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ORIGINAL PAPER

Role of Renewable Energy Sources in Evaluating Technical and Economic Efficiency of Power Quality

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Abstract

Due to the growing use of Renewable Energy Sources (RES) in many countries, the need for an accurate and detailed analysis from the technical and economic view point seems to be necessary. Power Quality (PQ) can also be another considerable matter that needs to be carefully evaluated. In this regards, in this article, an analytical and detailed approach is presented to evaluate the technical and economic performance of the strategy for PQ changes. In addition, an optimization-based PQ change strategy is presented to provide a distinct PQ in integrated grids with renewable generations. The proposed strategy is based on the assessment of financial losses due to changes in the quality of power and the cost estimation of various reduction approaches and repayment solutions. This approach presents various customer requirements and various levels of PQ in the power grid. In order to evaluate the performance of the proposed method, the effectiveness of the presented model has been utilised in an actual case study, and the results have been obtained and analysed. The results of the simulation provide both technical and financial advantages to obtain optimal change strategy.

Keywords Renewable energy · Power quality assessment · Technical evaluation · Economic analysis

Introduction

Background

Nowadays energy is an indispensable element in the country's economic development, and with increasing the standards of living in the world and also global population growth, global energy demand has been increased considerably [1, 2]. Renewable Energy Sources (RESs) are indigenous and could contribute towards energy sufficiency [3–5]. There are a number of financial motivations for installing renewable energy resources such as distributed photo-voltaic (PV), wind and biomass power plant to replace with fossil fuel power plant in several countries [6–9]. Before planning for the design, decision- making, and also operation of energy systems, it is important to have a quantificational analysis in terms of the economic and technical feasibility of RESs' exploitation [10, 11]. Besides, Power Quality (PQ) becomes serious importance for analysing power systems. For a number of years,

Power quality assessment is one of the most important areas of research in the entire power supply chain has been the production and transmission of electricity. Also, higher PQ has been one of the most important issues demanded by distribution companies and end users; inflation, voltage changes, power outages, imbalances, and harmonics are the most important factors in power quality changes in distribution networks [12, 13]. It should also be noted that the poor performance of energy quality leads to significant financial losses for both companies and services. Productivity and competitiveness in manufacturing industrial customers suffer most from interruptions caused by electricity and PQ phenomena [14]. Although the PQ requirements change from area to area, its changes depend on customers' policies and the sensitivity of their processes and equipment to PQ phenomena. [15]. Therefore it is suitable to consider possibility of providing differentiated levels of power quality to different zones of the grid whereas the PQ threshold of every zone is set based

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on customers' requirements in that zone [16]. Such methods require less mitigation attempt on the part of the utility whereas the important customers or those requiring premium PQ might still receive the service which they need.

Many researches have mentioned that the equipment can be made more immune to have a better quality of power supply, and the process design can incorporate more redundancy and fail proof approach; besides, PQ mitigation approach can be handled at plant and grid levels.

The overall improvement of PQ levels in demarcated zones of the grid can have a wider scope of application, and offers higher overall advantages when the mitigation activity is carried out at grid level. Grid wide mitigation can be performed by adopting several preventive strategies such as appropriate and suitable design, planning, operating and maintaining different aspects of grids. Nonetheless, such methods obtain suitable results, they are still not adequate to present a guaranteed quality of power supply at all-time. Additionally, maintaining a high level of system security can be one of the more important issues of power systems that should be noted as well as the economic and technical operation of such systems [17–19].

Literature Review

At the same time as the population is growing as well as the increasing use of electricity, various technologies from distributed generation units, including fossil fuel-based and renewable-distributed products, are being used to meet the needs of consumers along with centralized production and power plants. In this regard, the need for better power control on the consumption side has led to the formation of micro grids. One of the most important issues in micro grids is to improve network power quality to increase customer satisfaction and critical loads. On the other hand, today, the use of renewable energy sources based on renewable energy is expanding to reduce the use of fossil fuels and the production of environmental pollutants. Most of these units, like wind and photovoltaic units due to the random nature of their input energy (wind and solar), have output power of an irregular and variable nature, which can affect the quality of power in the subnets. Therefore, it can be used with Dynamic Voltage Restorer (DVR) to improve power quality in micro networks, where the DVR control structure including controller coefficients is optimally determined. Since the problem is a nonlinear problem, methods such as Particle Swarm Optimization (PSO) can be used to perform the optimization.

In the past decade, a number of methods have been presented for the economic quantification of various mitigation techniques. For instance, in the paper [20], authors provided a technical and economic assessment of a hybrid system in the city of Semirom in Iran which was carried out by a techno-economic assessment on combined utilization of diesel and solar-wind sub-system. Additionally, in recent years, wide variety mitigation methods have been provided at different levels of system hierarchy, to ensure appropriate PQ implementation at point of delivery. Several researches have pointed that with the improvements in voltage and current handling capabilities of the power electronic equipment which have allowed for the development of Flexible AC Transmission System (FACTS), the possibility and effectiveness have arisen in using different models of controllers for appropriate series and shunt compensation [21, 22]. It is vital to argue that FACTS and Static VAR Compensator (SVC) devices respond quickly to the changes in grid condition. For power transmission systems, the concept of FACTS devices is basically expanded, but similar idea has been started to be applied in power distribution systems. In addition, Distribution FACTS (D-FACTS) devices have been utilised widely for many purposes for compensation of several PQ problems in power distribution systems [21, 23, 24] that would occur in short duration in millisecond range.

Also, D-FACTS can inject both active and reactive power to the system for make-up of sensitive loads, and active power injection into the system can be provided by energy storage system. Furthermore, Distribution STATCOM (D-STATCOM) is a shunt connected voltage source converter that have been utilised to make up some of the PQ problems including voltage sag, unbalanced loads, voltage unbalance, and voltage fluctuation. DVR is also a series connected converter which is utilized to compensate PQ problems. Another equipment is Unified Power Quality Conditioner (UPQC) which is integrated of shunt and series compensators have been utilized to improve dynamic active and reactive power regulation, voltage flicker, voltage mitigation, voltage unbalance, and harmonics [23, 25].

