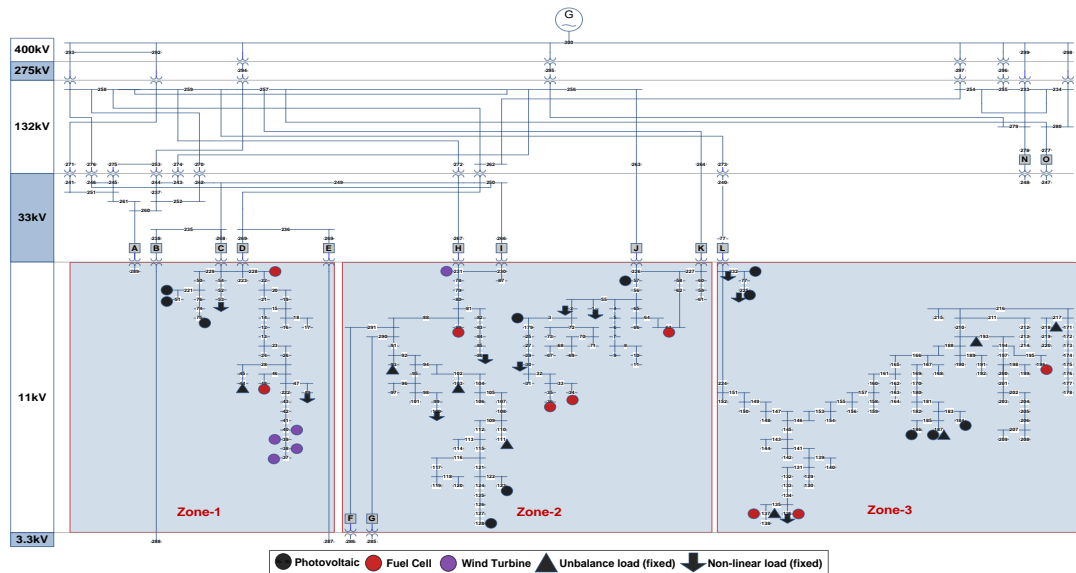


Fig. 1. Single line diagram of 295-bus generic distribution network.

of harmonic injection. The locations of the unbalanced loads, non-linear loads and different types of distributed generators are marked in Fig. 1. Based on the distribution of different classes of customers in certain area and the assumed PQ requirement of the predominated customers, the network is divided into three zones, as given in Fig. 1. The customers in zone 2 (predominately the industrial loads) have the most rigorous PQ requirement in the study, thus the $UBPI_{TH}$ in this zone is set to 0.1724. To present the different PQ requirements by customers in different zones, $UBPI_{TH}$ in zones 1 and 3 are set to 0.2492 and 0.4628 respectively [3]. In the study, the zone division given in Fig. 1 and zonal PQ requirement are set for illustrative purposes only. The BPI thresholds/limits in zones 1-3 are set to 0.8, 0.5 and 1.5 respectively; the THD thresholds are set to 0.5, 0.3 and 1 respectively; and the VUF thresholds are set to 1, 0.8 and 2 respectively. In total 500 sets of weights were adopted to calculate priorities among different PQ phenomena using AHP, and the ranges adopted to select weights for BPI, THD and VUF are [10, 20], [5, 15] and [6, 10], respectively. The average of the 500 obtained aggregated indices is then taken as the final aggregated index. Further details regarding the settings adopted to calculate $UBPI$ can be found in [3] and [29]. The simulations related to the modellings of mitigation devices and various PQ phenomena are implemented in commercial software DIgSILENT/PowerFactory.

Different components are assigned with different fault rates based on the types of the components and their voltage levels. The assessment of voltage sags takes into account failure probability of primary protection relays and the uncertainty of the fault clearing time, which are generated randomly based on predefined normal distributions. Real power demand at each phase of the unbalance loads is set based on true load profiles. The reactive power of these unbalance loads is derived from randomly generated power factors which follow a normal distribution with the mean of 0.95 representing a general load. Among the 30 non-linear loads, 10 of them inject

harmonic current into the grid at fixed locations, named as fixed non-linear loads. The rest 20 non-linear sources are randomly selected from the unselected load buses and their location varies with operating condition. The modelling of harmonic current injection takes uncertainty into account by setting the ratio of the injected harmonic current to the fundamental component based on predefined normal distributions.

