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Power Quality Assessment of Distorted Distribution Networks Incorporating Renewable Distributed Generation Systems Based on the Analytic Hierarchy Process

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ABSTRACT The proliferation of not only power electronics supported consumption technologies but also the expansion of the renewable-based distributed generation (DG) systems has given rise to severe power quality (PQ) phenomena in consort with the offered technical, economic and environmental benefits under deregulated environment. The forthcoming complexity of distribution power networks caused by incorporation of a large number of DG units in deregulated electricity market unquestionably makes PQ assessment procedure a quite cumbersome one. In present work, an analytic hierarchy process (AHP) inspired methodology is proposed for PQ assessment of distorted distribution power systems under the presence of renewable-based DGs. The proposed PQ assessment approach is based on formulating a unified power quality index (UPQI) for assessing the overall PQ performance of individual buses of the network along with the entire distribution network (DN) considered taking four PQ phenomena, viz. voltage harmonics, voltage sags, voltage unbalance and steady-state voltage profile at each bus into account. t. The application significance of the presented methodology is established by utilizing it on an IEEE 13 bus test distribution system modified through incorporating the nonlinear loads and DG systems based on three types of RES namely, photovoltaic (PV), wind and fuel cell, in MATLAB/Simulink environment. The results achieved validates the efficacy of the presented approach in assessing the overall PQ performance of each of the buses and the entire DN along with benchmarking it with respect to the threshold level of unity. Based on obtained results, also the comparative analysis is performed among PQ performances of DN with selected three RES based DGs. Moreover, the impact of the employing the custom power devices (CPDs) as well as excessive penetration level of renewable energy over PQ performance of distribution network, are also investigated by the application of the formulated index.

INDEX TERMS Analytic hierarchy process, distributed generation, harmonics, power quality, unified power quality index.

ABREVIATIONS

RES	Renewable Energy Source
PQ	Power Quality
AHP	Analytic Hierarchy Process
UPQI	Unified Power Quality Index
DN	Distribution Network
DG	Distributed Generation
PV	Photovoltaic
CPD	Custom Power Device
DER	Distributed Energy Resource
FRT	Fault Ride Through
HC	Hosting Capacity
BVD	Background Voltage Distortion
EPS	Electric Power System
FCA	Fuzzy Cluster Analysis

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ANN	Artificial Neural Network
MCDM	Multi-Criteria Decision Making
PF	Power Factor
TVHD	Total Voltage Harmonic Distortion
VUF	Voltage Unbalance Factor
VSS	Voltage Sag Score
VPPI	Voltage Profile Performance Index
RE	Renewable Energy
PWM	Pulse Width Modulation
PMSG	Permanent Magnet Synchronous Generator
WECS	Wind Energy Conversion Systems
FC	Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
TCSC	Thyristor Controlled Series Compensator
SSSC	Static Synchronous Series Compensator
DSTATCOM	Distribution Static Compensator
VCM	Voltage Control Mode
CCM	Current Control Mode
DER	Distributed Energy Resource
LV	Low Voltage
HFH	High-Frequency Harmonics

LIST OF SYMBOLS

m	Number of criteria
n	Number of alternatives
$TVHD$	Total voltage harmonic distortion
VSS	Voltage sag score
V_a, V_b, V_c	Post sag RMS voltages of phase A, B and C respectively
VUF	Voltage unbalance factor
V_p	Positive sequence voltage component
V_n	Negative sequence voltage component
V_{ab}, V_{bc}, V_{ca}	Three-phase imbalanced line voltages
V_{abe}	Difference between the line voltage V_{ab} and the average line voltage
$VPPI$	Voltage Profile Performance Index
A	Pairwise comparison matrix
a_{jk}	General element of pairwise comparison matrix
j, k	Names of criterion
w	Vector of criteria weight
S	Matrix of PQ phenomena scores
v	Vector of global PQ phenomena scores
F_i	Vector of individual corresponding indices of PQ phenomena
F_{thr}	Vector of threshold values of indices
p	Number of PQ phenomena considered
$UPQI_i$	Unified power quality index for the i^{th} bus
W_g, W_d, W_l	Weights assigned to grid, DG and load bus group respectively
A_g, A_d, A_l	PQ priority scores of grid, DG and load bus group respectively
g	Total number of utility grid buses
d	Total number of DG buses
l	Total number of load buses
w_i	Power quality importance score of the i^{th} bus of the corresponding bus group
$UPQI_g$	Unified power quality index of grid bus group
$UPQI_d$	Unified power quality index of DG bus group
$UPQI_l$	Unified power quality index of load bus group
$UPQI_{overall}$	Unified power quality index of the overall system
I_{ph}	Photocurrent
I_s	Load current
I_d	Diode current
I_{sh}	Shunt current
F_s	Solar radiation
T_o	Ambient temperature
V_s	Load voltage
P_1, P_2, P_3	Constants
T_j	Junction temperature
e	The charge of an electron
a	The ideality factor of a diode
N_s	The number of cells connected in series
K	Boltzmann's constant
R_s	The value of series resistance
E_g	Energy bandgap
P_4	Correction factor
R_{sh}	The value of shunt resistance

I. INTRODUCTION

During the past few years, the global power industry has expressed a vested interest in renewable energy sources (RESs) based distributed generation units and fossil fuel depletion, increasing energy demand and awareness towards environmental protection are crucial among the motivations for that [1]. Besides, the optimal placement of distributed energy resources (DERs) has the potential of enhancing power transfer efficiency of the distribution network also leading to energy sustainability in the smart grid [2]. The penetration of distributed renewable energy generation is growing and this growth is likely to sustain over the coming years. Nonetheless, the proliferation in integrating renewable DG systems into the existed distribution networks has offered many challenges also. The difficulties arose related to network stability, voltage profile control and especially power quality issues are foremost among them [3], [4]. Also if allocated erroneously, DG systems can deteriorate the steady-state voltage profile of the entire distribution network entirely up to a new level [5].

Quality of power supplied from the utility generation end is centrally controlled by its operators without the application of power electronics interfaces. But the quality of power obtained from renewable DG systems depends on environmental constraints and power electronics control. The oscillation in renewable energy owing to atmospheric factors is accountable for fluctuation in voltage and frequency whereas power electronics-based interfacing inverters are the

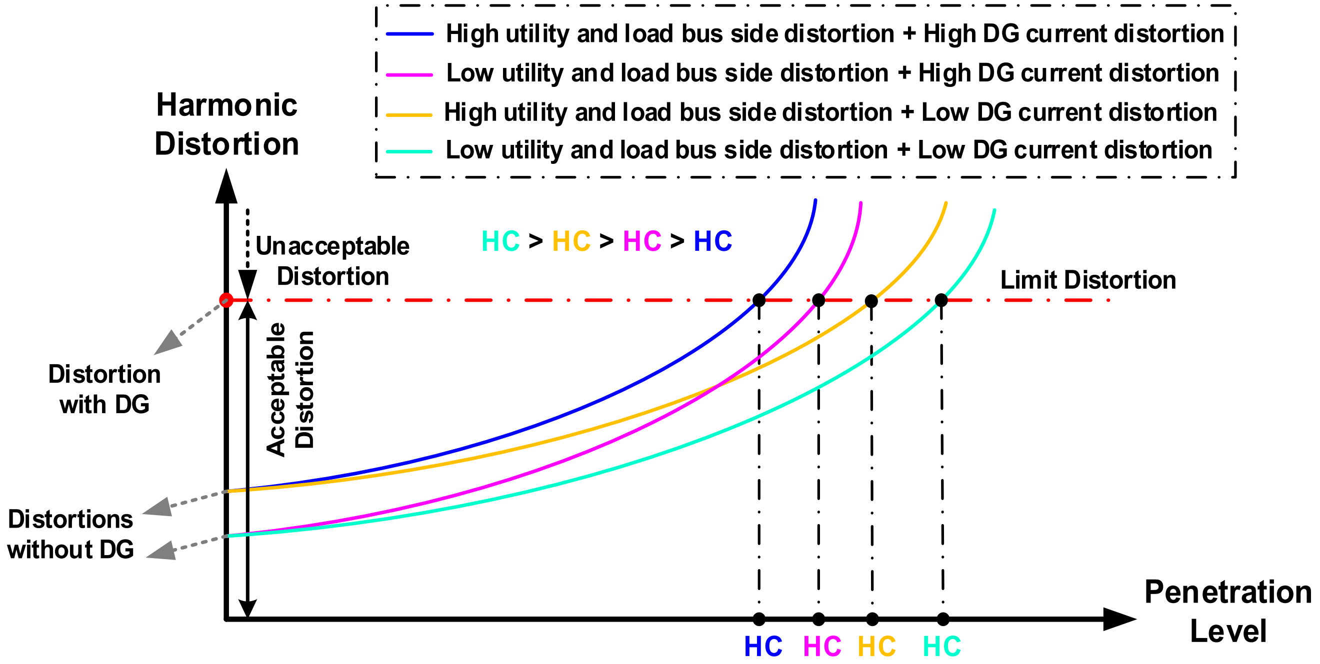

FIGURE 1. Impacts of different distortions on hosting capacity of the distribution system.

reason for the harmonics emission in the distribution system with RES's penetration. In case of penetration levels of DERs increase above the hosting capacity (HC) of the system, it can even proliferate the number of PQ phenomenon and thereby may exacerbate the PQ indices of entire distribution network buses. Moreover, DG system should follow the harmonic spectrum guidelines specified by IEEE Std. 1547 [6] according to which total THD in the DG's current should be below threshold limit of 5% along with satisfying individual order harmonic distortion limits. High harmonic emission by the DG system reduces the possible HC of the distribution system with it. In addition to DG's created PQ concerns, utility grid bus and load bus PQ concerns too impact the functioning of DG systems. For that reason only, the grid-code standards for grid-integrated renewable DG systems have gone through an incessant development worldwide for guaranteeing a steadfast functioning of distribution system with the growth in penetration of renewable energy to the higher levels [7]. In compliance to the latest grid-codes, renewable energy units should continue delivering energy even after any swings at either utility grid or load bus side as an effort to avoid some additional instabilities and triggering any new harsh hazards to the grid, which point toward that DG units, should attain some capability of riding through the fault (FRT) in case of voltage instabilities causes by either the grid bus or load bus [8]. High harmonic contamination at PCC, either owing to utility grid side or load bus side or both, decreases the HC of the system. The reason being IEEE Std. 1547 restricts the value of total voltage harmonic distortion (TVHD) as 2.5% at the PCC for the distribution system to be appropriate for renewable energy system's integration. The impact of utility bus and load bus harmonic distortion on hosting capacity is validated in [9]. Moreover, it is also evidenced that load bus's harmonic distortion is more detrimental than background voltage distortion (BVD) from HC point of view. The impacts of utility and load bus side distortions and DG current distortion on maximum allowed DG penetration (i.e. HC) can be understood from figure 1.

Poor operating efficiency due to increased losses, feeder overloading and protection collapsing are few among the prophesied effects of PQ issues caused by grid integrated operation of renewable sources at distribution level [10], [11].

A. MOTIVATION AND INCITEMENT

The quality of power delivered to the consumers have always been an important basis to evaluate the performance of distribution networks. Various authors have documented the effects of integration of RESs on PQ of distribution network by quantification of various power quality indices [12]–[14]. The technical guidelines, to be followed while connecting DERs with the utility electric power systems (EPSs), are mentioned in IEEE Std. 1547 [6]. As per power quality concern, there are six parameters, voltage unbalance, fluctuations, harmonics, grid protection, reactive power and time for reconnection. The documented standards help power system operators in assessing and tackling PQ issues arose due to the incorporation of distributed generators. Furthermore, numerous standards are too acknowledged for characterizing, quantifying and defining the maximum permissible level of several PQ events [15]–[22]. Nevertheless, it must be clearly understood that PQ performance evaluation only via observing several PQ indices, merely at utility grid buses along with load buses, is not adequate because the acceptable PQ performance of DG buses level is also essential for ensuring the overall strong PQ performance of DN and accordingly the seamless functioning of renewable energy systems. Consequently, it goes without saying that the meticulous observation and benchmarking of the entire set of PQ events, via related standard indices, at individual bus category, is found as a multifaceted task predominantly while the present RES supplied DGs are excessive in penetration level along with the number. Moreover, it necessitates quite a lot of PQ enhancement approaches for each bus category for retaining distinct PQ indices within their tolerable limits. Consequently, assessing and benchmarking the overall PQ performance of DNs under DG systems presence, turn out to be a cause of apprehension for operators of the system.