However, in several cases, if not exclusively, FACTS devices have been considered and applied for mitigation of one specific PQ phenomenon or for mitigating a few PQ subjects at a single bus bar. Typically, the FACTS devices can affect more than one PQ phenomenon and can help to PQ improvement to more than one bus bar simultaneously. From the viewpoint of efficiency and economy, it is vital to consider the critical and other related PQ phenomena at the same time as well as potential contribution to PQ improvement to more than one bus bar whereas planning the placement of FACTS devices for PQ mitigation [26, 27].

For poor PQ, financial compensation is still not widely spread, partly owing to the insufficient awareness among customers and end-users regarding the financial loss owing to inadequate PQ supply and the insufficient researches of the advantages resulting from applying PQ mitigation solutions. From an economic and efficiency point of view, these utilities will have incentive to develop service quality to the point that the cost of doing so equals the willingness to pay value of the quality [26].

If PQ mitigation be investigated by utilities at national network level, most individual customers are not compelled to make too much upfront investments in capital expenses for insulating themselves against PQ problems. As opposed to that, people can just pay relatively small tariffs to utilities for the mitigation of performing network-level activities. With the growth in the reported financial losses caused by PQ phenomena (which might be a consequence of other suitable accounting for these losses), and a drive and regulatory pressure to increase global power quality performance of the power grid, the economic advantages of PQ mitigation has to be studied more deeply. PQ mitigation has to be planed based on suitable technical and economic assessment of the mitigation solutions and the economic quantification of financial losses due to various PQ phenomena in power systems and end users. However, comprehensive analysis of financial advantages 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. Table 1 shows a literature review about the PQ considering financial, technical, and FACTS considering renewable energy generation effects.

Motivation and Main Contribution

In this paper, a comprehensive analytical methodology for technical and economic analysis of both ranges of PQ phenomena for voltage sags, unbalance and harmonics, and mitigation techniques for grid-based and device-based mitigation solutions are provided. Additionally, the methodology for assessing technical PQ performance with respect to different customers' requirements throughout the grid is proposed. The main objectives of this article are organised as follows: to begin with, a worldwide PQ planning issues by considering technical and economic perspectives that several PQ phenomena has been considered into account simultaneously is defined; then, an objective function which incorporates technical and economic perspectives into optimization for development of worldwide solution is presented; and at the end, an optimisation-based worldwide PQ planning approach to mitigate a range of critical PQ phenomena to different required levels across the grid simultaneously is developed and analysed. The long-term financial benefits of applying the proposed mitigation scheme are demonstrated on an IEEE 118-bus distribution power grid; optimal solutions for the selected FACTS devices considering renewable energy generation in different zones are presented.

Paper Structure

The rest of this article is organized as follows: in Section 2, the fundamental theories of the proposed approach are presented. Section 3 describes a detailed case study analysis for our assumed PQ approach. In Section 4, the simulation results are provided; and finally, the conclusions are given in Section 5.

Material and Method

Power Quality Change Procedures

In order to have a detailed study, in this article, most PQ phenomena including: voltage sags, unbalance, and harmonics phenomena are considered into account simultaneously as they are usually acknowledged to be the most likely causes of equipment failure, outage, malfunction and interruption of industrial processes which have direct causes of huge financial losses to customers and distribution grid as a whole. In this article, for PQ mitigation, both equipment-based and grid-based solutions that introduced below are considered.

Table 1 Literature review of power quality considering: financial issues, technical issues, FACTS issues, renewable energy issues

Ref	Economic factors	Technical factors	Data analysis	Using FACTS devices	Using renewable generations	Published year
[28]	No	Yes	No	Yes	Yes	2008
[13]	No	Yes	Yes	No	No	2009
[29]	No	Yes	Yes	No	No	2002
[26]	Yes	No	Yes	No	No	2011
[30]	No	Yes	Yes	No	No	2010
[31]	Yes	Yes	No	Yes	No	2010
[25]	No	Yes	No	No	No	2009
[16]	Yes	Yes	Yes	No	Yes	2017
[32]	No	Yes	Yes	No	Yes	2018
[33]	No	Yes	Yes	No	Yes	2018

- *Equipment-based solutions*: In recent years, FACTS devices have been making a good progress in their instructors. FACTS devices such as STATCOM, SVC, and DVR are investigated for PQ mitigation. It should be noted that Passive Filters (PFs) are also selected as the potential device-based solution for mitigation of harmonics, and they are still widely utilised to reduce harmonics in industrial facilities and electric power networks.
- *Grid-based solutions*: Voltage disturbance such as voltage sags and interruption observed in distribution grids originate specially from short circuit faults in the transmission and distribution grids. Consequently, voltage disturbance of this type can be mitigated by reducing the possibility of fault occurrence. For example, in Table 2, the effectiveness and possibility of the mitigating solutions that can be performed at critical locations (ones with higher trip rates) are presented.

As opposed to decreasing failure rates, the phenomena of voltage sags can be also reduced by decreasing the fault intensity. The intensity of failures can be decreased by diminishing failure clearing time; by placing failure current limiters around the network, or the Circuit Breakers' response time. Apart from filters, harmonics can also be reduced by placement of line reactors [36], by the selection of appropriate transformer winding connections [12], and with using grounding and zigzag connected, or phase shifting transformers in quasi 12-pulse methods [36].

Economic Assessment

Firs, at planning stage, when financially evaluating PQ mitigation, it is important to consider our attention to the advantages during the entire life span of the deployed solution. It has to be mention that the upfront investment made for a mitigation solution approach pays back its returns just during the life span duration. This makes it vital to consider the Net Present Value (NPV) of future advantages, also the NPV of future maintenance. It should be mentioned that this brings the investment cost and its future advantage to a common ground or stage of comparison to planning or deployment year as the reference.

NPV method accounts for the factors including inflation rate which defined as$i$, discount rate which defined as$r$, and escalation rate which defined as e, where required for the assessment of time value of money. NPV is depicted in Eq. (1):

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

where in the Eq. (1), CI defines as an initial capital investment that it usually used as a negative amount, C_{tb} defines the benefit component that demonstrates difference between original cost and remaining cost after the assembling of the solution, occurring at the beginning of time period t; C_{tc} gives the cost of component that is the annual maintenance cost, occurring at beginning of time period, and it usually accounted as a negative amount.

Analysis of Economic Consequence of Power Quality Phenomena

Detailed evaluation of economic impact due voltage sag, unbalance and harmonics are important as attending to the investment in PQ mitigation. Economic effects can be analysed by identifying losses to different types of business due to changes of PQ phenomena. Attending to the change of business types which exists, customers can be classified based on their previous history of economic losses due to inappropriate PQ performance, similarities in their business process and the sensitivity of their equipment or devices. This classification can enable the analysis of the economic effects of a group of customers with using a normal model; consequently, every category has a unique model for assessment.

