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REVIEWS **Open Access**

Electric vehicle integration's impacts on power quality in distribution network and associated mitigation measures: a review

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Abstract

The problem of global warming, along with environmental concerns, has already led governments to replace fossil-fuel vehicles with low-emission electric vehicles (EVs). The energy crisis and environmental problems, such as global warming and air pollution, are essential reasons for the development of electric vehicles (EVs). Electric vehicles are one of the most fascinating and essential fields to emerge in recent years. According to the current report, electric vehicles are attempting to replace older, traditional automobiles. These vehicles not only help to reduce pollution but also to save natural resources. The presence of electric vehicles may cause several problems for the conventional electrical grid due to their grid-to-vehicle (G2V) and vehicle-to-grid (V2G) charging and discharging capabilities. With increased EV adoption, many power quality (PQ) issues in the electrical distribution system arise. With the penetration of EVs in distribution networks, power quality issues such as voltage imbalance, transformer failure, and harmonic distortion are expected to arise. The focus of this research is on exploring and reviewing the issues that the integration of EVs poses for electrical networks. The existing and future situations of electric vehicles' integration, as well as new research on the subjects, have been reviewed in this paper. This study provides a thorough examination of power quality issues and their mitigating approaches.

Keywords: Electric vehicles, Power quality, Harmonics power flow, Harmonics and voltage imbalance, Mitigation techniques

Introduction

Due to the emission of harmful gases and environmental pollutants, conventional vehicles are being replaced with plug-in hybrid electric vehicles (EVs). As a result, electric vehicle usage is increasing. Electric vehicle chargers and renewable energy sources such as solar are critical in reducing our reliance on fossil fuels, and they represent the normal progression of our energy structure [1]. Due to the nonlinear nature of the load, the temperature of the transformer and its associated loss rise during EV battery charging, reducing the transformer's lifetime. The non-linear nature of some loads during EV charging induces total harmonic distortion (THD) in the charging current, i.e., the THD of the current influences the power quality of the distribution network [2, 3]. Active power filters and FACTS devices such as shunt and series active power filters, dynamic voltage restorers, and unified power quality conditioners (UPQC), etc. are utilized to overcome these issues. Power quality concerns such as neutral currents, reactive power needs, and THD rise as AC/DC functions on high-frequency switches are changed. Several papers on electricity power quality [3–5] and the grid have already been published in the literature. Regarding the optimization objective, Fig. 1 shows the maximization and minimization objective functions of electric vehicle integration into an electric distribution system.

An EV battery charger is a device that charges electric vehicles. One or more power electronics circuits that are utilized with a proper converter transform AC electrical energy into DC to charge the batteries at a certain voltage. The battery charging mechanism of electric vehicles (EVs) is a critical power electronic component that introduces nonlinearity into the network, resulting in harmonic distortion of the electric grid side voltage or current [6]. The negative effects of this harmonic distortion include an increased insulation temperature voltage, a lower power factor, decreased insulation life, decreased efficiency, and increased heating losses, as shown in Table 1.

Unregulated EV connection and disconnection in the grid cause voltage imbalance. Due to the voltage imbalances in the electric grid, the cost of voltage correction devices may rise. Switching losses in the AC-DC converters of the electric vehicle charging station account for a portion of the power loss [15, 16]. When electric vehicles are integrated into the grid, the distribution transformer is the part of the system that is most susceptible to failure. An electric vehicle's harmonic level can vary from 3% at the beginning of charging to about 28% at the end [17, 18]. In addition to the charging action, there are various other functions for improved grid integration, especially in terms of electricity quality. The research on charging EVs and their influence on the power grid will assist stakeholders in implementing mitigation strategies and implementing the necessary technologies to reduce the negative impact on the power distribution system. This work illustrates numerous impacts on the power distribution system as a result of EV charging through various research reviews. This work illustrates various impacts on the power distribution system as a result of EV charging through various research reviews. This article investigates the causes of EV-related power quality issues in the distribution system and possible mitigation measures that distribution companies must use to