Despite many standards being documented for quantification and characterization of different PQ phenomena by different PQ indices, there is no standard index which can facilitate the utility operators to scale the overall PQ performance of each bus and whole network in one go. This truly arises the need of developing a compound index by coalescing all significant PQ phenomena indices which can be used to assess and benchmark overall PQ performance of the DN under the company of distributed RESs. Such a compound index can enable the utility operators also to associate the opportunities and challenges of technologies in distributed generation planning and assessment.

B. LITERATURE REVIEW

Over the past decade, few publications have been reported in journals and mostly conference proceedings attempting to standardize the overall PQ evaluation by a combined index. A unified power quality index modelling based on the AHP model that has three states namely best, real and worst, was proposed by the authors [23]. Reliability and voltage sags were the power quality indices taken into account for an overall evaluation of network buses.

A synthetic technique for assessment of PQ formulated on Fuzzy Cluster Analysis (FCA) is proposed in [24]. FCA is a widely applied mathematical classification approach inspired from multi-analysis method of mathematical statistics. Simultaneously, the FCA also nullifies assessment standard constraint on assessment outcomes, considers the weight of general elements on PQ and guarantees objective and accuracy. For evaluation testing purpose five basic PQ indices have been taken into consideration.

Another similar attempt was made by authors in [25] and a quantitative global index developed on combined fuzzy logic and artificial neural network (ANN) is suggested aimed at PQ assessment and valuing in the deregulated electricity environment. Following the cataloguing of PQ index meant for each event into ten distinct levels, the planned network is trained through patterns those are produced by the concept of random distribution for the respective level of power quality indices and applied cost factors. Then a fuzzy technique is applied for computing the compound index utilizing discrete as well as continuous indices.

The amalgamation of the analytic hierarchy process with exponential smoothing methods used in time series estimating was established to formulate a quality index intended for distribution power utilities [26]. In this approach, the utility companies are given a score between zero and ten to represent the level of PQ performance.

In article [27], projection technique of principal component and comprehensive weighting approach is implemented to estimate the steady-state PQ because projection technique of principal component holds many qualities of good categorization, simple programming and not as much of calculation. This method is stated as an effective solver for problems of power quality hierarchical integrated assessment. In addition to these, few other modelling methodologies based on entropy, fuzzy synthetic technique and probability statistics are also described in the literature for gauging the global PQ performance of the DN under consideration [28]–[30].

In [31] authors have applied AHP for formulating a compound index to be used for assessing the overall PQ performance of DG system integrated with a two bus distribution system. However, if the power network is large and multiple DGs are incorporated then also the procedure results in a set of distinct indexes by considering the Thevenin's equivalents. Nevertheless, in a large distribution network, the approach proposed in [31] suffers from issues such as computation and assessment complexities.

C. PROBLEM FORMULATION

Nevertheless, there still exists a gap between the real and estimated global PQ performance of the DN. Existing methodologies are still inadequate to gauge the PQ performance of practical distribution networks precisely and the reason being the loopholes present in methodologies due to incorrect selection of weights (also called scores) for different PQ phenomena. In most of the methodologies weights for different PQ, phenomena have been selected based on single criteria only while practically there may be more than one, impact criteria such as financial losses, the disturbance caused and lifespan reductions of equipment etc., based on which importance of two phenomena can be compared. Further, the weights of different impact criteria are also possible to be different rather than being equal in weightage, for example, a residential consumer will probably value the physical disturbance and financial losses owing to equipment failure, more than the lifespan reductions. Again the assignment of similar PQ phenomena weights at each bus is also adopted in some of the proposed methodologies which can lead to impractical and erroneous power quality evaluation of DN concerned. In the last and most importantly the PQ constraints emerged owing to renewable energy incorporation in distribution network demands a novel algorithm for a more accurate evaluation of network PQ performance along with the fulfilment of aforementioned research gap. Such accurate methodology can assist in proper planning, monitoring and PQ evaluation of the modern power distribution networks.

D. CONTRIBUTION TO KNOWLEDGE

This article attempts to formulate a novel unified power quality index for power quality assessment of a distorted DN with integrated renewable-based DG units. Development of the proposed *UPQI* is inspired by the analytic hierarchy process and the single index is expected to be sufficient for quantification and benchmarking the PQ performance of individual network buses and also the entire DN that is concerned and thereby also aims at reducing the intricacy of large data supervision centered PQ monitoring of contemporary distribution power networks with renewable distributed generations. In case the magnitude of the computed *UPQI* is larger than the unity then it indicates that global PQ performance of the concerned bus or DN, under attention, is unsatisfactory. The larger the magnitude of the *UPQI* is than the unity, the worse PQ performance the concerned bus or DN has and above the reference threshold boundary. Correspondingly, the more the magnitude of the *UPQI* is less than the unity, the healthier PQ performance the concerned bus or DN has and under reference threshold limit. To measure the compound PQ performance of distribution network, four PQ phenomena namely voltage harmonics, voltage sags, voltage unbalance and voltage profile, are selected at each bus and corresponding indices used for their quantification are as per the associated standards [16]. To enable proposed *UPQI* with the unique feature of benchmarking the network performance, threshold limits of all four performance indices at generator bus and load buses are taken as per IEEE Std. 1159 [16], 519 [15]. For selecting the limits other standards are also taken into account [19]–[21]. Further, the selection of weights for all four indices is done in compliance with multiple criteria. The introduced *UPQI* is calculated by measuring all four indices at each bus of a distribution network. The standard IEEE-13 bus test distribution system customized with multiple nonlinear loads and the integration of three types of renewable technologies based DG systems namely, photovoltaic, wind and fuel cell and non-linear loading, is simulated in MATLAB/Simulink environment for illustrating the application of proposed PQ evaluation methodology and comparing the PQ performance of the network by the proposed approach under different RES scenarios and weather conditions. Also, the impact of CPDs application and excessive penetration level of renewable energy on PQ performance of DN has been analysed via the employment of the presented approach.

E. PAPER ORGANIZATION

The outstanding portion of the paper is organized in this manner: Subsequent to the introduction part, a concise overview of the philosophy of analytic hierarchy process is comprised in section 2.1 and the selection of PQ phenomena and indices used for the formulation of the proposed approach are discussed in section 2.2. In section 2.3, the stepwise categorized process of framing the presented methodology by AHP is addressed. Section 3 emphasizes the technical parameters and modelling of the system on which the proposed methodology is verified as well as a short detail of CPDs those have been considered for analysis purpose in present work. In section 4, results are discussed under three cases of RESs, application of CPDs and increased penetration of renewable energy. In the end, section 5 concludes the paper afterwards the references listed in the end.

II. DEVELOPMENT OF THE PROPOSED UNIFIED POWER QUALITY INDEX

Development of the proposed *UPQI* is inspired by the analytic hierarchy process. The single index is sufficient for comparison and benchmarking of PQ performance of the buses or the entire network for which it is calculated. Also, it will be useful for comprehensive PQ evaluation for achieving many benefits like fast PQ monitoring and assessment, decrease in large data management on PQ events, and well-organized planning and estimating strategies in modern restructured power markets. The discussion on the development procedure of the proposed *UPQI* is categorized into three subsections. The first subsection discusses a short about the analytic hierarchy process. The second subsection describes the indices used for quantification of different power quality phenomena selected for overall PQ evaluation at each bus and the end subsection presents the development methodology of proposed *UPQI* by applying AHP. The detailed discussion is as follows.

A. A BRIEF ABOUT ANALYTIC HIERARCHY PROCESS

The analytic hierarchy process, developed by Thomas Saaty (1980), is a valuable means for coping with multifaceted decision making and may help the decision-maker to fix priorities and take the finest decision [32]. Through changing complicated human decisions to a sequence of pairwise comparisons, and thereafter combining the results, the AHP offers to grab both subjective and objective characteristics of a decision. The output of AHP comes in the form of a vector of scores obtained by each of the alternatives participating in the process of decision-making. The AHP can be applied in three simple successive steps as shown in figure 2.

Adaptability and mathematical simplicity are the two main strengths of AHP those make it one of the most preferred decision-making means among all multi-criteria decision making (MCDM) approaches. Moreover, due to being established on a hierarchical structure, each criterion can be well focussed and leads to better transparency. Public policy, business policy and strategy, energy forecasting and logistics, resource supervision along with transportation engineering, are the principal application areas of AHP [33]. In last decade AHP has found very wide application in energy resource planning in the power system [34]–[37]. Moreover, it is being perceived that the emphasis is now confining to the applications of the combined AHPs also instead of the standalone AHP [38]–[40]. The subsequent section gives details about the quantification tactic of PQ phenomena considered at each bus for compound PQ evaluation.

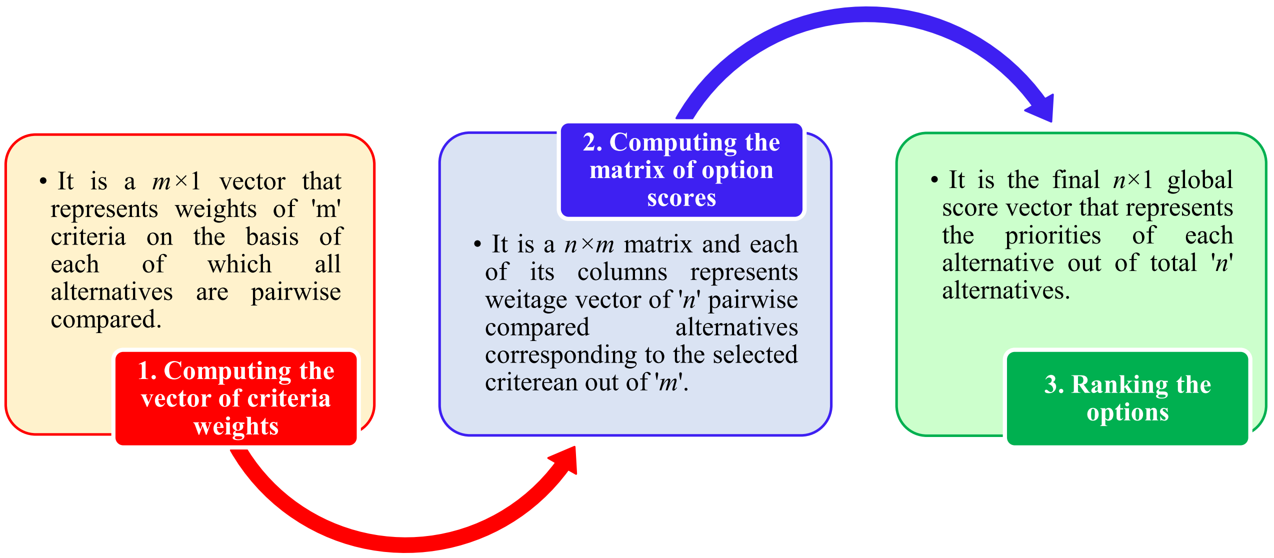

FIGURE 2. Steps for implementation of AHP.