The variation of network parameters and load profiles are considered in the study in order to accurately evaluate the PQ performance. Annual hourly output curves of wind turbines and photovoltaic are extracted from realistic outputs data in UK [30, 31]. The outputs of fuel cells are assumed to be constant. The annual hourly loading information of various types of loads, including industrial, commercial and residential loads, are obtained from 2010 survey [32]. The maximum loadings of various types of customers and the maximum outputs of the wind turbine and photovoltaic are at different times of the year. In total 8760 operating points are obtained to present the annual operating condition. Though loadings of different types of loads (commercial, industrial and domestic loads) and the outputs of different types of DGs have their own variation patterns in terms of day and season, similar operating conditions repeat throughout a year. In the study, the annual operating points are clustered using Cluster Evaluation of Statistics Toolbox in Matlab, and the centroids of the clusters are selected as the representative operating conditions. The method of Silhouette is applied to evaluate the appropriateness of the obtained clusters. The study also take into account the extreme operating points, e.g., the operating condition corresponding to the maximum loadings of various types of loads (i.e., domestic, industrial and commercial loads) and the maximum outputs of various DGs (wind turbines and photovoltaic). In total 16 characteristic operating points are simulated in the study. The mean of the PQ performance evaluated from the 16 operating points respectively is used to calculate the aggregated PQ performance and incorporated in the objective function for

the purpose of optimisation. Table 2 provides the examples of the structure of industrial processes used for calculating the financial loss to industrial customers [10]. The nominal life of the motors used in the financial assessment is set to 40 years, and the nominal operating temperature is 85°C. The distribution of the causes of the faults in the network, i.e., lightning faults, animal contact, tree contact and dig-in faults etc., are based on [16].

Table 2

| Details of Processes Adopted for Financial Assessment | | | |
|---|---------------------|-------------|---------------------------|
| Cust. | Equipment | Sub Process | Process dependency Matrix |
| A | PLC, ASD | 1,2,3,4 | 1111,1101,1010,0111 |
| B | PLC, ASD | 1,2,3,4 | 1111,1101,0010,0111 |
| C | PLC, ASD, Contactor | 1,2,3,4 | 1111,1101,0010,1001 |
| D | PC, ASD | 1,2,3,4 | 110,110,001 |

3.2. Simulation Results

In the study, the Lagrange multiplier β in (11) is set in a way that the evaluated technical constraint component ($\beta \times PQGI_{UBPI}$) is approximately equal to (or slightly larger than) the costs of PQ phenomena. Based on this, β is set to 1E8. The convergence curves of various variables, including F , ΔC , $PQGI_{UBPI}$, C_m , and C_{PQ} (i.e., the NPV cost of PQ phenomena calculated over the life span of mitigation solution), are presented in Fig. 2.