Such economic effects present an estimate of financial losses for that particular customer at a given stage of PQ in the network. It should be considered that some problems arise from voltage changes, imbalances and harmonics for a variety of reasons, which require separate financial and economic evaluation models for each of them.

Table 2 Cost and effectiveness of various grid based solutions [34–36]

Techniques	Effect on improved feeder	Assumed cost/km
undergrounding	Dig-in faults remains	$140,000
Shield wire	78% reduction in lightning faults	$31,920
Surge arrester	78% reduction in lightning faults	$ 11,410
Animal guard	50% reduction in animal caused faults	$280
Tree trimming	20% reduction in tree caused faults for every year earlier than 5 years	$280/trim
Insulated line	75% reduction in lightning faults, 100% reduction in contact faults	$14,000
Communication	Assume 50% less dig-ins	$140

In industrial customers, for example, the financial losses due to voltage changes are basically caused by the subsequent process trips and failures. With realistic modelling of process cycle and proper probabilistic modelling of uncertainties associated with every of the influential parameters, risk-based analysis approach is applied to evaluate the probability and possibility of having industrial process failure and faults by modelling the industrial process and carrying out risk analysis with the consideration of process immunity time. The economic loss due to a sag event is depicted in Eq. (2):

$$(Economic\ Loss) = (Process\ Failure\ Risk) \times (Loss\ owing\ to\ process\ fault) \tag{2}$$

In the Eq. (2), the loss due to process failure can be taken from customers directly or through survey. According to the general categorisation of unbalance cost presented by reference [26] report in the context of customers, financial losses due to unbalance phenomena basically result in energy and power losses and the shortened life of equipment. While the customers are concerned, the principle effect of unbalance phenomena occurs in induction motors. Such electrical equipment is considered as one of the basic resources of financial losses for the customers due to de-rating of induction motors and loss of useful life. When the Voltage Unbalance Factor (VUF) exceeds 5%, as per National Electrical Manufacturers Association (NEMA) (The Association of Electrical Equipment and Medical Imaging Manufacturers) guidelines induction motors are not expected to operate. NEMA suggested using of de-rating curves for computing power loss in induction motors [37].

Over a period of time, the difference in rated and de-rated power can be taken into account as loss of power due to unbalance phenomena and can be transformed to economic cost using the rate of energy unit cost. By applying the NPV approach, over the period of system study,

The cumulative cost of energy losses can be identified. These costs are considered as operating costs because they are considered to be the operating costs incurred by a business paying for electricity charges. According to the reference [38], customers with financial activities where specified in "Statistical classification of economic activities in the European Community" (NACE) including manufacture of motor vehicles, electronic products, food products, etc., have remarkable installation of induction motors and suffer from the most equipment ageing matters. Consequently, based on the references [39, 40], the equipment ageing due to thermal stress is presented by:

$$L = L_0^{'} e^{-(Bc\theta)} \tag{3}$$

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 $JK^{-1}mol^{-1}$; $c\theta = {}^{1}/_{\theta_0} - {}^{1}/_{\theta}$ where θ_0 is the nominal operating temperature of the insulation in sinusoidal regime whereas θ is the operating temperature in the presence of unbalance.

As per NMEA guidelines the approximate growth in winding temperature $\Delta\theta$ in induction motors due to percentage voltage unbalance V_{as} can be computed by$\Delta\theta = 2V_{as}^2$. A decline in useful life of the motors terminates the economic loss due to equipment replacement and process disruption affected by the equipment damage. According to papers [26, 37], the economic cost due to equipment ageing can be provided to a good approximation by $\frac{L_0^{'}-L}{L_0^{'}} \times C_{re}$, where gives the cost of replacing the motors.

Economic losses due to voltage or current harmonics can be categorised into the classification of energy losses, losses due to premature ageing and losses due to equipment malfunction or outage. According to paper [26] report, it provides the methodologies for evaluating financial losses arising from wave form distortion give rise to harmonics. The additional power losses due to voltage and current harmonics happen in the form of dielectric losses, copper losses, and core losses in electrical equipment. In order to evaluate the overall costs of industrial systems, each type of equipment should be taken into account separately for computing power losses. In reference [26] has pointed that the losses in electrical motors brought about harmonics is provided by:

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

where in the Eq. (4), V^h represents the voltage harmonic of order h; Z_M^h, and R_M^h is the equivalent impedance and resistance of the motor at the harmonic of order h, respectively. P_{co}^1 is the core loss at the fundamental frequency; and m_M defines the numerical coefficient. It has to mention that harmonic distortions also bring extra thermal and electric stresses in the insulating materials of electric equipment. Extra electric stresses are mainly due to the raised peak factor of voltage level resulting from the presence of harmonics. Increase in thermal stress is due to the growth in temperature by extra core and copper losses of equipment gave rise to harmonic contents. Extra stresses can bring the failure of the devices insulation, therefore reducing the devices life span. Economic losses to customers due to devices aging happen by replacing the costly equipment. Based on the references

[39, 40], a simple model of electro thermal life that proposed by reference [26] is provided by:

$$L = L_0^{'}\left(K_p\right)^{-n_p} e^{-(Bc\theta)} \tag{5}$$

Where in the Eq. (5), K_p defines the peak factor of the voltage waveform that represented by $K_p = {}^{V_p}/{}_{V_{1p}^*}$ where V_p defines the value of the distorted voltage and V_{1p}^* defines the peak value of the fundamental voltage, besides,n_p is the coefficient related to the shape of the distorted waveform based on the equation $\theta = {}^1/{}_{\theta_0} - {}^1/{}_{\theta}$. The operating temperature rises at the hottest point can be calculated using the equation $\Delta\theta \approx \left({}^{P_h}/{}_{P_0}\right) \times \Delta\theta_0$, where $\Delta\theta$ and $\Delta\theta_0$ are the operating temperature growth from ambient under the condition of non-sinusoidal operation, and the operation of nominal power P_0, respectively; besides, P_h is the harmonics content of the power. The aforementioned economic costs due to different PQ phenomena can be computed by NPV approach so that the present worth of future economic losses can be identified.