B. CHOICE OF PQ PHENOMENA AND INDICES FOR REPRESENTATION

As per the IEEE Std. 1100, the power quality is characterised as: "The idea of powering and grounding particular sensitive equipment in a matter that is appropriate for the functioning of that equipment" [41]. PQ issue might cause harm or inappropriate functioning of equipment connected to the grid along with end-user equipment [42]. Power quality turbulences associated to both current and voltage like poor voltage regulation, excessive harmonics current overloading in line, load unbalancing, deteriorated power factor (PF), unnecessary neutral current, sag, swell, voltage flicker short interruption, notch and spike worsen the excellence of power delivered. Moreover, each type of PQ phenomenon can lead to multiple negative impacts on load bus. These impacts may be in terms of financial and energy losses, safety deficit, equipment failure, lifespan reduction, device malfunctioning and failure etc. Distributed generation has a significant role concerning the quality of power since the operational events of renewable energy affect the PQ of DNs. Specifically, large current fluctuations all through outage and synchronization of RES based DGs may result in substantial voltage transients [42]. The complete PQ performance of the distribution network is further exacerbated with high penetration of renewable energy along with non-linear loads at the same time [43]. Pertinent PQ issues namely voltage harmonics distortion, voltage unbalance, voltage fluctuation (sags/swells) and steady-state voltage profile deterioration have been monitored at each bus for overall power quality evaluation by a unified index in presence of RES based DGs. Though this work emphasis more on a generalization of PQ evaluation methodology and other PQ phenomena can be easily incorporated in the proposed algorithm.

1) VOLTAGE HARMONICS DISTORTION

The overall performance in terms of harmonic, at each bus, is quantified by total voltage harmonic distortion, an index used for evaluating harmonic performance as per IEEE Std. 519 [15]. TVHD is characterized as the square root of the ratio of the addition of the power of total voltage harmonic components to the power of the component of voltage at fundamental frequency [15]. Calculation of TVHD has been performed up to 100 cycles utilizing the Fast Fourier Transform (FFT) analysing tool available in MATLAB/Simulink. In MATLAB based IEEE test system model used in this work, harmonics emission of DG units is supplemented by non-linear loads, for instance, 3-phase induction motor (IM) drives and 1-phase in addition to 3-phase rectifier DC motor drives, at different load buses. However, some demo projects with a lot of small PV-inverters in a distribution network, indicate high levels of voltage distortion, even though the emission level of a single PV inverter satisfies the PQ standards [44]. The total voltage harmonics distortion constraints of 5 percent are selected as the permissible limits at each bus following the IEEE Std. 519 [15].

2) VOLTAGE UNBALANCE

The performance of the network, in terms of voltage unbalance, has been gauged through an index known as voltage unbalance factor (VUF) which is determined as the ratio of the negative sequence component to the positive sequence component of the voltage [45]. The% voltage unbalance factor (% VUF) is given by equation no. 1.

$$\%VUF = \frac{\text{negative sequence voltage component } (Vn)}{\text{positive sequence voltage component } (Vp)}.100 \tag{1}$$

The positive and negative sequence voltage components are gotten by resolving 3-phase unbalanced line voltages V_{ab}, V_{bc}, and V_{ca} (or phase voltages) into two symmetrical components V_p and V_n. Thus V_p and V_n are positive and negative sequence voltage components of line voltages V_{ab},

V_{bc}, and V_{ca} respectively. The two balanced components are given by equations no. 2 and 3.

$$V_p = \frac{V_{ab} + \alpha.V_{bc} + \alpha^2 V_{ca}}{3}(2) \tag{2}$$

$$V_n = \frac{V_{ab} + \alpha^2.V_{bc} + \alpha.V_{ca}}{3} \tag{3}$$

where α is a constant.

However, the formula is given by equation no. 4 circumvents the need for complex algebra nevertheless offers a worthy guesstimate to the aforementioned definition [46]. In current work, voltage unbalance factor indices have been computed by means of the equation no. 4 only.

$$\%VUF = \frac{82.\sqrt{V_{abe}^2 + V_{bce}^2 + V_{cae}^2}}{\text{average line voltage}} \tag{4}$$

where $V_{abe} =$ difference between the line voltage V_{ab} and the average line voltage, etc.

Voltage unbalance factor constraints of 2% is opted as the thresholds at the all buses as suggested by Std. EN 50160 [17]. Unequal apparent power in each phase, either via having single-phase active power supplies from DG systems or uneven active or reactive power feedings at the load buses, is the frequent source of voltage unbalances in a distribution power system. Though in MATLAB based IEEE test system model used in this work, voltage unbalances are originated by 1-phase real power injections from the DG unit as well as uneven active and reactive power feedings at some load buses.

3) VOLTAGE SAG

Voltage sag is amongst the discrete PQ events that are instigated due to fast fluctuations in the accessibility of distributed RESs. Furthermore, faulting in the transmission line, transformer's energization and starting of large induction motor loads are also a few of the significant reasons. Plants and machines are commonly prone to voltage sags as there exist some control devices in the equipment which function gratuitously through the voltage sags. As stated by the IEEE Std. 1159 [16], voltage sag is characterized by "a decrease of the RMS voltage in the range of 0.1 to 0.9 per unit (pu) during an interval of 0.5 cycles to 1 minute". The performance in terms of voltage sag, of a particular system bus, is built upon the chain of sag frequencies it goes through throughout the year (also called sag frequencies), and the intensity of each event (quantification). The severity of voltage sag is usually assessed by sag indices computed on the basis of magnitude plus duration in association with threshold limits specified by related standards. Processes are mentioned in IEEE Std. 1564 [18], for intensity quantification of specific voltage sag events (single-event), for quantifying the performance at a particular location (single-site indices), and for quantifying the performance of the whole system (system indices). A procedure is recommended in [47] which employs voltage magnitudes in the 3-phases for computation of voltage sag score (VSS) which is mentioned in equation no. 5. The equation no. 5 applies to the case where system voltage before the sag is balanced regardless of post sag circumstance. Therefore, pre sag voltages are averaged in this work instead of selecting unity in equation no. 5.

$$VSS = 1 - \left(\frac{V_a + V_b + V_c}{3}\right) \tag{5}$$

Voltage sag score thresholds of 4% have opted as the maximum permissible limits for all the buses as suggested by the Std. EN 50160 [17]. In MATLAB based IEEE test system model used in this work, two voltage sag frequencies are considered. First sag event is made to occur by a sudden change in weather characteristics while the second event is caused by sudden switching of induction motor load. Though both sags occur at two different time intervals. Average of sag scores of the two events has been compared with the standard threshold for assessing the sag performance of each bus.

4) STEADY-STATE VOLTAGE PROFILE

There are also the possibilities of undesirable effects on the steady-state voltage profile due to dissimilar penetration levels of DGs in secondary networked distribution systems in case the customers are permitted to freely install DGs on respective sites [48]. To evaluate steady voltage profile performance of the network with distributed generation, new indices "Voltage Profile Performance Index (VPPI)" has been defined in this work and to give the same context to VPPI indices as other indices considered it is taken as equal to reciprocal of per unit voltage profile at buses. The threshold limit of steady-state voltage profile is taken as per standard EN 50160 [17] and for that reason, 1.0526 pu (inverse of 0.95) has been taken as the threshold value of VPPI indices. Moreover, the average of voltage profile of three phases is taken as done in equation no. 5, due to unbalance present in the system.

C. DEVELOPMENT OF PROPOSED UPQI BY APPLYING AHP

The analytic hierarchy process has been utilized in present work intending to rank the importance of different power quality phenomena at each bus more realistically. Calculating the scores of PQ phenomena at respective buses of the distribution power network is the first step towards the development of a proposed unified PQ index. As aforementioned there are four alternatives namely voltage harmonics distortion, voltage unbalance, voltage sag and steady-state voltage profile those are participating in the decision-making process at each bus. These four alternatives are pairwise compared individually concerning three bus impact criteria. The procedure for obtaining ranking of importance of PQ phenomena at the i^{th} bus is as follows.

1) COMPUTING THE VECTOR OF BUS IMPACT CRITERIA WEIGHTS

Each of the PQ phenomena can have different and more than one negative impacts on the consumer loads being fed at an i^{th} bus and along with that one impact can be more crucial than the other one. This section deals with computing a common vector that represents the importance ranking of negative impacts of PQ phenomena at each network bus. The process initiates by producing a pairwise comparison matrix $\boldsymbol{A}$. The matrix $\boldsymbol{A}$ is a 3×3 real matrix if three evaluation impact criteria are undertaken. Each element a_{jk} in matrix $\boldsymbol{A}$ signifies the importance of the j^{th} criterion compared with the k^{th} criterion. If $a_{jk} > 1$, then the j^{th} criterion is rather important than the k^{th} criterion, though if $a_{jk} < 1$, then the j^{th} criterion is less important than the k^{th} criterion. In case two criteria have the matching importance, then the element a_{jk} is 1. The elements a_{jk} and a_{kj} fulfil the following constraint:

$$a_{jk}.a_{kj} = 1 \tag{6}$$

The relative importance between the two criteria is scaled consistently with a numerical scale from 1 to 9, as depicted by Table 1.

TABLE 1. Table of relative scores.

Value of a_{jk}	Interpretation
1	j is as important as k
3	j is somewhat more important in comparison to k
5	j is more important than k
7	j is strappingly more important than k
9	j is absolutely more important than k

As soon as the matrix $\boldsymbol{A}$ gets constructed, it is converted to such a matrix that sum of all entries of each column is unity. For that, each element of the column is divided by sum of all entries of the corresponding column. To end with, the vector of bus impact criteria weights is obtained by taking the average of the elements on each row of the previous matrix.

The number of total criteria considered and assignments of weights depending on the planner. Though in present work only three bus impact criteria have been considered and computed vector of criteria weights is assumed common for all the network buses which can be the most common practice. Thus computed vector of criteria weight for each bus if denoted by $\boldsymbol{w}$, is $[0.6333\ \ 0.2605\ 0.1061]^{\text{T}}$ as a result of considering first impact criterion as most important and third one as least important. Moreover, giving equal importance to all three impact criteria will obviously result in $\boldsymbol{w} = [0.3333\ 0.3333\ 0.3333]^{\text{T}}$.

2) COMPUTING THE MATRIX OF PQ PHENOMENA SCORES AT EACH BUS

In the distribution network, each type of bus namely load bus, DG bus and generator bus has different characteristics. A particular bus can be more prone to one PQ phenomenon than others and different from each bus impact criterion standpoint. Now for a particular i^{th} bus, the matrix of PQ phenomena scores is a 4×3 matrix. Each column vector of such a matrix represents the importance ranking of all PQ phenomena regarding concerned impact criterion. Each such column vector is computed by the same procedure as followed in the previous subsection. Hence for considered m number of impact criteria such total m column vectors are computed and those columns form the required matrix of PQ phenomena scores. For example, if at particular load bus voltage sag causes more financial losses to the consumers than voltage distortion and consumer loads are slightly less susceptible to voltage unbalance than the voltage distortion like semiconductor industry suffers huge financial losses due to large voltage sag frequencies and controlled rectifier based DC drives as well as much electronic equipment are more prone to supply voltage harmonics. In such a case, one possible vector representing importance ranking of all four phenomena is $[0.555\ \ 0.266\ 0.120\ 0.059]^{\text{T}}$.