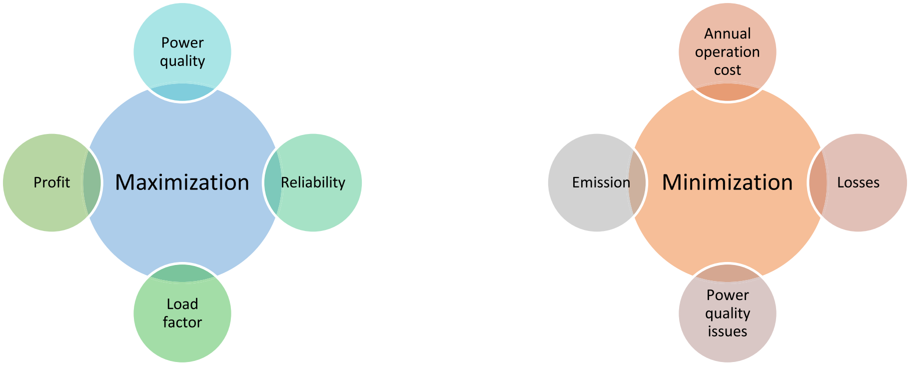

Fig. 1 Electric vehicles objective function

Table 1 Challenges of electric vehicle integration in power quality

Challenges	Description
Power losses	With a large number of unregulated and single-phase EV charging stations, power loss rises. High EV penetration causes distribution transformer losses and overloading [7–10]
Voltage Unbalance	Single phase electric vehicle charging large load increases voltage unbalance, due to incorrect distribution of all single-phase load by three phases of system [9]
Voltage Fluctuations	Impact increase as charging rate and penetration increases [11–13]
Harmonics	Impact increase as charging rate and penetration increases also increases with random EV charging [14, 15]

address these issues. These PQ challenges are reviewed as shown in Fig. 2, with a focus on distribution transformer protection.

Main text

"Literature review" section describes the overview of the charging impact of EVs on the distribution grid and EVs controlled and uncontrolled charging. "Issues in electric vehicle's integration on distribution grid and their mitigation measures" section describes the issues with electric vehicles' integration on the distribution grid and its mitigation measures. "Calculation of power quality parameters of supply system" section includes the calculation of power quality parameters. "Approaches to mitigate impact of EV on power quality" section describe an approach to mitigating EVs impact on power quality and also describe different types of facts devices. "Some others power quality issue" section describe an overview of some other types of power quality issues in EV integration with the grid. "Discussion" and "Conclusions" sections concludes the overall review of this paper.

Literature review

Charging impact of EVs on the distribution grid (voltage unbalances and fluctuation)

Due to uneven magnitudes and phase angles of voltages in a 3-phase power system (under- or over-voltages), a voltage unbalance problem occurs, and it can be caused by

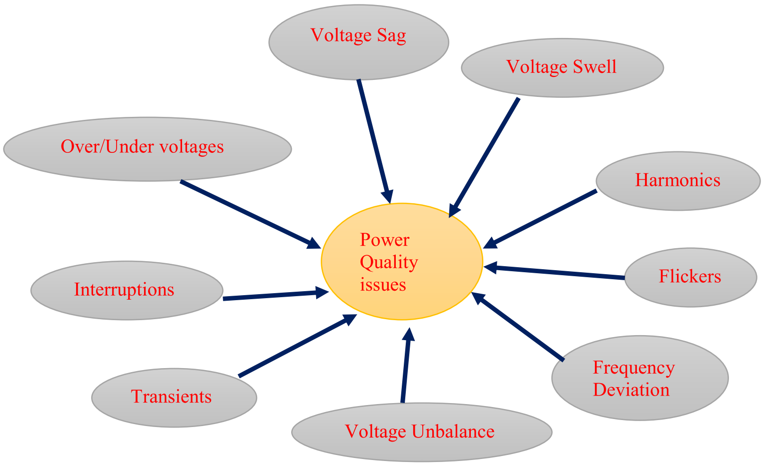

Fig. 2 Power quality issues

a variety of factors, i.e., a home distribution network in a city, and single-phase loads are imposed heavily, notably in remote areas. The impact of EV charging and discharging on the voltage imbalance in a residential low voltage (LV) distribution grid has been evaluated using the Monte Carlo modelling approach due to the uncertainties in EV charging rates and connection sites [19]. The findings showed that EVs have a negligible effect on the voltage balance at the feeder's beginning, but they can increase the feeder's end voltage imbalance factor. Because most domestic loads are connected to only one phase, voltage unbalance is always present in the network, even in the absence of low-carbon technology. Figure 3 shows the pattern of EVs charging on peak load or apparent power. It shows that the graph is acquiring a peak value between a time duration of 16 h and 20 h.

Single-phase photovoltaics (PVs), household battery storage, and EV charging stations can all contribute to system voltage imbalance. Power distribution systems with long power lines have negative sequence voltage components present, resulting in a significant order of unbalance in the system's line current [20]. Low negative sequence impedance causes 6–10 times the voltage unbalance in a power circuit [21]. As a result, phase currents that flow in excess can damage cable insulation and trip overload protection circuits, shortening the life of the cable, increased losses, additional heating effects, and vulnerability of the system to failures (because an unbalanced system may not be able to feed loads efficiently) are some of the repercussions [22]. As a result, identifying and determining the presence of voltage unbalance in a circuit is critical to deal with it quickly and ensure that the power system and linked loads run smoothly. Figures 4 and 5 show the comparison of charging levels for different levels of AC and DC charging with respect to voltage and current. Level 1 chargers are available in both slow and fast charging modes, depending on whether the power supply is ac or dc. Level 1 ac chargers are 120-V, single-phase ac with power ratings ranging from 1.4 to 1.9 kW. At 6 amps of current, charging the battery takes 10 to 36 h. Level 1 DC chargers with voltage ranges of approximately 200 V to 450 V and up to 36 kW for plug-in hybrid electric vehicles with 80-A current rating level 2 chargers work on both on-board and off-board chargers at different power levels. Level 2 ac chargers rectify 240-V single-phase ac supplies up to 4 kW to 19.2 kW