Economic Assessment of Mitigation Methods

The capital costs of SVC, DVR and PF can be taken based on curve fitting method using available cost records. The costs of DVR and STATCOM are considered equal. According to reference [31], the capital cost such as construction cost of these devices can be provided as follows:

$$C_{STAT+Con} = 553\left(0.0008S_{STAT}^2 + 0.155S_{STAT} + 120\left(\frac{\$}{MVAr}\right)\right. \tag{6}$$

$$C_{DVR+Con} = 553\left(0.0008S_{DVR}^2 + 0.155S_{DVR} + 120\left(\frac{\$}{MVAr}\right)\right. \tag{7}$$

$$C_{SVC+Con} = 553\left(0.0003S_{SVC}^2 + 0.3051S_{SVC} + 127.38\left(\frac{\$}{MVAr}\right)\right. \tag{8}$$

In the Eqs. (6), (7), and (8): S_{STAT}, S_{DVR}, and S_{SVC} are the sizes of STATCOM, DVR and SVC, respectively. The ongoing maintenance costs incurred every year during the life span have been assumed to be 5% for SVC and 10% for STATCOM and DVR, of their capital cost.

A conservative reactance of 0.1per unit is utilised for every Fault Current Limiter (FCL); besides, the cost of installing and maintenance of FCL is based on the financial model with the ten-year costs according to ABB products (Based on the reference [41]), with annual maintenance and operation costs at 5% of initial cost.

According to the reference [42], the transformer connection related cost is computed, assuming that the weight of distribution transformers is based on the ABB oil distribution transformer catalogue, and the copper wire is 3% of the weight of the distribution transformers. The costs of investment of other grid-based mitigation techniques are provided in Table 2, with annual maintenance costs at 5% of the initial cost. Tree trimming is planned to be performed every 5 years.

Power Quality Levels Expression

Overall, customers with similar type of activity tend to be sighted in the same geographical region. Based on the type of customers, for instance, commercial, residential, industrial, or sensitivity of their process or equipment to PQ phenomena, a can be separated into several zones with different PQ requirements. In this article, we consider most important changes, typically as most disturbing PQ phenomena such as the voltage sags, unbalance and harmonics. To reflect the concerns of utilities and customers, a proper PQ severity index is selected for each of them. To account for the practical results of voltage sags from the system and customers' stand point, a bus performance index (BPI) has been selected as this takes various sag characteristics into account while simultaneously considering the sensitivity of equipment to voltage sags.

Likewise, as mentioned in the references [12, 43], the Total Harmonic Distortion (THD) and the Voltage Unbalance Factor (VUF) are accepted to analysis unbalance effects and harmonics, respectively. The sensitivity threshold of each of considered PQ phenomenon is set based on the effect of the phenomenon on customers' equipment or process. Since integrity and variety of modern power electronics based PQ mitigation devices, each of them can contribute to mitigation of more than one PQ phenomenon. Consequently, the most aforementioned PQ phenomena should be considered simultaneously while searching for the solution of optimal mitigation.

In order to represent the aggregate PQ performance at the bus, several methods have been provided in the past decades, such as Weighting Functions (WF), Fuzzy Logic (FL), Artificial Neural Network (ANN) and Analytic Hierarchy Process (AHP) methods [29, 30, 44]; In this regards, we considered Unified Bus Performance Index (UBPI) which is provided as follows:

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

Besides, to reflect the customers' satisfaction level with the PQ performance received, the gap between the actual PQ performance *UBPI* and the aggregated thresholds *UBPI*TH is provided as:

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

Powe Quality Problem Formulation

In this article, in order to minimise the overall economic cost, the problem is defined as an optimisation problem, which applies the mitigation solutions in the network optimally that provides as the following: firstly, investment cost; secondly, maintenance or operation cost and the cost brought about various PQ phenomena; and finally to maximise the advantages as a result of the application of mitigation solution.

Concurrently, in scheduling PQ mitigation, the expression of PQ levels has to be facilitated among different zones of the network based on customers' requirements. The expression of PQ levels is considered as a technical requirement, and behaved as a constraint to be imposed during the optimisation process. Therefore, in this article, with using Lagrangian relaxation which was provided in the reference [45], the technical requirement is included in the objective function.

The present value of annual maintenance or operation cost and that cost due to various PQ phenomena during the entire life span of the deployed solution is computed using Net Present Value approach.

To achieve the aforementioned objectives, an objective function (O*F*) to be minimised in the optimisation problem is proposed and defined in Eqs. (11), (12), and (13):

$$OF = C_m - C_b + \gamma * PQGI_{UBPI} \tag{11}$$

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

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

Where C_{PQ}^{1t} and C_{PQ}^{2t} are the costs of PQ phenomena with mitigation and without mitigation, respectively at time period t and γ is a multiplier of Lagrange that imposes the penalty to the selected mitigation plan if the technical constraints are violated.

In this article we assumed the total period for evaluation is 40 years. To avoid confusion, all cost variables in the Eqs. (11)–(13) are stated as positive values $.

Additionally, it can be observed that the smaller C_m defines, the less investment cost is required. As can be seen from the Eq. (13), the economic advantage of placing the mitigation techniques, defined asC_b, is computed by$\left(C_{PQ}^{1t} - C_{PQ}^{2t}\right)$.

As given in the Eq. (11), negative sign has been applied to so that the optimisation procedure will attempt to maximise the benefit. $\Delta C = (C_m - C_b) < 0$ suggests that the subsequent economic advantages resulting from the application of mitigation techniques will cover the initial capital investment and maintenance cost of such mitigation techniques, and placing the selected mitigation plan would be highly beneficial in the long term.

Optimisation Methodology

In order to have optimal extension the mitigation solutions introduced in Section 2.1, the effective potential locations are selected beforehand based on evaluated PQ performance together with sensitivity assessment, and used initially in the optimisation process. Also, during selection the potential mitigation techniques, geographical feasibility of the potential mitigation location should be considered. These locations are therefore selected considering bus ranking according to the bus performance index, voltage unbalance factor and total harmonic distortion, and the sensitivity of the voltages to the injection of real and reactive power.

Concurrently, with such rankings, global and zonal selections of the potential locations have been performed based on the whole grid and zonal information.