Similarly vectors for other two impact criteria are $[0.235\ 0.490\ \ 0.155\ \ 0.119]^{\text{T}}$ and $[0.540\ \ 0.265\ \ 0.144\ 0.051]^{\text{T}}$ respectively. MATLAB simulation point of view these vectors are computed according to the analogy of load at different load busses. Though for the buses with a similar type of loads, common vectors have been considered. Hence the matrix of PQ phenomena scores at the concerned i^{th} bus if denoted by $\boldsymbol{S}$, is as follows:

$$S = \begin{bmatrix} 0.555 & 0.235 & 0.540 \\ 0.266 & 0.490 & 0.265 \\ 0.120 & 0.155 & 0.144 \\ 0.059 & 0.119 & 0.051 \end{bmatrix}$$

3) RANKING THE PHENOMENA AT EACH BUS

After the vector of bus impact criteria weights $\boldsymbol{w}$ and the PQ phenomena score matrix $\boldsymbol{S}$ is calculated, the AHP achieves a vector $\boldsymbol{v}$ of global PQ phenomena scores at each bus by multiplying $\boldsymbol{S}$ and $\boldsymbol{w}$, i.e.

$$\boldsymbol{v} = \boldsymbol{S}.\boldsymbol{w} = \begin{bmatrix} 0.555 & 0.235 & 0.540 \\ 0.266 & 0.490 & 0.265 \\ 0.120 & 0.155 & 0.144 \\ 0.059 & 0.119 & 0.051 \end{bmatrix} . \begin{bmatrix} 0.6333 \\ 0.2605 \\ 0.1061 \end{bmatrix}$$
$$= \begin{bmatrix} 0.4699 \\ 0.3242 \\ 0.1316 \\ 0.0738 \end{bmatrix}$$

Obtained vector $\boldsymbol{v}$ indicates the global ranking of all four PQ phenomena bearing in mind all three impact criteria at the bus under consideration. Similarly, at each bus of the distribution power network, the global scores of PQ phenomena are computed according to the characteristics.

Now say vector $\boldsymbol{F_i} = [\text{VSS}_i\ \text{TVHD}_i\ \text{VUF}_i\ \text{VPPI}_i]^{\text{T}}$ of order $p \times 1$ represents the vector of individual corresponding indices of PQ phenomena and $\boldsymbol{F_{thr}}$ the vector of threshold values of indices for the i^{th} bus. Where p is the number of PQ phenomena considered at the i^{th} bus. For threshold vector subscript, i have been omitted since the threshold vector for each bus is considered similar in this work according to the IEEE/EN standards. Although special thresholds can be designated for one particular or all PQ indices because of consumers for which the joint compatibility levels stated in standards of IEEE are not acceptable owing to their extremely vulnerable equipment or functioning which would still be affected even though bus complies with PQ thresholds stated by standard and meant for various PQ phenomena.

Unified power quality index for the i^{th} bus is expressed as follows:

$$UPQI_i = \frac{[v_i]^{\mathrm{T}} . [F_i]}{[v_i]^{\mathrm{T}} . [F_{thr}]} \tag{7}$$

where v_i is a $p \times 1$ real vector obtained by applying AHP at each bus and again p is the entire number of PQ phenomena considered at the i^{th} bus.

Now AHP is applied for computing PQ priority score of each of the bus groups. That score signifies the priority for better PQ performance of concerned bus group from a distribution network operator (DNO) perspective. If W_g, W_d and W_l are the weights assigned to grid, DG and load bus group individually then the mandatory PQ priority scores vector if represented by $[A_g \ A_d \ A_l]^{\mathrm{T}}$, is gotten by the eigenvector corresponding to the largest eigenvalue of following 3×3 order judgement matrix.

$$\begin{bmatrix} 1 & {}^{W_g}/_{W_d} & {}^{W_g}/_{W_l} \\ {}^{W_d}/_{W_g} & 1 & {}^{W_d}/_{W_l} \\ {}^{W_l}/_{W_g} & {}^{W_l}/_{W_d} & 1 \end{bmatrix}$$

Therefore, the unified power quality index of the overall distribution network is expressed as follows:

$$UPQI_{overall} = A_g \sum_{i=1}^{g} w_i \times UPQI_i + A_d \sum_{i=1}^{d} w_i \times UPQI_i + A_l \sum_{i=1}^{l} w_i \times UPQI_i \tag{8}$$

$$UPQI_{overall} = A_g \times UPQI_g + A_d \times UPQI_d + A_l \times UPQI_l \tag{9}$$

where, $g =$ Total number of utility grid buses

$d =$ Total number of DG buses

$l =$ Total number of load buses

$w_i =$ Power quality importance score of the i^{th} bus of the corresponding bus group

$A_g =$ Score of utility grid buses group

$A_d =$ Score of DG buses group

$A_l =$ Score of load buses group

If each bus of the distribution network has equal power quality importance (as in general), then equation no. 8 can be approximately stated as equation no. 10.

$$UPQI_{overall} = \frac{\sum_{i=1}^{g} UPQI_i + \sum_{i=1}^{d} UPQI_i + \sum_{i=1}^{l} UPQI_i}{(g + d + l)} \tag{10}$$

Figure 3 gives a short description of the steps required to be followed for determining proposed *UPQI* for power quality evaluation by applying AHP.

III. TEST SYSTEM CONFIGURATION

The proposed methodology of power quality evaluation is verified on Std. IEEE-13 bus test distribution system modified with the integration of three types of renewable technologies based DG systems namely, photovoltaic, wind and fuel cell and different industrial drives as non-linear load. The present section covers the explanation on the modified test distribution system, modelling and topology used for different DGs and custom power devices are taken into consideration to analyse the effect on proposed *UPQI*. The succinct explanation of various components is delivered in the following subsections.

A. A MODIFIED TEST DISTRIBUTION SYSTEM

The standard IEEE-13 bus test system is basically a 60 Hz, 5 MVA, multiple voltage levels of 0.48 kV plus 416 kV, supplying balanced as well as unbalanced linear loads without any integrated RES based DGs [49]. The standard test system is subjected to required modification by means of integrating distributed energy resources and single-phase as well as three-phase nonlinear loads at buses, to carry out the proposed methodology. The overall configuration is shown in figure 4. Three 3-phase DG units of 100 kW and one single phase DG unit of 50 kW is integrated at different buses of a standard system by transformers and feeders. Though the parameters for feeders and transformers of all DGs of similar capacity have been chosen similarly. The four bus nodes of DG units are named from DG_1 to DG_4. The harmonic spectrum of DGs was measured by FFT tool in case of PV-fed case and depicted in table 2 up to 49th order harmonic frequency. Single-phase rectifier DC drive acts as single-phase nonlinear load and 3-phase rectifier DC drive and FOC induction motor drive acts as a 3-phase nonlinear load. Three load buses numbered 611, 671 and 675 carries the aforementioned nonlinear loads. The harmonic spectrums of the three nonlinear loads were measured by FFT tool and depicted in table 3 up to 49th order harmonic frequency. Only bus number 692 feeds unbalanced load and intention behind this modification is to reflect the voltage unbalance triggered by DGs in proposed *UPQI*. All the load buses those triggers the PQ issues are shown by the red colour. Though the DGs along with the PQ issues causing buses (611, 671, 675 and 692) trigger similar kind of PQ disturbances at all rest of the buses also by acting as the background. The modified test system's overall bus data is depicted in table 4. Transformer and feeder data of load buses are as per the standard IEEE-13 bus test system while data of the same for DG buses are shown in table 5 and 6 respectively.

B. MODELING AND TOPOLOGY OF DISTRIBUTED GENERATION SYSTEMS

As aforementioned, three types of RES based DG units have been integrated with the DN to carry out the network PQ performance evaluation by applying the proposed methodology. Each type of DG units has the same rated

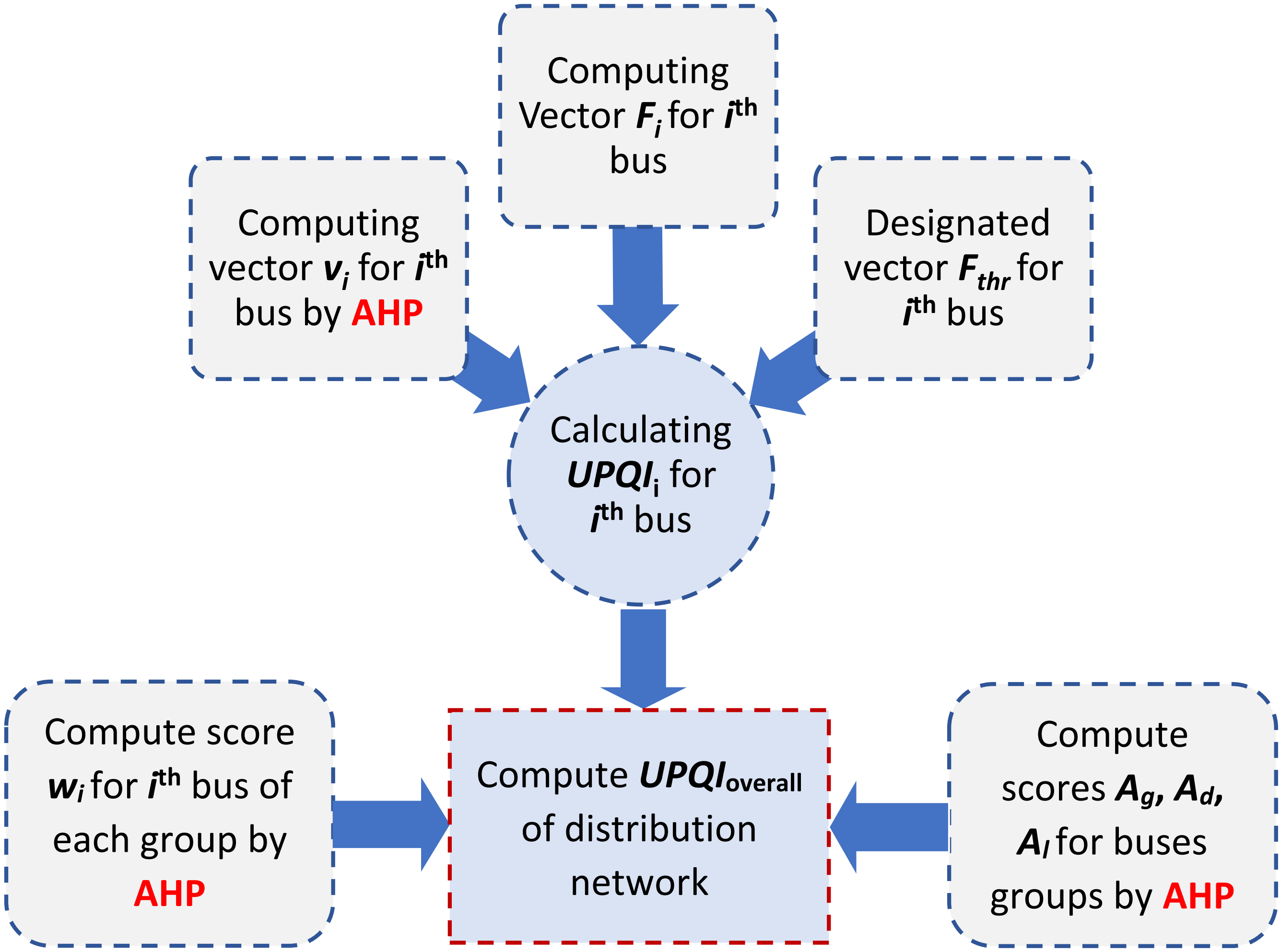

FIGURE 3. Steps for determining the proposed unified power quality index.

TABLE 2. The harmonic spectrum of PV based DG'S current with respect to fundamental component.

Harmonic Order	Magnitude (%)	Harmonic Order	Magnitude (%)	Harmonic Order	Magnitude (%)
3	9.2708	19	2.6377	35	0. 2345
5	7.4828	21	2.3987	37	0. 2445
7	6.1229	23	1.9093	39	1.1555
9	5.4866	25	1.6338	41	0. 1876
11	4.1719	27	0.6109	43	0. 3467
13	3.6559	29	1.4976	45	1.0234
15	3.3045	31	0.4321	47	0. 2389
17	3.0810	33	0. 3534	49	0.1111

voltage level of 260 V and the same power level of 100 kW. Moreover, the transformer, as well as feeder parameters, are also identical for DGs based on all three types of renewable energy sources as per table 5 and 6 respectively. Detailed modeling and topology of different DGs are demonstrated in the succeeding subsections.