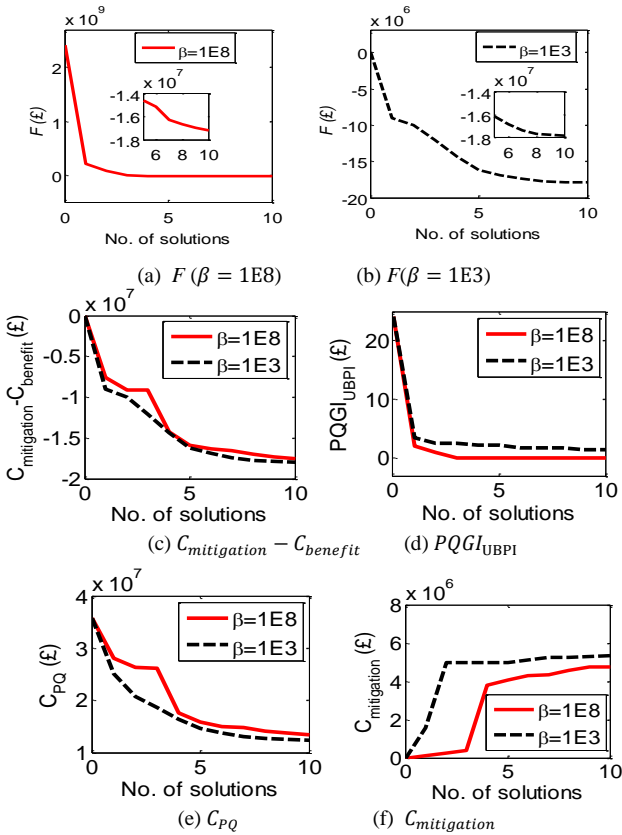


Fig. 2. Convergence curves of various components against the number of mitigation solutions applied.

Table 3

| PQ Costs and Benefits Obtained Over the Lifetime of Devices and Pay Back Period | | | |
|---|----------------|----------------|------------------|
| Case | PQ cost | Benefits | Pay-back (years) |
| No mitigation | £35,700,000.00 | N/A | N/A |
| $\beta = 1E8$ | £13,400,000.00 | £22,300,000.00 | 6 |
| $\beta = 1E3$ | £12,400,000.00 | £23,300,000.00 | 5 |

Without mitigation, only the Lagrange component $\beta \times PQGI_{UBPI}$, i.e., the technical constraints of ($UBPI - UBPI_{TH}$), contributes to the objective evaluation. At the leftmost points in Fig. 2 (a), $F = 2.41E9$ when $\beta = 1E8$. It can be seen that the objective value F is reduced significantly after one solution is applied to the grid. When the number of mitigation solutions > 5 , F tends to converge steadily, though its improvement is not as significant as that when the number of mitigation solutions < 5 . As seen from (11), F is composed of ΔC and $\beta \times PQGI_{UBPI}$. The two components are presented in Fig. 2 (c) and (d), respectively. Without any mitigation, both C_m and C_b are zero. Thus it can be seen from Fig. 2 (c) that $\Delta C = 0$ when the number of solutions applied is zero. Afterwards, the obtained ΔC is smaller than zero constantly, which suggests that the financial benefits resulting from the application of the selected mitigation solution at the network level will cover the initial capital investment and maintenance cost of the mitigation. The costs of PQ phenomena and PQ mitigation are presented in Fig. 2 (e) and (f) respectively, and it can be seen that C_{PQ} follows the same convergence trends as that in Fig. 2 (c). Table 3 provides the PQ related financial loss (without and with mitigation), the benefits over the lifetime of devices and the pay-back periods. The investment cost can be paid back within six years when $\beta = 1E8$.

To present the PQ performance throughout the network visually, and for the convenience of comparing the aggregated $UBPI$ obtained with and without mitigation, the heatmaps of $UBPI$ s obtained without mitigation and with 10 devices ($\beta = 1E8$) are plotted in Fig. 3 (a) and (b) respectively. The critical area marked in red in Fig. 3 (a) is exposed to severe PQ disruption, and it is greatly improved by applying the optimal mitigation solution obtained, as shown in Fig. 3 (b).

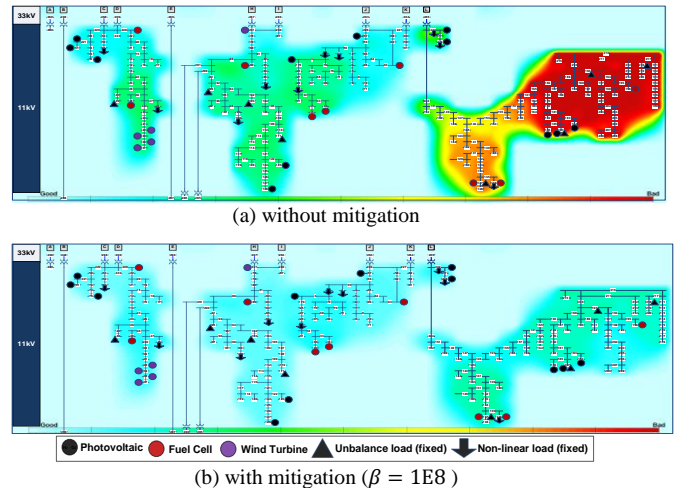


Fig. 3. Heatmaps of $UBPI$ s obtained with the application of 10 solutions with and without mitigation.