Based on the pool of preselected locations and the applied mitigation techniques, greedy algorithm has been applied to carry out the optimal mitigation solution, to minimise the O*F* as defined in the Eq. (11), which incorporates both economic assessment such as PQ cost and cost of PQ mitigation and technical requirement that presented in the Section 2.

In the optimisation process, if either of the following requirements is met, the search procedure is confirmed: the number of iterations reaches the predefined maximum number; or, the improvement of PQ efficiency between two consecutive iterations is smaller than a present value.

Description of Case Study

In this paper, in order to validate the proposed method, the described approach is applied on a generic 118- bus-bars test case system. This comprises different types of sub-networks including transmission in-feeders, predominantly meshed sub-transmission networks and predominantly radial distribution network in different voltage levels. This case study comprises 118 bus-bars and also 28 transformers with various winding connections; besides, 177 lines with various type lines including overhead and underground lines and cables. In this test case we have 91 loads representing different types of customers including industrial, domestic and commercial which thirty of them are nonlinear.

In addition to this, 26 distributed generators (DGs) are connected in distribution system comprises 11 PV cells, 6 wind turbines 9 and fuel cells. PVs have either 3-phase or 1-phase connection. The fuel cells are connected in 1-phase and the wind generators which modelled as DFIG in 3-phase. Various types of DGs are given to inject various levels of harmonics in the network using the embedded models applied in DIgSILENT software. In this study, the zonally PQ requirements are set for demonstrative objects only and can be easily adjusted to any other value. All studies are applied in DIgSILENT software using embedded models and modules. Various network components are situated with various fault rates based on the type of the components and voltage level. The assessment of voltage sags takes into account malfunction and failure probability of primary protection relays and the uncertainty of the fault clearing time, that are generated randomly based on predefined normal distributions.

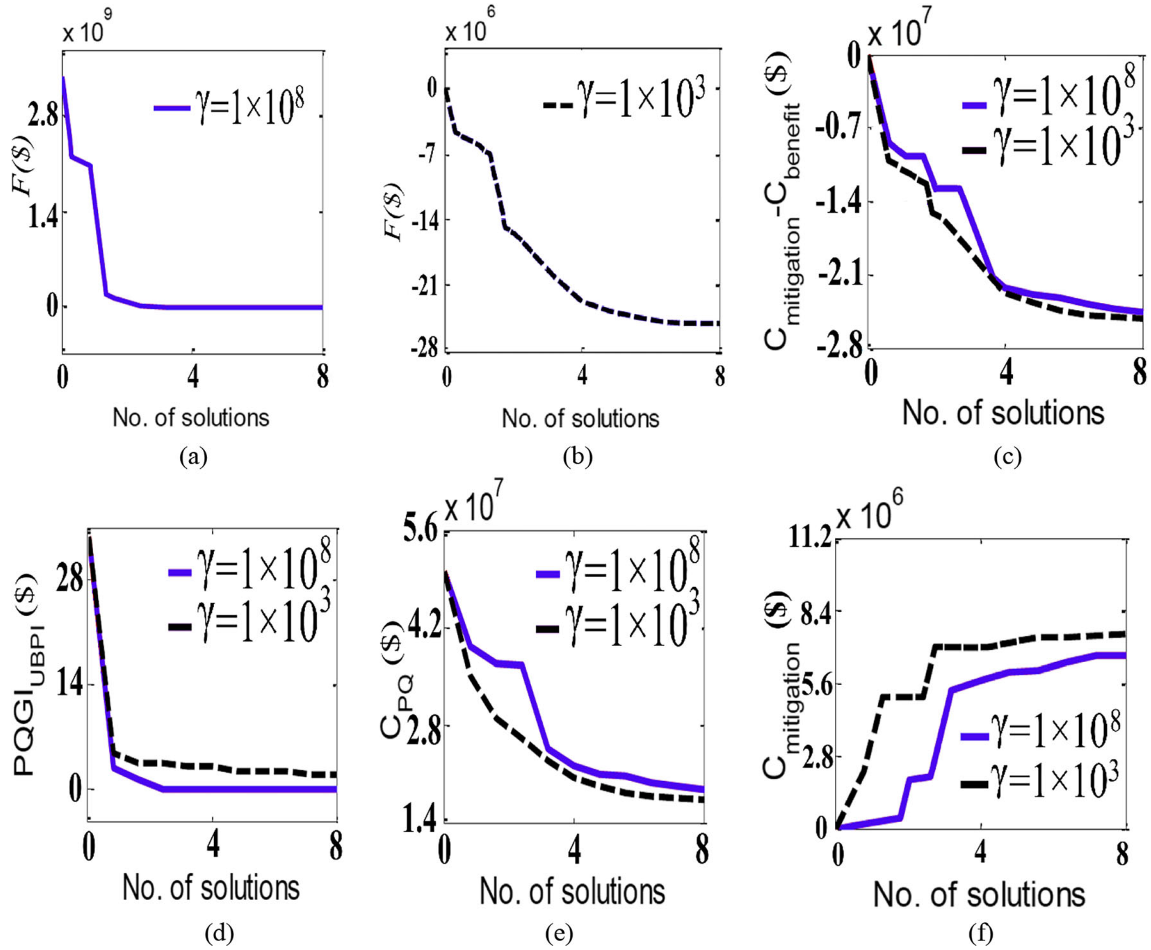
In the part of unbalanced loads, the real power demand at every phase is set based on the profiles of true load.

The reactive power of such unbalanced loads is derived from randomly generated power factors which pursue a normal distribution power with the mean of 0.95 representing a general load. Additionally, the harmonic current injection is given to be uncertain and modelled by setting the ratio of the injected harmonic current to the fundamental component based on predefined normal distribution power. In order to accurately analyse the PQ implementation, the variation of profile of the loads and network parameters are also given in the article. It is vital to mention that the outputs of fuel cells are assumed to be fixed.

The annual hourly loading information of different types of loads comprises commercial, industrial, and residential are taken from 2010 survey according to the reference [46]. The maximum outputs of the wind generators and PVs and the maximum loadings of customers might occur at various times of the year.

By and large, 8760 operating points during the year are given where 8760 has been considered the number of hours in the calendar year. Even though the demand for various types of loads and outputs of different types of DG varies with time, day and season, the same operating conditions are repeated over a calendar year. Consequently, using Cluster Evaluation of Statistics Toolbox in the MATLAB software, the annual operating points have been clustered, and the centroids of the clusters have been selected as the representative operating conditions.