1) PHOTOVOLTAIC (PV) BASED DISTRIBUTED GENERATION SYSTEM

The overall diagram of grid-connected PV based distributed generation system is depicted in figure 5. It comprises of a PV array ported with modified test distribution system utilizing the PE-converter system further comprising of an

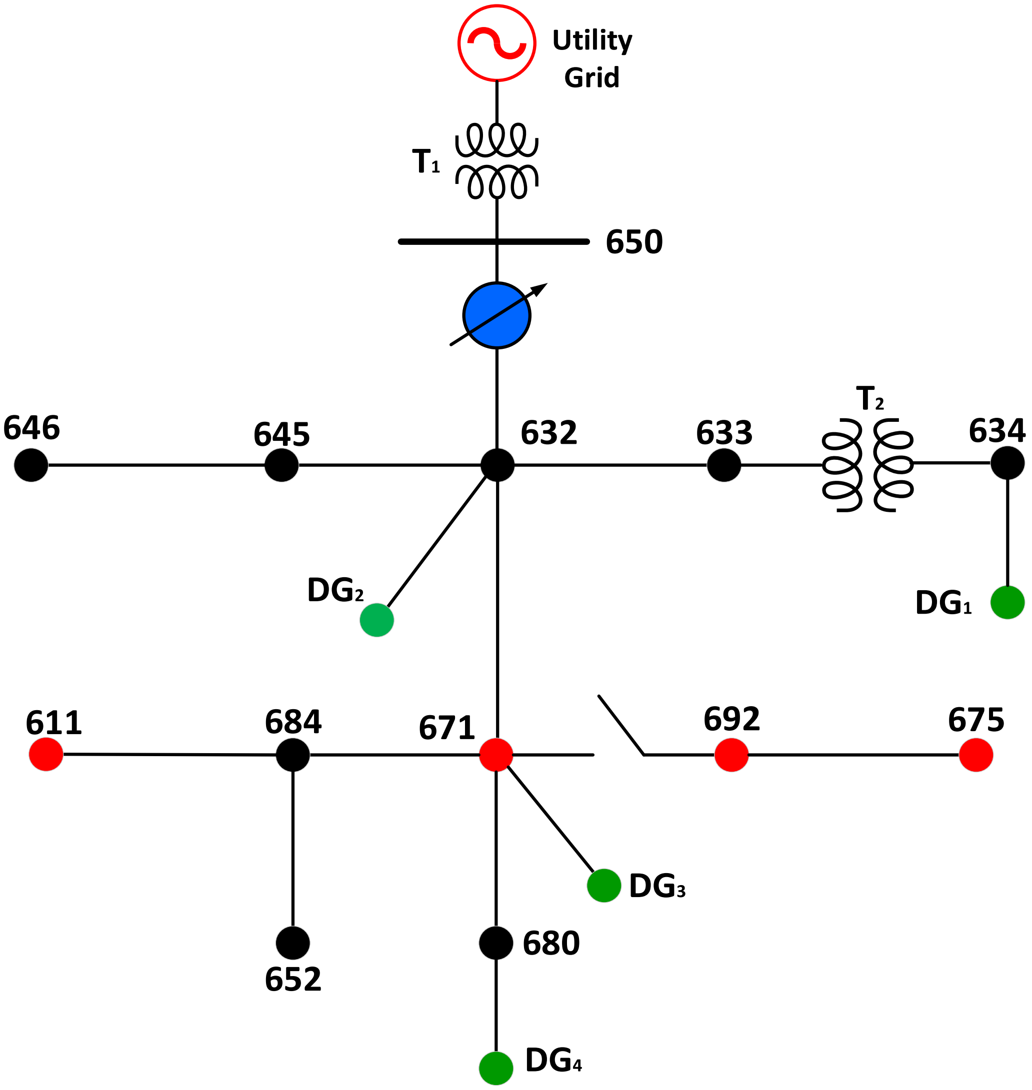

FIGURE 4. Configuration of the modified test distribution system.

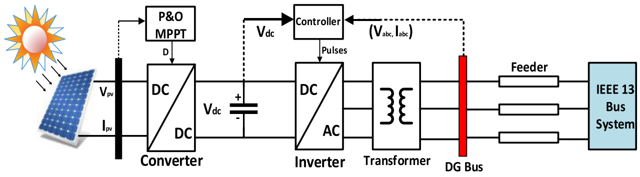

FIGURE 5. The complete representation of grid-connected PV based distributed generation system.

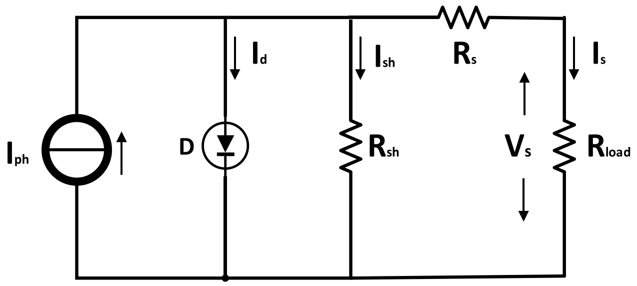

FIGURE 6. One diode equivalent model of solar cell.

MPPT controlled DC-DC boost converter and an inverter, transformer and feeder. A clear explanation of the available PV energy conversion systems, the PV converter topologies those have been substantially employed in grid-integrated systems, is addressed in [50].

Individual solar PV unit of 100 kW entails of an array made up of 66 parallel-connected strings. In that array, each string contains 5 modules coupled in series as well as each module contains 96 solar cells. Solar cells are usually coupled in series and parallel for generating the demanded level of power at the output and called solar arrays. A solar cell is made by sandwiching two different layers of silicon those have been specifically treated or doped to flow electricity through them in a particular manner [51]. One diode model represents a solar cell's electrical equivalent circuit as depicted in figure 6.

TABLE 3. The harmonic spectrum of nonlinear load's current with respect to fundamental component.

Harmonic Order	Bus No.		
	611	671	675
	Magnitude (%)	Magnitude (%)	Magnitude (%)
1	100	100	100
5	27.35	83.76	77.34
7	19.21	78.64	58.73
11	14.43	45.98	21.58
13	12.87	44.20	10.31
17	9.23	19.62	8.67
19	7.44	10.44	7.31
23	5.07	6.36	3.34
25	4.13	4.61	3.01
29	2.78	3.82	2.64
31	1.56	1.98	1.68
35	1.26	1.43	1.25
37	1.11	1.28	1.13
41	0.84	1.17	1.08
43	0.66	1.11	1.03
47	0.25	0.97	0.89
49	0.13	0.89	0.81

Herein model, a current source and a diode are parallelly coupled. The photocurrent I_{ph} is produced by the current source and is directly proportional to the solar radiation F_s in W/m^2, ambient temperature T_a in °C, Current I_s in amp and Voltage V_s in volt. The PN-Junction area of the solar cell is equivalent to the diode.

Now by applying KVL in the one diode model circuit, the load current can be obtained using (11),

$$I_s = I_{ph} - I_d - I_{sh} \tag{11}$$

where I_{ph} denotes photocurrent, I_s denotes load current, I_d denotes the diode current and I_{sh} denotes the shunt current. The photocurrent I_{ph} can be computed by the expression shown in (12),

$$I_{ph} = P_1.F_s\left[1 + P_2.\left(F_s - F_o\right) + P_3.\left(T_j - T_o\right)\right] \tag{12}$$

In (12), P_1, P_2, P_3 are the Constants, the value of T_o is 298.15 K, the value of F_o is 1000 W/m^2 and T_j denotes Junction temperature. Diode's reverse saturation current I_d can be computed by the expression shown in (13).

$$I_d = I_{sat}\left[e^{\left[\frac{e}{aN_sK} \times \frac{V_s+R_sI_s}{T_j}\right]} - 1\right] \tag{13}$$

Here, diode saturation current

$$I_{sat} = P_4.T_j^3.e^{\left(\frac{-E_g}{K.T_j}\right)}$$

where e denotes the electron's charge, a denotes the diode's ideality factor, N_s denotes the number of series-connected cells, K denotes Boltzmann's constant, R_s denotes series resistance's value, E_g denotes bandgap and P_4 denotes a correction factor. Thus applying KVL in the circuit depicted in fig. 6, the photocurrent I_{sh} can be computed by the expression shown in (14).

$$I_{sh} = \frac{V_s + R_sI_s}{R_{sh}} \tag{14}$$

Technical specifications corresponding to each PV module is stated in table 7.

Since one PV string's output voltage is extremely low despite applying MPPT (P&O), a dc-dc boost converter with a front end is required to integrate the low voltage PV modules to the corresponding bus and transferring the power over a feeder. An inverter converts the DC output power of boost converter into 50 Hz AC power. In the proposed study the dc-dc boost converter hikes dc output voltage of PV array from 273.8 V (at 1000 W/m^2 and 25 $^{\text{o}}$C) to

TABLE 4. Bus data of the modified test system.

Type of the Bus	Bus No.	No. of Phases	Bus Voltage	Generation		Load		Nature of the Load
				kW	kvar	kW	kvar	
Utility Grid (Slack Bus)	650	3	1.0 + j0.0	0	0	0	0	N/A
DG Buses (Constant P model)	DG$_1$	1	1.0 + j0.0	50	0	0	0	N/A
	DG$_2$	3	1.0 + j0.0	100	0	0	0	N/A
	DG$_3$	3	1.0 + j0.0	100	0	0	0	N/A
	DG$_4$	3	1.0 + j0.0	100	0	0	0	N/A
Load Buses (Constant PQ model)	611	1	1.0 + j0.0	0	100	175	82.5	Linear and Nonlinear
	632	3	1.0 + j0.0	0	0	200	114	Linear and Balanced
	633	3	1.0 + j0.0	0	0	0	0	No Load
	634	3	1.0 + j0.0	0	0	400	290	Linear and Balanced
	645	1	1.0 + j0.0	0	0	170	125	Linear
	646	2	1.0 + j0.0	0	0	230	132	Linear
	652	1	1.0 + j0.0	0	0	128	86	Linear
	671	3	1.0 + j0.0	0	0	355	140	Nonlinear and Balanced
	675	3	1.0 + j0.0	0	600	48	12	Nonlinear and Balanced
	680	3	1.0 + j0.0	0	0	0	0	No Load
	684	2	1.0 + j0.0	0	0	0	0	No Load
	692	3	1.0 + j0.0	0	0	370	220	Linear and Unbalanced

TABLE 5. Transformer data of DG buses.

DG Capacity (kW)	Transformer Parameters					
	kVA		kV High	kV Low	R(pu)	X(pu)
50	(a)	50	2.401	0.260	0.002	0.06
	(b)	50	2.401	0.277	0.002	0.06
100	100		4.160	0.260	0.001	0.03

500 V and the dc-ac inverter converts 500 V dc to 260 V, 50 Hz, three-phase ac supply. The boost converter functions at switching frequency of 5 kHz. The inverting is done through a 3-level VSC functioning at switching frequency

TABLE 6. Feeder data of DG buses.

From Node	To Node	Feeder Parameter (Per km)						
		$R_1(\Omega)$	$R_0(\Omega)$	L_1(mH)	L_0(mH)	C_1(nF)	C_0(nF)	Length (km)
DG_2	632	0.1153	0.413	1.05	3.32	11.33	5.01	5
DG_3	671	0.1153	0.413	1.05	3.32	11.33	5.01	5
DG_4	680	0.1153	0.413	1.05	3.32	11.33	5.01	5
DG_1	634	R(Ω)		L(mH)		C(nF)		
		0.01273		0.9337		12.74		2

of 19.8 kHz. The dc-dc boost converter is controlled by applying P&O and I-regulator based MPPT method applied in the solar PV system. For a comprehensive explanation of the P&O method [52], [53] can be referred. The DQ frame pulse-width modulation (PWM) control scheme has been used for controlling the inverter circuit. The thorough explanation of this control scheme is described in [54]. The control techniques are not mentioned in depth owing to article length limits because the core focus of the present study is the network power quality evaluation.