The data provided by customers present different accuracy levels depending on data sources and customer nature. Industrial customers may have more sophisticated approaches to collect data and thus have more accurate cost information. In the simulation, customers are classified into three groups with each assigned with one of the uncertainty levels, i.e., 2.5%, 5% or 7.5% variation. The obtained solution is analysed and it gives that the standard deviation of the PQ cost obtained is 1.59E5, while that of the benefit is 1.83E5. The benefit is slightly larger than PQ cost as the uncertainty of the PQ cost without mitigation also contributes to the variation of the final benefit calculation. As for the economic assessment of the mitigation solutions, the capital investment cost and annual maintenance cost are also assigned different level of accuracy, namely 2.5% and 7.5% variation, respectively. The value of capital investment is assumed to be more accurate than the maintenance cost as the latter will occur in the future. The results yield 4.43% variation in the assessed total mitigation cost due to the assumed variation (inaccuracy) in capital and maintenance costs. At the same time the results show that the variation of the assumed capital investment cost is more critical than the variation of the maintenance cost, even though the latter was three times higher (7.5% compared to 2.5% variation), due to its much higher share (61.35%) of the total mitigation cost. In this simulation, the most likely cost is used in the process of selecting the mitigation solution.

1) Comparison on different settings of β

In the study, β is also set to a much smaller value 1E3, i.e., 1×10^3 , to present the impact of β on the solution selection. The convergence of various components obtained by setting β to 1E3 is shown in Fig. 2. In Fig. 2 (c), for each convergence curve, except for the leftmost points of the curves, ΔC obtained when $\beta = 1E3$ is always slightly smaller than that obtained when $\beta = 1E8$. However, in Fig. 2 (d), $PQGI_{UBPI}$ obtained with $\beta = 1E3$ is constantly larger than that obtained when $\beta = 1E8$. It can be seen that when β is set to $\beta = 1E8$, the optimisation will favour the mitigation schemes which are able to meet the technical constraints well and at the same time are financially preferable, especially at the early stage of the optimisation process. From a financial perspective the mitigation cost can be paid back one year earlier when $\beta = 1E3$ compared to the case of $\beta = 1E8$ as seen from Table 3.

With smaller β , the importance of technical constraints are not addressed as well as when $\beta = 1E8$, as shown in Fig. 2(d). The satisfaction of the received PQ performance in comparison to customer specified thresholds, $UBPI$ s evaluated at all buses together with the specified thresholds are provided in Fig. 4 (a). It can be seen that without mitigation, most buses violate the PQ thresholds. With the application of the mitigation solution obtained with $\beta = 1E8$, the PQ performance received at almost all buses meet the corresponding PQ thresholds. If the mitigation solution obtained with $\beta = 1E3$ is applied to the grid, there still exist a relatively large number of $UBPI$ s which are larger than the PQ thresholds. To present the gap between the received $UBPI$ s and the thresholds, $(UBPI - UBPI_{Th})$ evaluated at all buses are also given in Fig. 4 (b). With $\beta = 1E8$, the technical constraints are met

stringently. However, when $\beta = 1E3$, in total there are 64 buses violating the requirements.

The solutions obtained for $\beta = 1E3$ and $\beta = 1E8$ respectively are listed in Table 4 including the type, size and installation location of the selected FACTS devices and the zones of the selected network-based techniques. The network-based solutions which can be implemented at critical locations in zones are selected, in both cases, based on to their cost-effectiveness advantage. When $\beta = 1E8$ (see Table 4) the obtained optimal solutions consist of three FCLs that contribute to the mitigation of fault severity and when $\beta = 1E3$ the obtained solution consists of three phase shift transformers that contribute to the harmonic mitigation. When $\beta = 1E3$, apart from the sag mitigation, harmonic mitigation is emphasized as well due to the financial cost caused by this phenomenon. It can be seen that the influence of the PQ phenomena on their contribution to economic and technical evaluations.