This article also considers the extreme operating points as well as the operating condition corresponding to the maximum loadings of different types of consumers including domestic, commercial, and industrial loads, and the maximum outputs of different types of distributed generations.



(a) (b) (c)

(d) (e) (f)

Fig. 1 Convergence curves of various components against the number of mitigation solutions applied

Additionally, in the article, the average value of the PQ implementation assessed form every of such conditions has been used to compute the aggregated PQ implementation and incorporated in the objective function for the purpose of optimisation. The nominal life of the motors utilised in the economic assessment has been set to 40 years, and the nominal operating temperature is 85 °C. In addition to this, one of the most vital items of energy research is the study of the PV system in every region. According to the reference [47], annual hourly output information of PVs and wind generators have been extracted from the real data from the London, in the Great Britain; the location of London is 51°30′26" North, 0°7'39" West. Based on the Joint Research Centre (JRC) from European Commission, the average daily solar irradiance based on Photovoltaic Geographical Information System (PVGIS) has been calculated.

Simulation Results

In order to provide the results of the impact of Lagrange multiplier γ in Eq. (11), on the final selected mitigation plan, γ has been set to 1×10^3 and1×10^8. The former setting is to ensure the appraised technical constraint component ($\gamma * PQGI_{UBPI}$) is larger than the costs of PQ phenomena; while the latter is to ensure the cost of PQ phenomena has had larger influence on the objective evaluation. The convergence curves of various variables, consist of F,ΔC,$PQGI_{UBPI}$, $C_m$and C_{PQ} consist of the NPV cost of PQ phenomena computed over the life span of mitigation solution are provided in the Fig. 1.

On the other hand, without mitigation, only the Lagrange component$\gamma \times PQGI_{UBPI}$, including the technical constraints of $(UBPI - UBPI_{TH})$, helps to the objective assessment. At the leftmost points in the Fig. 1 (a-b), $F = 3.33 \times 10^9$ when $\gamma = 1 \times 10^8$, and $F = 3.33 \times 10^4$ when$\gamma = 1 \times 10^3$.

For both settings of γ, the objective value F has been dipped dramatically after one solution has been applied to the grid. F tends to converge steadily when the number of mitigation solutions >4, while its improvement is not as considerable as that when the number of mitigation solutions <4. For 8 mitigation solutions, the objective value F taken with $\gamma = 1 \times 10^3$is smaller than that taken when$\gamma = 1 \times 10^8$. As can be seen from the Eq. (11), F has been composed of $\Delta C$and$PQGI_{UBPI}$. The two components have been provided in the Fig. 1 (c) and (d). Both $C_m$and $C_b$are zero without any mitigation.

Table 3 Economic loss owing to power quality phenomena

Case	PQ cost	Profits	Pay-back periods (years)
$\gamma = 1 \times 10^3$	\$17,360,000	\$32,620,000	5
$\gamma = 1 \times 10^8$	\$18,760,000	\$31,220,000	6
No mitigation	\$49,980,000	–	–

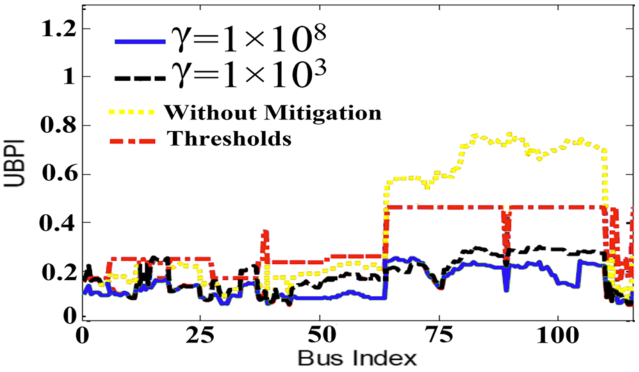


Fig. 2 *UBPI*

Consequently, it can be seen from the Fig. 1 (c) that $\Delta C = 0$ when the number of solutions applied is zero. Hence, the obtained ΔChas been smaller than zero constantly, which suggests that the economic 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.

In the Fig. 1 (c), for every convergence curve, except for the leftmost points of the curves, ΔC taken when $\gamma = 1 \times 10^3$ is always slightly smaller than that taken when$\gamma = 1 \times 10^8$. However, in Fig. 1 (d), $PQGI_{UBPI}$ taken with $\gamma = 1 \times 10^3$ is constantly marginally larger than that taken when$\gamma = 1 \times 10^8$. It can be observed that when γ has been set to a larger number, consist of $\gamma = 1 \times 10^3$in this case; the optimisation will favour the mitigation plan that can meet the technical constraints well especially at the early stage of the optimisation process.

With a smaller γ, the economic cost has had more influence on the selection of mitigation solutions. The costs of PQ phenomena and PQ mitigation have been provided in the Fig. 1 (e) and (f). It can be observed that $C_{Power-Quality}$pursues the same convergence trends as displayed in the Fig. 1 (c).

In Table 3, the economic loss owing to phenomena, the profits over the lifetime of devices taken by adopting different settings of Lagrangian multiplier γ and the pay-back periods