TABLE 7. Technical specifications corresponding to each PV module.

Parameter Name	Symbol	Value
Maximum power	P_{max}	305.62 W
Open circuit voltage	V_{oc}	64.2 V
Short circuit current	I_{oc}	5.96 A
Voltage at MPP	V_{mp}	54.70 V
Current at MPP	I_{mp}	5.58 A
Series Resistance	R_s	0.3715 Ω
Shunt Resistance	R_{sh}	257.5321 Ω
Saturation current of diode	I_{sat}	$6.3014e^{-12}$ A
Ideality factor of diode	Q_d	0.9450
Photocurrent	I_{ph}	6.0092 A

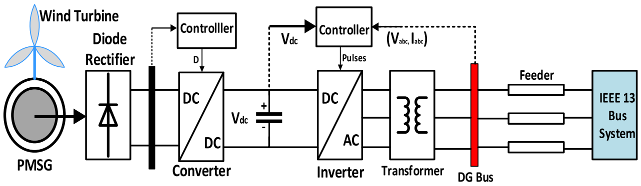

FIGURE 7. The complete representation of the grid-connected wind-based distributed generation.

2) WIND-BASED DISTRIBUTED GENERATION SYSTEM

The whole schematic of grid-integrated wind-based DG system is depicted in figure 7. The same comprises of a wind turbine fed Permanent Magnet Synchronous Generator (PMSG) integrated to modified IEEE test distribution system by the PE-converter system further involving a diode-bridge rectifier, DC-DC boost converter, an inverter, transformer and feeder. Reference [55] gives the complete insight of modeling and control of grid-connected PMSG based wind energy conversion system (WECS) used in the present study. The employed diode rectifier changes the variable output ac voltage of PMSG to variable dc voltage and the boost converter boosts the variable output dc voltage of rectifier to a higher in addition to constant dc voltage at a level appropriate for the operation of the inverter. The boost converter also regulates the speed of the generator or the active power of the generator to draw the supreme amount of power from the blowing wind. The inverter generates 50 Hz AC power by converting the DC output power of the boost converter. In the present study, the dc-dc converter boosts dc output voltage of diode rectifier from 271.2 V (at 15 m/sec wind speed) to 500 V and successively 260 V, 50 Hz, 3-phase ac supply is obtained from 500 V dc by inverter action. Both boost converter as well as 3-level VSC functions with a high frequency of switching at 50 kHz. Technical data PMSG is mentioned in table 8. The discussion on control and modeling of WECSs is well covered in literature [56], [57], hence details on the same are kept here as short as possible.

TABLE 8. Technical data of PMSG.

Parameter Name	Value
Nominal Power (kVA)	100
Voltage Rating (Volt)	220
Frequency (Hz)	60
X_d, X_d', X_d'' (pu)	1.305, 0.296, 0.252
X_q, X_q'', X (pu)	0.474, 0.243, 0.18
Resistance (pu)	0.006
Inertia constant, friction factor (pu)	0.62, 0.01
Pairs of poles	1

3) FUEL CELL-BASED DISTRIBUTED GENERATION SYSTEM

PV in addition to wind-based systems generates power merely after the sun shines or the wind blows. Therefore, they are considered as secondary power support for the grid. Fuel cells (FCs) have also engrossed attention as a source of distributed power generation, particularly for the period of peak load. As long as fuel (hydrogen and oxygen) is made available by the operators, FC consistently produces DC electricity with significant efficiency, unlike climate reliant power sources, for example, solar and wind. Sometimes, also the uncertainty of RESs and the variations of load demand is compensated by energy supplied by fuel cells [58]. Fuel cells have the potential of providing energy without noise pollution, clean, consistent and higher efficiency at the required scale. Numerous kinds of FCs are reported in the literature but proton exchange membrane fuel cells (PEMFCs) are the best suitable for a distributed generation due to their lower emissions, low operational temperature, high power density, fast starting and the same is used in present work [59]. Fig 8. shows a complete schematic of a grid-connected fuel cell-based DG system. The boost DC-DC converter is associated with the FC to maintain the DC bus voltage at high and sustained magnitude. To maintain the voltage of DC bus at 500 V i.e. reference value and a PI controller is used for regulating the duty cycle of the same. Rest of the converter have technical data and operation identical to the previous subsections. Technical data of fuel cell stack is mentioned in table 9. Reference [60] is recommended to readers for getting insight into modeling, control of active power and voltage and simulation of PEMFC-based power supply system.

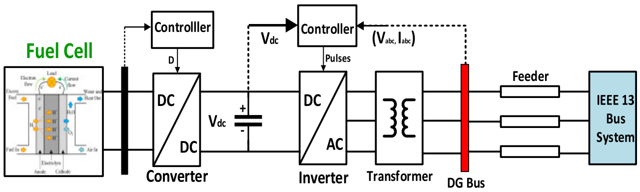

FIGURE 8. The complete representation of the grid-connected FC based distributed generation.

TABLE 9. Technical data of FC stack.

Parameter Name	Value
Type	PEMFC
Power Rating (kW)	100
Voltage Rating (Volt)	365
Number of Cells	1200
Cell Resistance (Ω)	0.66404
Nominal Air Flow Rate (lpm)	2100
Nominal Supply Pressure [Fuel (bar), Air (bar)]	[1.5 1]
Nominal Composition (%) [H_2 O_2 H_2O(Air)]	[99.95 21 1]
Rated Efficiency	55
Temperature	65

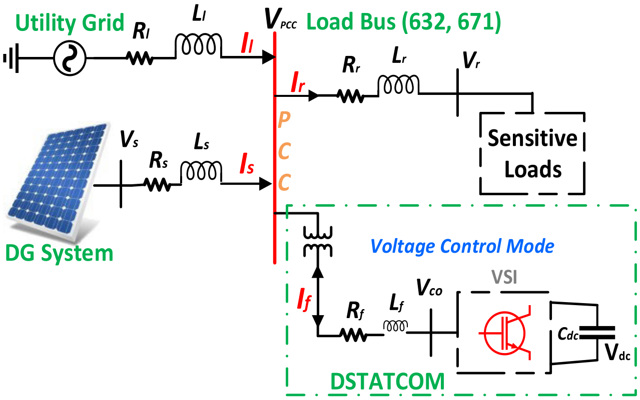

FIGURE 9. Distribution network configuration with DSTATCOM in voltage control mode.

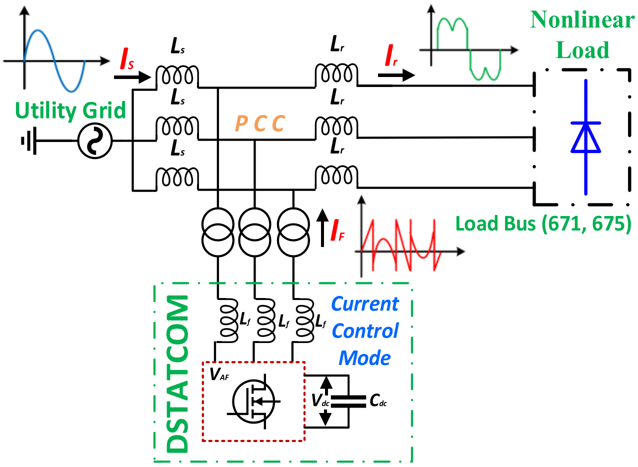

FIGURE 10. Distribution network configuration with DSTATCOM in current control mode.

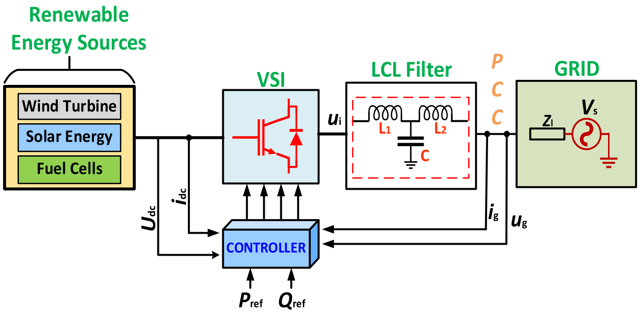

FIGURE 11. Grid integration of renewable DG system through LCL filter.

C. CUSTOM POWER DEVICES FOR POWER QUALITY ENHANCEMENT

The growing usage of energy conservation practices, the initiatives are taken towards the smart grid and the swelling presence of distributed energy resources in addition to consumers own generation by means of inverter circuits have all influenced energy usage, and simultaneously has raised new challenges in the area of power quality. It goes without saying that PQ is a significant characteristic of

TABLE 10. Global PQ phenomena score vector-*v* computed at each bus by AHP.

BUS NO.	***GLOBAL SCORES***			
	Voltage Sag	Voltage Harmonics Distortion	Voltage Unbalance	Steady State Voltage Profile
650	0.4699	0.3242	0.1316	0.0738
DG$_1$	0.5257	0.4126	*N/A	0.0617
DG$_2$	0.4432	0.3403	0.1397	0.0763
DG$_3$	0.4511	0.3324	0.1216	0.0944
DG$_4$	0.4126	0.3452	0.1344	0.1072
611	0.5123	0.3711	*N/A	0.1166
632	0.4825	0.3197	0.1089	0.0817
633	0.2500	0.2500	0.2500	0.2500
634	0.3922	0.3498	0.1390	0.1118
645	0.4478	0.4023	*N/A	0.1498
646	0.3749	0.3065	0.1659	0.1478
652	0.4569	0.3647	*N/A	0.1852
671	0.3391	0.3021	0.1849	0.1698
675	0.4547	0.3323	0.1309	0.0815
680	0.2500	0.2500	0.2500	0.2500
684	0.3333	0.3333	*N/A	0.3333
692	0.3895	0.3136	0.1605	0.1330

*N/A: Not Applicable

TABLE 11. Vector- F_i of different PQ phenomena indices measured at each bus in Case-I.

BUS NO.	***PQ PHENOMENA INDICES***			
	Voltage Sag Score (VSS)	Total Voltage Harmonic Distortion (TVHD)	Voltage Unbalance Factor (VUF)	Voltage Profile Performance Index (VPPI)
650	3.1452	5.2145	1.8632	1.0031
DG$_1$	5.3648	9.0139	*N/A	1.0137
DG$_2$	5.7215	8.3785	3.2195	1.0052
DG$_3$	4.9372	7.6933	4.3545	1.0248
DG$_4$	6.1894	9.0443	4.2492	1.0272
611	5.9742	8.3215	*N/A	1.0279
632	5.6584	7.9644	3.9198	1.0354
633	4.9354	8.1365	2.5482	1.0451
634	5.6161	7.1668	3.1647	1.0136
645	6.1488	8.1945	*N/A	1.0240
646	4.8113	7.2356	2.1995	1.0215
652	4.2694	6.3015	*N/A	1.0105
671	5.1649	9.1905	4.1644	1.0215
675	5.6865	10.9121	3.9743	1.0105
680	4.2969	6.6241	3.9138	1.0205
684	5.7956	5.1140	*N/A	1.0353
692	4.4962	7.3564	5.3476	1.0431

*N/A: Not Applicable

modern distribution networks since loads are going rather more sensitive conversely the strength of loads is growing in the DNs. CPDs, for instance, STATCOMs, SVCs, DVRs, static synchronous series compensators (SSSCs), thyristor controlled series compensators (TCSCs), and an amalgamation of shunt and series active power filters are the newest innovations of devices, integrated at the PCC, between grids and consumer loads that mitigate voltage and current disturbances and enhance the power quality through compensating harmonic and reactive power [61]. Distribution static compensator (D-STATCOM) is being progressively more employed for improving dynamic voltage stability of

TABLE 12. Computed *UPQI* at each bus in Case-I.