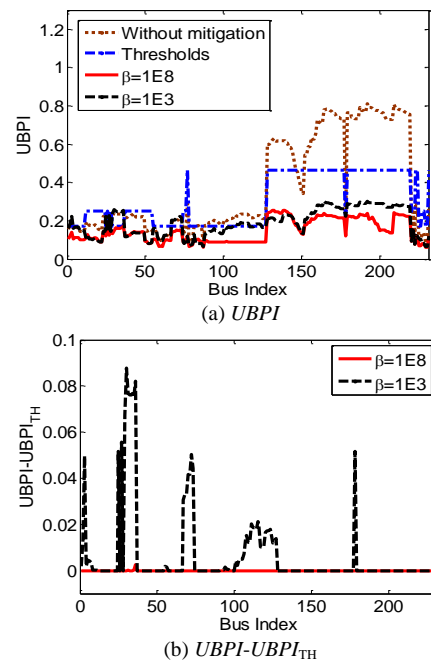


Fig. 4. PQ performance of various buses obtained with 10 solutions.

Table 4

| Optimal Solutions for Different PQ Phenomena | |
|--|---|
| PQ | type (size MVA) and location of mitigating solutions |
| $\beta = 1E3$ | DVR (4.73) at B82; PF (2.18) at B135; phase shifting transformer installation at B2, B86 and B100; cable communication improvement at critical locations in zones 2 and 3; animal guard at critical locations in zone 3; tree trimming at critical locations in zone 3; line insulation at critical locations in zone 3 |
| $\beta = 1E8$ | STATCOM (5.47) at B29; SVC (2.66) at B201; DVR (6.01) at B291; FCL at B47-B222; FCL at B153-B155; FCL at B211-B216; cable communication improvement at critical locations in zones 2 and 3; tree trimming at critical locations in zone 3; line insulation at critical locations in zone 3 |
| Tech only | STATCOM (5.47) at B29; SVC (7.85) at B27; SVC (2.66) at B39; DVR (6.79) at B66; Animal guard at critical locations in zone 2 |

2) Comparison from technical performance index only

The optimisation based on technical performance index only is also carried out in the study. In total nine alternative mitigation strategies which meet $PQGI_{UBPI}=0$ are obtained in the simulation. In this case one strategy

should be selected. The one with the least cost is selected (see Table 4). The convergence of its performance is shown in Fig. 5, together with that obtained from previous techno-economic analysis. It can be seen that the two approaches produce very similar technical convergence characteristic. However the technical index based approach is likely to choose device-based solutions which are more expensive as shown in Table 4.

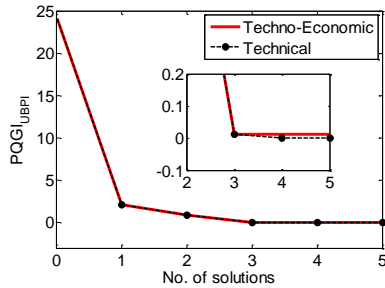


Fig. 5. The comparison between two different analysis approaches.

4. Conclusions

The paper presents an optimisation-based methodology for global techno-economic PQ mitigation in distribution networks with renewable generation. It considers for the first time in published literature: i) Financial losses due to industrial process trips, equipment aging issues and power losses, etc. caused by several PQ phenomena simultaneously; ii) The cost of versatile mitigation solutions (including network-based and device-based mitigation solutions) over the entire life span of the deployed solution; iii) The provision of differentiated PQ levels to customers in different zones based on different zonal requirements by incorporating the technical requirements in the optimisation process using the approach of Lagrangian relaxation.

The simulation results illustrated using heatmaps of distribution network based on *UBPIs*, demonstrate that applying chosen mitigation solution is beneficial in the long run, as the financial benefits of applying the solution are much larger than the initial capital investment and maintenance cost of the PQ mitigation. The impact of the setting of Lagrangian multiplier β on the final selected mitigation solution is also analysed. The results show that a larger β allows the technical PQ requirements (minimizing the violation of set thresholds for considered PQ phenomena) to have more influence on the selection of the final solution, and smaller β places more influence on the final cost of the solution, i.e., payback period.

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