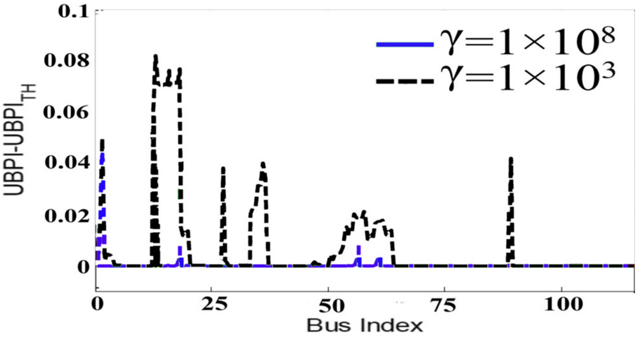
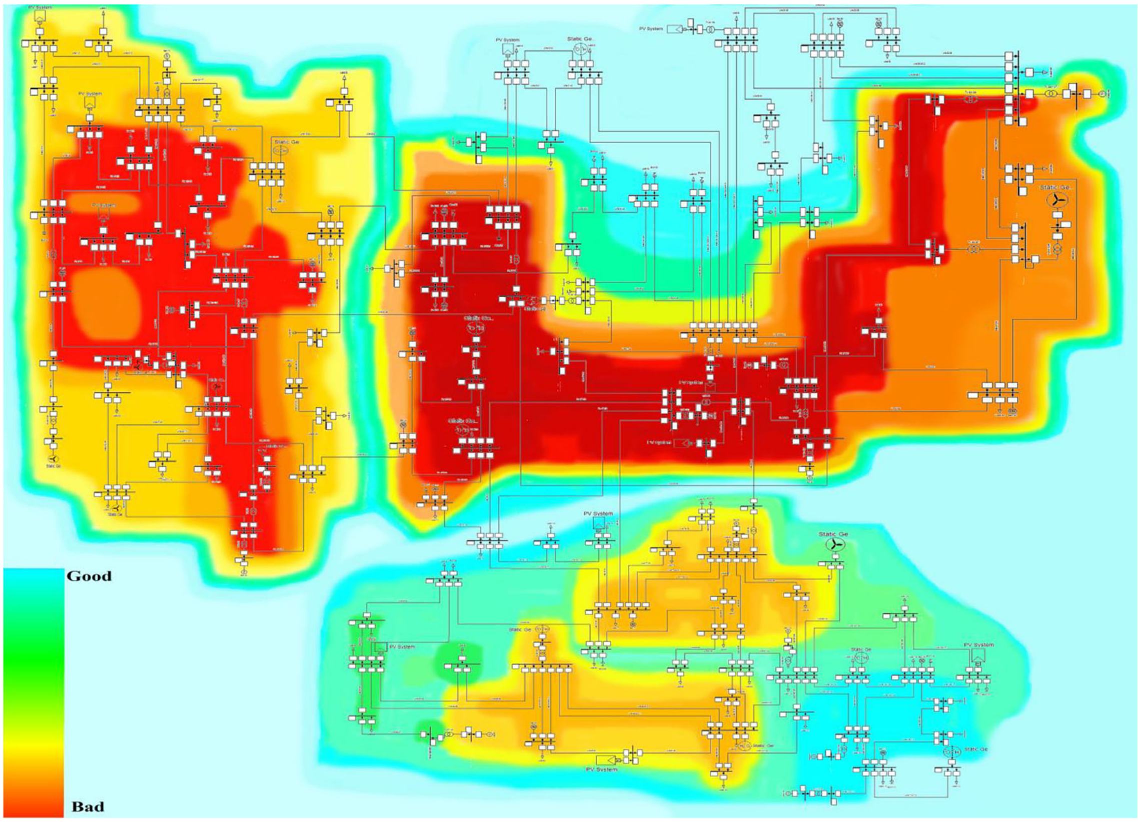
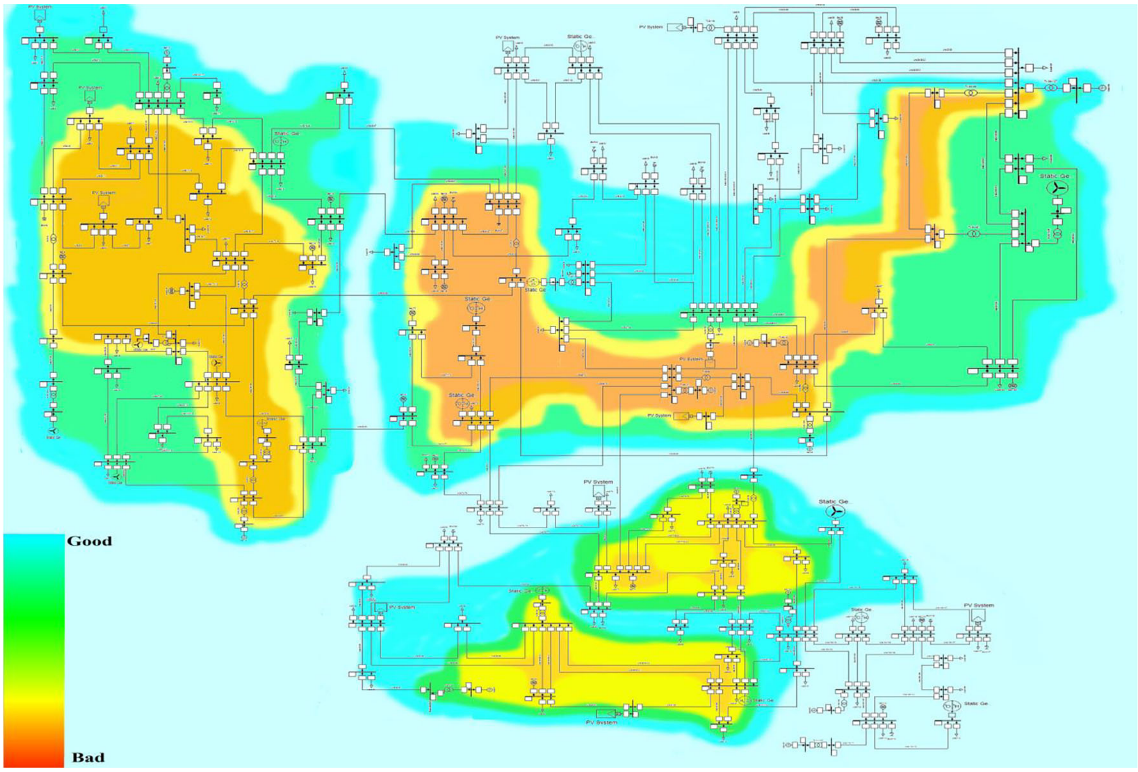