BUS NO.	650	DG$_1$	DG$_2$	DG$_3$	DG$_4$	611	632	633	634	645	646	652	671	675	680	684	692
UNIFIED POWER QUALITY INDEX (UPQI)	0.9078	1.5603	1.5422	1.4204	1.6915	1.5563	1.5088	1.3826	1.3873	1.5662	1.2891	1.1373	1.6017	1.7801	1.3155	1.1881	1.4092

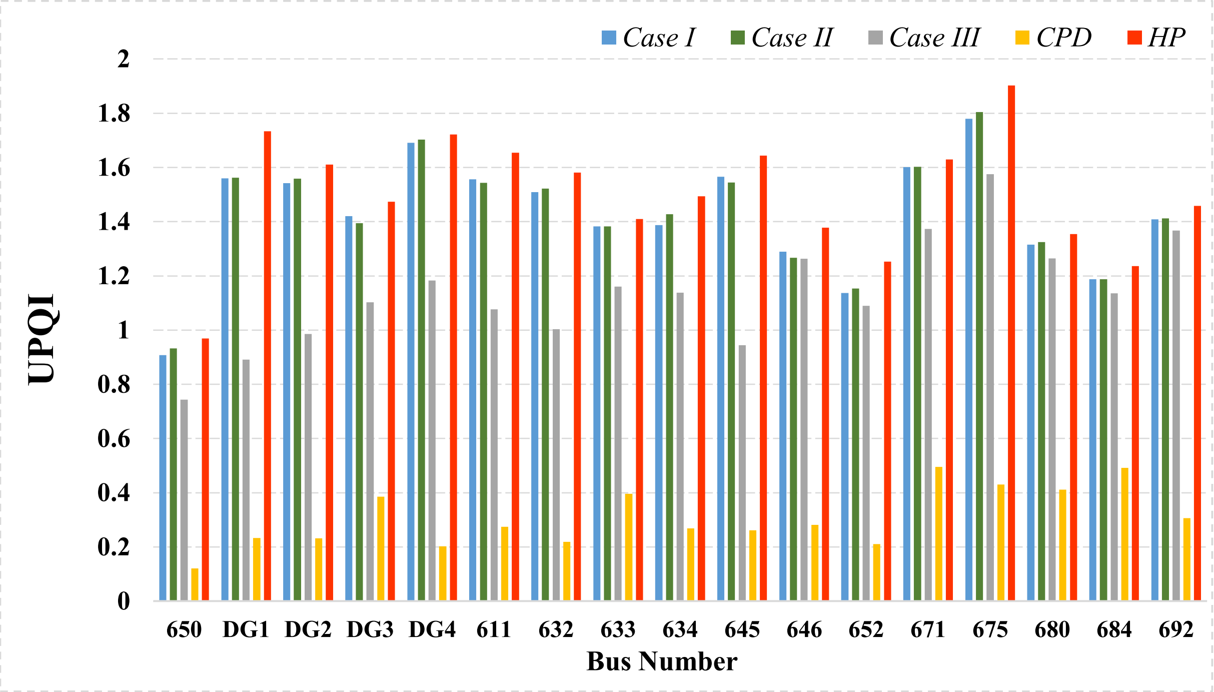

FIGURE 12. Comparative analysis of *UPQIs* of individual buses under all cases.

TABLE 13. Computed *UPQI* of individual bus groups and overall distribution network in Case-I.

$UPQI_g$	$UPQI_d$	$UPQI_l$	$UPQI_{overall}$
0.9078	1.5536	1.4269	1.2961

grid integrated RES based DGs when functioned in voltage control mode (VCM) [62]. It is extensively employed in industry as well as a distribution system, proficient of maintaining load voltage by either absorbing or supplying reactive power to it and equipped with a voltage source inverter to control the output voltage constantly unlike SVC that regulates the output voltage in a discontinuous manner [63], [64]. Reference [65] gives insight into modelling, control and capabilities of D-STATCOM systems used for enhancing PQ in low voltage (LV) grids with distributed energy resources (DERs). In current control mode (CCM), D-STATCOM can compensate for load harmonics, reactive power and unbalance [66]. In present work, D-STATCOM operates in VCM to control voltage quality disturbances caused by RES intermittency. Figure 9 and 10 depicts the distribution network configurations with DSTATCOM in VCM and CCM respectively. Here it must be noted that DG systems have two categories of harmonics associated with them, and collectively they may source extreme harmonic voltage distortion at PCC. The primary kind of harmonics is produced by PE devices employed in DG systems like PV systems, that also encloses high-frequency harmonic (HFH) components at multiples of the carrier frequency of the DG interfacing inverter [67]. HFH injected by renewable-based DGs can be effectively filtered by the grid-connected passive filters like *L*, *LC* or *LCL* filters if engaged at the interfacing end of the inverters. The possible functioning effect, at the system level, on proposed *UPQI* because of passive filters connected at the inverter end to filter such harmonics is considered in this work. *LCL* filter is a promising way out of harmonics at the point of common coupling due to integration of DERs because of its economic viability,

TABLE 14. Vector- F_i of different PQ phenomena indices measured at each bus in Case-II.

BUS NO.		650	DG$_1$	DG$_2$	DG$_3$	DG$_4$	611	632	633	634	645	646	652	671	675	680	684	692
PQ PHENOMENA INDICES	Voltage Sag Score (VSS)	3.3491	5.3751	5.8216	4.7373	6.2693	5.8748	5.7586	4.9152	5.7167	6.1491	4.8115	4.2698	5.1656	5.6858	4.2996	5.7946	4.4945
	Total Voltage Harmonic Distortion (TVHD)	5.2144	9.0140	8.3985	7.6989	9.0341	8.3216	7.9842	8.1367	7.1676	7.9754	7.2452	6.3014	9.1901	11.1121	6.6248	5.1141	7.3762
	Voltage Unbalance Factor (VUF)	1.8534	*N/A	3.3189	4.2645	4.3496	*N/A	3.8297	2.6486	3.1646	*N/A	2.1894	*N/A	4.1641	4.1748	4.0236	*N/A	5.3775
	Voltage Profile Performance Index (VPPI)	1.0019	1.0138	1.0050	1.0246	1.0271	1.0281	1.0356	1.0456	1.0135	1.0239	1.0212	1.0106	1.0216	1.0102	1.0206	1.0354	1.0432

TABLE 15. Computed *UPQI* at each bus in Case-II.

BUS NO.	650	DG$_1$	DG$_2$	DG$_3$	DG$_4$	611	632	633	634	645	646	652	671	675	680	684	692
UNIFIED POWER QUALITY INDEX (UPQI)	0.9324	1.5617	1.5593	1.3944	1.7030	1.5438	1.5220	1.3827	1.4279	1.5441	1.2667	1.1534	1.6019	1.8043	1.3248	1.1881	1.4122

TABLE 16. Computed *UPQI* of individual bus groups and overall distribution network in Case-II.

$UPQI_g$	$UPQI_d$	$UPQI_l$	$UPQI_{overall}$
0.9324	1.5546	1.4309	1.3059

size and high attenuation of HFH while achieving enhanced decoupling between the filter and grid impedance and the same is used in present work. Figure 11 depicts the grid integrated renewable DG system through LCL filter. The secondary kind of harmonics is injected by other nonlinear local, PCC, and utility loads in the distribution network, which are a common type of harmonics at multiples of the power grid frequency, 50/60 Hz. Harmonic compensation for such harmonics done either by innovative controlling of the DG interfacing inverter functioned like a PQ conditioner or local load compensation by D-STATCOM operating in CCM. In present work, the active power of all considered non-linear loads is locally filtered by D-STATCOM operating in CCM.

IV. RESULTS AND DISCUSSION

The modified test distribution network, depicted in fig. 4, is simulated in MATLAB/Simulink environment with three types of renewable energy-based DGs sequentially to validate the proposed PQ evaluation criterion by *UPQI*. Continuous disturbances like voltage distortion, voltage unbalance, steady-state voltage profile deterioration as well as the considered only discrete disturbance i.e. voltage sag are present due to both DGs and network loadings. Voltage fluctuation occurs due to DGs resulting from a change in ecological factors suchlike irradiation/wind velocity as well as sudden induction motor load switching at the bus no. 671. The power rating of induction motor is selected very small to avoid large variation in system PQ indices from pre switching to post switching. It should be noted that power injected by DG oscillates from 1.25 sec to 2 sec and motor load is switched on at instant of 2.5 sec.

Control algorithm of DSTATCOM is based on the well-known PQ theory and the same has been employed for extracting the reference current components from local

TABLE 17. Vector- F_i of different PQ phenomena indices measured at each bus in Case-III.

BUS NO.		650	DG1	DG2	DG3	DG4	611	632	633	634	645	646	652	671	675	680	684	692
PQ PHENOMENA INDICES	Voltage Sag Score (VSS)	2.1452	2.2531	2.9512	2.6372	1.9824	4.3742	2.6629	3.2194	3.5181	2.4742	3.4103	4.6424	4.6529	5.2315	4.1049	5.1957	4.3212
	Total Voltage Harmonic Distortion (TVHD)	4.7162	6.1209	5.7206	7.1697	6.6258	5.3215	6.4098	7.1815	6.5609	6.1649	8.6480	5.1649	7.1741	9.1672	6.1981	5.1823	7.0891
	Voltage Unbalance Factor (VUF)	1.8631	*N/A	3.2196	4.3544	4.2495	*N/A	3.9199	2.5483	3.1648	*N/A	2.1996	*N/A	4.1648	3.9746	3.9149	*N/A	5.3476
	Voltage Profile Performance Index (VPPI)	1.0029	1.0141	1.0101	1.0252	1.0271	1.0281	1.0356	1.0453	1.0135	1.0241	1.0218	1.0107	1.0213	1.0109	1.0206	1.0355	1.0434

*N/A: Not Applicable

TABLE 18. Computed *UPQI* at each bus in Case-III.

BUS NO.	650	DG1	DG2	DG3	DG4	611	632	633	634	645	646	652	671	675	680	684	692
UNIFIED POWER QUALITY INDEX (UPQI)	0.7435	0.8916	0.9863	1.1024	1.1826	1.0772	1.0034	1.1609	1.1386	0.9447	1.2630	1.0899	1.3727	1.5747	1.2643	1.1354	1.3669

nonlinear loads. Also the DC-link voltage control has been achieved by the PI-controller being further tuned by the PSO.

In DG systems, inverter control strategy is selected similar for each RES type. Both external control loop which regulates DC link voltage as well as internal control loop which regulates I_d and I_q grid currents, employs PI-controller. I_q current reference is set to zero in order to maintain unity power factor. Internal and external control loop are first simplified by block reduction method. The Routh Hurwitz stability criteria is then applied to check the range of values for parameters in PI-controller. At this stage it is known how much gain and phase margin is required in the system. By writing codes in MATLAB, bode plots are easily generated for the system. Thus PI-controller gains are tuned depending upon the required margins that we have already set for our system.

Computed threshold vector F_{thr} is [4.000 5.000 2.000 1.0526]^T and [4.000 5.000 1.0526]^T and taken identical as well as in accordance with associated standards at each bus for PQ evaluation purpose (refer section 2.3). Table 10 shows global PQ phenomena score vector $\boldsymbol{v}$ computed at each bus by applying AHP according to part-c of section 2.3. Since the bus number 633, 680 and 684 does not carry any load, so equal importance has been given to each of the PQ phenomena. Moreover, the order of all vectors at bus number DG$_1$, 611, 645, 652 and 684 is 3×1 because only three PQ phenomena are concerned at single as well as two-phase buses after exclusion of voltage unbalance. Table 11 depicts vector $\boldsymbol{F_i}$ of different PQ phenomena indices measured at each bus when

TABLE 19. Computed *UPQI* of individual bus groups and overall distribution network in Case-III.