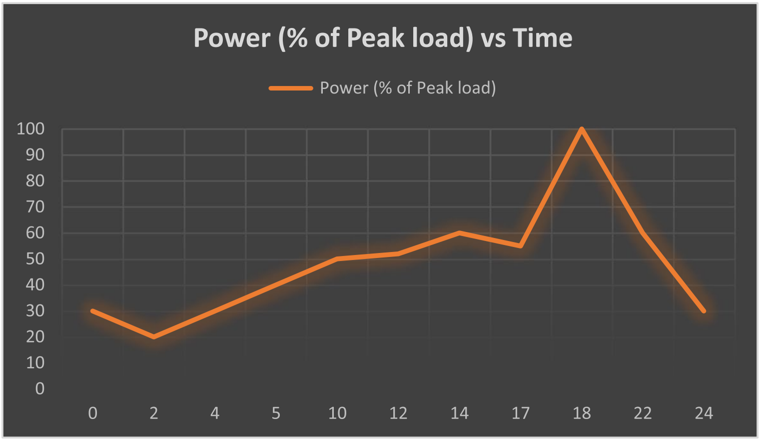

Fig. 3 Impact of EVs charging on voltage unbalance

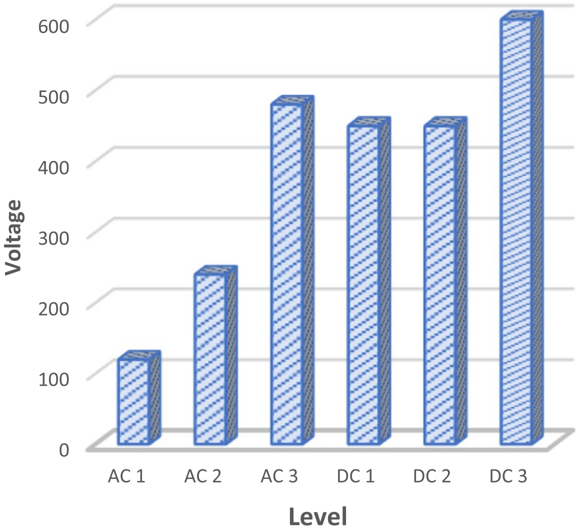

Fig. 4 Comparison of AC and DC level (voltage)

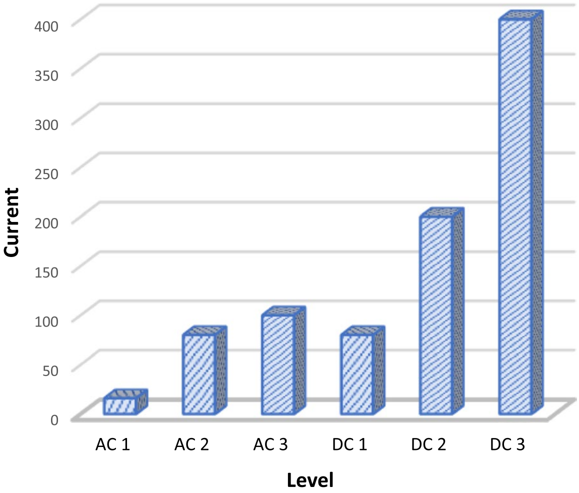

Fig. 5 Comparison of AC and DC level (current)

for plug-in hybrid electric vehicles at an 80-A current rating. Level 2 dc chargers have the same voltage level as level 1 dc chargers, but they contain 90 kW at a 200-A current rating for off-board charging [23–25].

Advancements in electric vehicle chargers require fast charging through the charger. With level 3 chargers, the battery can be charged in less than 30 min. As it reduces the charging time, it comes with level 3 charging or fast charging. Level 3 ac chargers have a power rating greater than 20 kW for single-phase and three-phase ac power at off-board charging. Level 3 DC chargers charge ultra-fast with 600-V DC up to 240 kW at 400 amperes of current [17, 18]. When a utility provides a symmetric load at high power levels, grid stability is improved. Renewable energy grid integration is standardized, ensuring optimum safety as well as maintenance procedures, consistent performance of operation, and capability of testing. As a result, interconnecting renewable sources ensures that cascade failure is avoided [19]. The harmonic current and its matching phase angle are given in Eqs. (1) and (2). The harmonics are introduced into the distributed system and, when charging, produce switching oscillations. Apart from regular EVSEs, focus must be given to renewable energy grid integration with appropriate standardization. Because the voltage imbalance's effect is determined by the power range of the device.