Fig. 3 *UBPI-UBPI*$_{TH}$

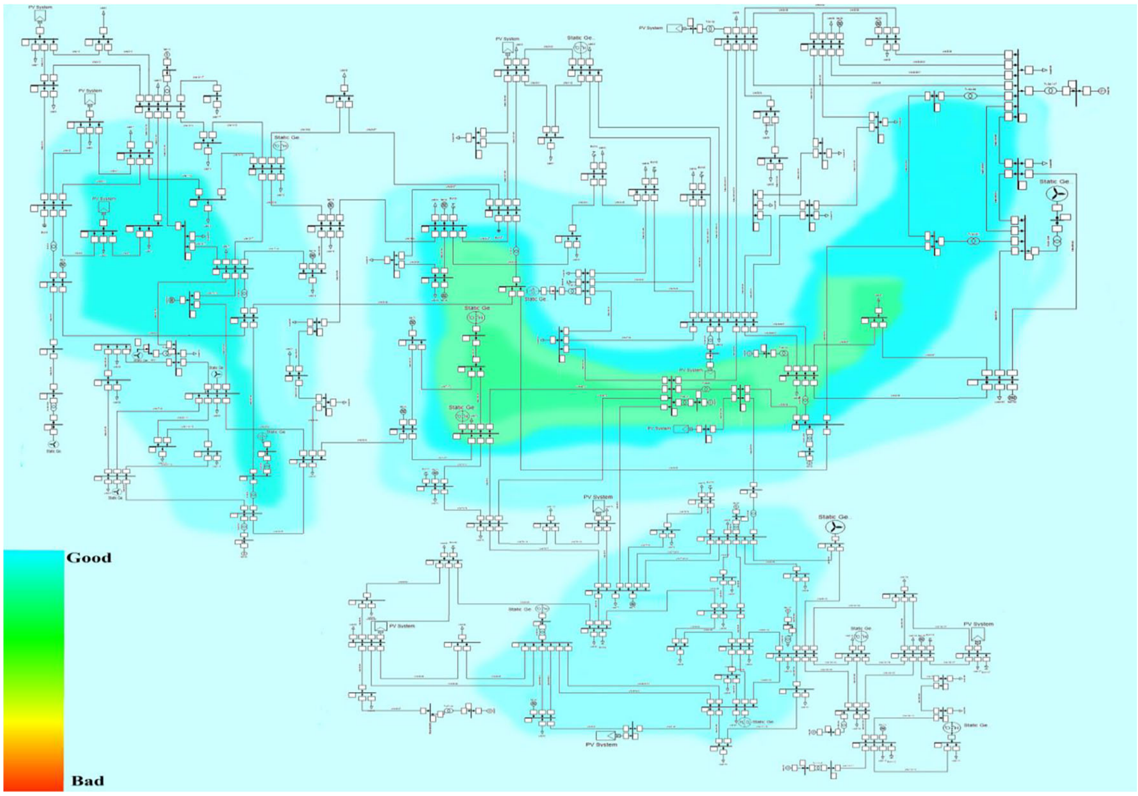


(a) Without mitigation



(b) With mitigation $\gamma = 1 \times 10^3$

Fig. 4 (a). Without mitigation (b). With mitigation $\gamma = 1 \times 10^3$ (C). With mitigation $\gamma = 1 \times 10^8$



(c) With mitigation $\gamma = 1\times10^8$

Fig. 4 (continued)

are depicted. It can be observed that the setting of $\gamma = 1 \times 10^3$from an economic perspective has been superior to the setting of$\gamma = 1 \times 10^8$, as more profit is taken and the mitigation cost has been paid back earlier.

In order to provide the satisfaction of the received PQ implementation in comparison with the customer specified thresholds, *UBPI*s appraised at all buses together with the specified thresholds are depicted in the Fig. 2.

As shown in the Fig. 2, without mitigation, most buses violate the PQ thresholds. With the application of the mitigation solution taken with$\gamma = 1 \times 10^8$, the PQ implementation received at almost all buses meet the corresponding PQ thresholds.

If the mitigation solution taken with has been applied to the grid, there still exit a relatively large number of *UBPI*s which are larger than the PQ thresholds. In order to provide the gap between the obtained *UBPI*s and the thresholds, $UBPI - UBPI_{TH}$appraised at all buses are also given in the Fig. 3.

These results acknowledge the conclusion that larger γ makes the technical constraints more influential in selecting mitigation solution. In order to provide the PQ implementation visually, and for the convenience of comparing the aggregated *UBPI* taken with and without mitigation, the heat-maps of *UBPI*s taken without mitigation and with 10 devices (when $\gamma = 1 \times 10^3$ and$\gamma = 1 \times 10^8$) are plotted in the Fig. 4 (a), (b) and (c), respectively.

Table 4 Optimal solutions for different power quality phenomena

PQ factor	Type, size (MVA) and location of mitigating solutions
$\gamma = 1 \times 10^3$	DVR (4.73) at B33; PF (2.18) at B54; phase shifting transformer installation at B3, B34 and B40; 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
$\gamma = 1 \times 10^8$	STATCOM (5.47) at B12; SVC (2.66) at B80; DVR (6.01) at B116; fault current limiter at B19-B89; fault current limiter at B61-B62; fault current limiter at B84- B87; 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

The critical region marked in red (Bad condition) in the Fig. 4 (a) has been shown to severe PQ disruption, and it is greatly improved by applying the optimal mitigation solution taken by the suggested mitigation approach, as displayed in the Fig. 4 (b) and (c). Aa can be seen from the Fig. 4 (b) and (c), the one with larger γ has had slightly better technical performance (Good condition). The optimal solutions for $\gamma = 1 \times 10^3$and $\gamma = 1 \times 10^8$are listed in Table 4 consist of the installation location, type, and size of the selected FACTS devices and the zones of the selected network-based techniques. The network-based solutions that can be performed at critical locations in zones have been selected, in both cases, based on to their cost-effectiveness advantage.

When$\gamma = 1 \times 10^8$, the taken optimal solutions include three faults current limiters that help to the mitigation of trip severity and when$\gamma = 1 \times 10^3$ the taken solution includes three phase shift transformers that help to the harmonic mitigation. When$\gamma = 1 \times 10^3$, apart from the sag mitigation, harmonic mitigation has been emphasized as well, due to the economic cost resulted in this phenomenon. It is clearly see that the influence of the PQ phenomena on the final mitigation solution changes depending on their contribution to financial and technical assessment.

Conclusion

In this article, the role of renewable energy sources in evaluating technical and economic efficiency of power quality has been presented in detail. In this way, in order to analyse the technical and economic implementation of power quality changes considering the effects of renewable energy resources and FACTS devices on power systems, a detailed methodology has been provided. Hence, the technical and economic assessment of both ranges of power quality phenomena for voltage sags, unbalance and harmonics, and mitigation techniques for network-based and device-based mitigation solutions have been provided. Additionally, the methodology for assessing the technical power quality implementation with respect to various customers' requirements across the network has been suggested. The simulation results have confirmed that using heat-maps of distribution network-based on Unified Bus Performance Index with applying selected mitigation solution would be highly beneficial in the long term, as the financial profits of using the solution were much larger than the initial capital investment and maintenance cost of the power quality changes.

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