*UPQI*g	*UPQI*d	*UPQI*l	*UPQI*overall
0.7435	1.0407	1.1993	0.9945

TABLE 20. Vector- F_i of different PQ phenomena indices measured at each bus with CPDs.

	BUS NO.	650	DG1	DG2	DG3	DG4	611	632	633	634	645	646	652	671	675	680	684	692
PQ PHENOMENA INDICES	Voltage Sag Score (VSS)	0.4746	0.4219	0.6715	0.9850	0.4943	0.6985	0.3094	0.3607	0.2922	0.1949	0.4791	0.2906	0.7924	0.3294	0.3196	0.6544	0.2515
	Total Voltage Harmonic Distortion (TVHD)	0.3971	1.6976	1.4211	2.6327	1.1649	1.6912	1.8948	2.9795	2.0949	1.9742	1.9477	1.3229	3.8206	4.1025	3.1752	3.2504	2.3215
	Voltage Unbalance Factor (VUF)	0.2897	*N/A	0.2164	0.4228	0.3291	*N/A	0.2105	0.3852	0.2441	*N/A	0.3521	*N/A	0.4995	0.3697	0.4224	*N/A	0.8321
	Voltage Profile Performance Index (VPPI)	1.0325	1.0481	1.0235	1.0325	1.0427	1.0311	1.0354	1.0534	1.0335	1.0226	1.0465	1.0511	1.0435	1.0394	1.0378	1.0455	1.0536

*N/A: Not Applicable

TABLE 21. Computed *UPQI* at each bus with CPDs.

BUS NO.	650	DG1	DG2	DG3	DG4	611	632	633	634	645	646	652	671	675	680	684	692
UNIFIED POWER QUALITY INDEX (UPQI)	0.1213	0.2332	0.2320	0.3854	0.2028	0.2745	0.2189	0.3965	0.2684	0.2613	0.2812	0.2106	0.4955	0.4301	0.4111	0.4924	0.3066

PV fed DGs are integrated i.e. Case-I. It can be observed that bus no. 671 and 675 show the worst performance in terms of TVHD due to the penetration of nonlinear loads. Therefore, applying the method mentioned in equation no. 7, computed *UPQIs* at each bus are shown in table 12. It can be seen from table 12 that bus DG3 performs the best while bus DG4 performs the worst in the sense of overall power quality among the candidates of the entire DG bus group. Though each of the buses underperforms in terms of overall power quality since *UPQI* of each of the buses is greater than unity. Hence also the overall PQ performance of each of the DG buses can be benchmarked just by its corresponding *UPQI* obtained from equation 7. Similarly, also table 12 shows that bus 652 performs the best while bus 675 performs the worst in the sense of overall power quality among the candidates of the entire load bus group.

Afterwards, the overall PQ performance of individual bus groups and entire distribution network as a whole is evaluated by compound indexes computed and shown in table 13. For computing the *UPQI* of individual bus groups as well as overall DN, equal weightages were assigned to each group though it goes without saying that the proposed approach also has the flexibility of assigning the dissimilar ones. For the system, under consideration in present work, overall index, denoted as $UPQI_{\text{overall}}$, is obtained as 1.2961, indicating the deteriorated overall PQ condition of the network. While the indexes corresponding to other bus groups i.e. $UPQI_g$, $UPQI_d$ and $UPQI_l$ are obtained as 0.9078, 1.5536 and 1.4269 respectively. Though there may be circumstances

TABLE 22. Computed *UPQI* of individual bus groups and overall distribution network with CPDs.

$UPQI_g$	$UPQI_d$	$UPQI_l$	$UPQI_{\text{overall}}$
0.1213	0.2634	0.3731	0.2526

TABLE 23. **Vector- F_i of different PQ phenomena indices measured at each bus under high penetration.**

BUS NO.		650	DG_1	DG_2	DG_3	DG_4	611	632	633	634	645	646	652	671	675	680	684	692
PQ PHENOMENA INDICES	Voltage Sag Score (VSS)	3.4218	6.1265	5.9672	5.2034	6.2972	6.4571	5.8622	5.2364	5.9323	6.5258	5.3202	4.6828	5.4021	6.0824	4.4228	5.9006	4.7235
	Total Voltage Harmonic Distortion (TVHD)	5.5332	9.8130	8.8237	7.9321	9.2381	8.7236	8.5017	8.1542	7.6221	8.5330	7.6246	6.8233	9.2360	11.7712	6.9624	5.4822	7.6301
	Voltage Unbalance Factor (VUF)	1.8721	*N/A	3.2256	4.3624	4.2526	*N/A	3.9216	2.5510	3.1734	*N/A	2.2136	*N/A	4.1722	3.9852	3.9211	*N/A	5.3501
	Voltage Profile Performance Index (VPPI)	1.0104	1.0248	1.0084	1.0311	1.0318	1.0294	1.0379	1.0487	1.0177	1.0276	1.0242	1.0162	1.0231	1.0152	1.0226	1.0385	1.0481

*N/A: Not Applicable

where one or more of the DN's buses perform better while rest perform poor and in such cases, the net PQ performance of individual buses can be exactly benchmarked by equation no. 7 while the accuracy of the decision made, regarding the overall PQ performance, decreases with a rise in the number of buses in the distribution system. The reason lies behind the fact that load buses generally form 90% part of the overall distribution network while it is certainly limited and fixed number of PQ indices to be monitored at each bus. Hence it can be said that the application-flexibilities of the proposed approach are constrained by the size of the distribution network concerned.

In the same way, the proposed approach of PQ assessment is applied on distribution network simulated and modified with wind and fuel cell sourced DGs i.e. Case-II and III. Table 14 and 17 show the vector F_i of different PQ phenomena indices measured at each bus for Case-II and III. Table 15 and 18 depicts the computed *UPQIs* at each of the buses. Afterwards, the overall PQ performance of individual bus groups and entire distribution network as a whole is evaluated by compound indexes computed and shown in table 16 and 19. Figure 12 shows the comparative analysis of *UPQIs* of individual buses under three considered cases as well as two other scenarios. Recalling that the objective behind considering different cases of energy source in DG systems is to assess and compare the power quality performance of the distribution network by the proposed approach under different RES scenarios and weather conditions. In case I and II, active power productions from DGs experience large variation due to change in ecological factors such as irradiation/wind speed that results in power quality concerns suchlike voltage fluctuations and voltage distortion at DG as well as load buses while in case III fuel supply has been assumed continuous which results in considerably improved sag as well as distortion performance at DG as well as load buses. The impact of continuity of energy source can be evidently seen from overall UPQI at each of the buses in case III in comparison to the case I and II as depicted in figure 12. The overall UPQI of DG bus group in case III is also pretty close to unity while slight deviation being the result of voltage unbalance at DG as well as load buses. The impact of continuity of energy source can also be clearly seen saturating while moving from DG buses to load buses owing to the persistence of similar grid side disturbances also in case III.

For analysing the impact of installing CPDs on power quality of distribution network, two D-STATCOMs were installed at buses carrying the nonlinear loads i.e. 671 and 675 for providing the local harmonic compensation while two D-STATCOMs were installed at the bus no. 632 and 671 respectively for regulating the bus voltages. Table 20 shows vector $\boldsymbol{F_i}$ of different PQ phenomena indices measured at each bus when CPDs are installed at aforementioned locations in the system of case I. Improvement in sag performance, after installing voltage regulating devices, can be seen from VSS of each of the buses.

TABLE 24. Computed *UPQI* at each bus under high penetration.

BUS NO.	650	DG$_1$	DG$_2$	DG$_3$	DG$_4$	611	632	633	634	645	646	652	671	675	680	684	692
UNIFIED POWER QUALITY INDEX (UPQI)	0.9690	1.7332	1.6105	1.4733	1.7215	1.6549	1.5808	1.4097	1.4939	1.6435	1.3780	1.2522	1.6301	1.9022	1.3548	1.2356	1.4582

TABLE 25. Computed *UPQI* of individual bus groups and overall distribution network under high penetration.

$UPQI_g$	$UPQI_d$	$UPQI_l$	$UPQI_{overall}$
0.9690	1.6346	1.4995	1.3677

Likewise, the advantages of employing local compensators for nonlinear loads as well as passive filters at DG terminals is also evident from the TVHD index of each of the buses. The computed *UPQI* of each of the buses is depicted in table 21 while the overall PQ performance of individual bus groups and entire distribution network as a whole, is evaluated by compound indexes computed and shown in table 22. Comparing table 12 with table 21 as well as table 13 with table 22 shows that the application of CPDs has resulted in overall PQ enhancement of each bus as well as an overall system since without CPDs $UPQI_{\text{overall}}$ is 1.2961 while with CPDs the value of the same amounts to 0.2526 which is much lesser than the standard threshold of unity and indicates the significant improvement in DN's characteristics under the presence of DGs. Therefore, the performance of the proposed PQ assessment approach gets validated also under the application of PQ enhancement devices.

In order to analyse the effect of increased renewable energy penetration on PQ performance of DN by the proposed approach, the rated generation capacity of each of the integrated PV based DG systems is increased by 50 kW whereas maintaining remaining part of the system of the case I completely unchanged. Afterwards snowballing the penetration levels of the DG units, the variation in PQ indices' data, measured at each bus, is shown in table 23. Equating the data of original test system i.e. case I showed in table 11 and that with the increased penetration depicted in table 23, it turns obvious that there exists a substantial increase in the magnitude of each of the power quality indices at each of the buses. Moreover, the overall UPQI of each bus is also increased considerably in comparison to the case I as shown by the blue and red bar in figure 12. It similarly points out the necessity for cutting-edge PQ enhancement techniques to empower the distribution system in hosting a high capacity for renewable energy. So the proposed PQ assessment approach visibly reflects also the influences of excessive penetration on the PQ of DN.

V. CONCLUSION

This work has presented an AHP inspired innovative methodology for PQ assessment of distorted distribution power networks with the amalgamation of distributed energy resources.

1). The methodology outcomes in a single unified power quality index that brings whole PQ performance of individual network buses as well as the entire DN to a collective threshold reference with unity base.

2). The only index is ample for conducting comparative assessment between PQ performance of several buses of DN concerned as well as multiple DG units distinguished by either RES categories or locations in the DN and also for benchmarking it with regard to a threshold level and therefore decreases the intricacy of large data management centered PQ monitoring of distribution power network with renewable DGs integration. Hence the proposed PQ assessment methodology can enable the system operators with many flexibilities suchlike the necessity of monitoring just a single index rather than multiple indices for individual buses as well as entire DN, curtailing the requirement of PQI technologies and streamlined way of comparing the PQ performance of multiple DGs as well as load buses.

3). Power quality performance of DN with the integration of PV, wind and fuel cell sourced DGs have been assessed and compared based on the proposed approach and it has been proved that how better fuel cell-based DG system performs in terms of PQ due to continuity of fuel supply unlike PV and wind-based DGs where active power production experience large variation due to change in environmental parameters such as irradiation/wind speed that results in PQ concerns suchlike voltage fluctuations and voltage distortion at DG as well as load buses.

4). The PQ performance enhancement of DN, by application of CPDs, has also been analysed by utilization of the proposed methodology based *UPQI*. Hence, the proposed methodology finds the scope also in establishing a substantial means of comparison among the performances of multiple PQ improvement techniques.

5). Additionally, the proposed approach evidently reflects also the influences of excessive penetration on quality of power in DN.

The achieved results, in each of the five well-thought-out scenarios, authenticate the importance of the proposed methodology in streamlining the PQ assessment of distorted DNs under the presence of renewable DGs.

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