$$\mathrm{I}_{\text{Harmonics}} = \mathrm{I}_{\text{Fundamental}} * \frac{\mathrm{I}_{\text{Harmonics}} - \mathrm{I}_{\text{Spectrum}}}{\mathrm{I}_{\text{Harmonics}} - \text{Spectrum}} \tag{1}$$

$$\phi_{\text{Harmonics}} = \phi_{\text{Harmonics}-\text{Spectrum}} + \mathrm{h} * \left(\phi_{\text{Fundamental}} - \phi_{\text{Fundamental}-\text{spectrum}}\right) \tag{2}$$

Electric Vehicle controlled and uncontrolled charging nature

An increase in EV linked to the distribution system affects the voltage profile in the system. Single-phase on-board charging starts at 1.6 kW for families and rises to tens of kW for fast charging. Uncontrolled charging occurs when electric vehicles are allowed to charge and discharge at the same time. If the public is aware of the incentives and penalties that are assessed to the consumer during peak and off-peak hours, they can choose whether to charge their EVs immediately or to consider a good time to charge. The cost of charging power is determined by the ideal charging conditions and the EV driver's eagerness. For charging EVs, the tariff is higher in the afternoon and evening and lower at night and in the morning.

Figure 6 shows that around the same time as the peak for the existing demand occurs, the green peak showing the desire for EV charging also appears.

In Fig. 7, the peak demand from EV charging is compensated by the off-peak consumption from the current demand.

The average distance traveled by electric vehicle is between 25 and 30 miles. Based on the vehicle mileage analysis, following factors are defined: -

1. Utility factor
2. Electric range utility factor
3. State of charge (SOC)

1. Utility factor (UF): the percentage of daily vehicle miles that are less than or equal to the stated distance is known as UF [22–24]. This factor indicates how many miles driven on gasoline would be replaced by miles driven on electricity if all vehicles were converted to PHEVs. Plug-in hybrid electric vehicles (PHEVs) are characterized by their all-electric range (AER). A PHEV-k is one that can travel a certain distance entirely on electricity.

$$\mathrm{UF} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{D}_{\mathrm{ei}}}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{D}_{\mathrm{i}}} \tag{3}$$

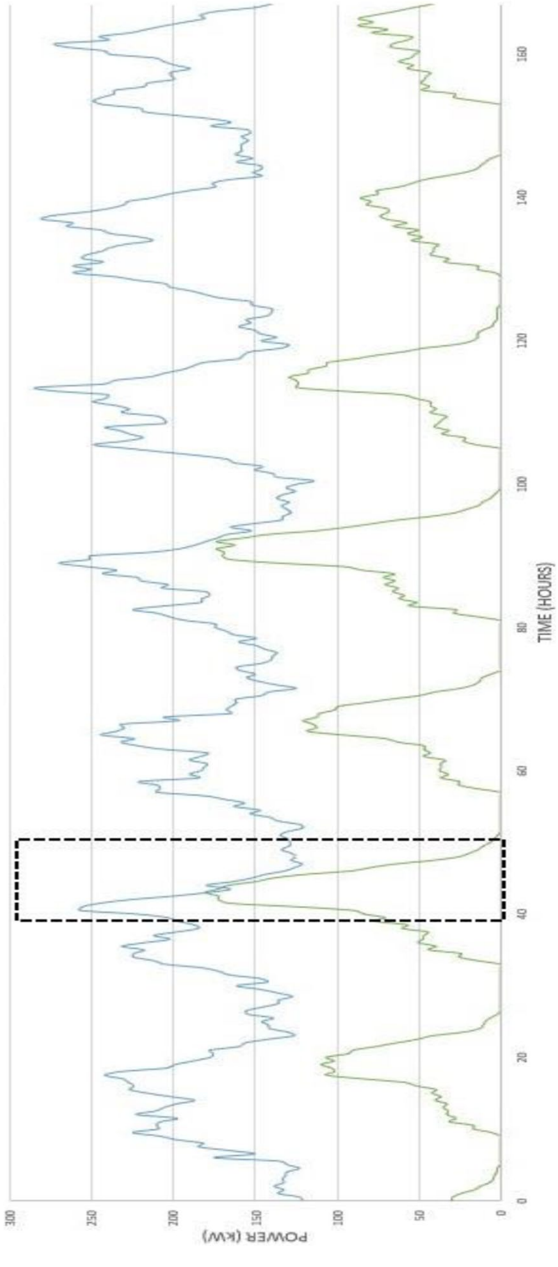

Fig. 6 Uncontrolled charging nature of EVs

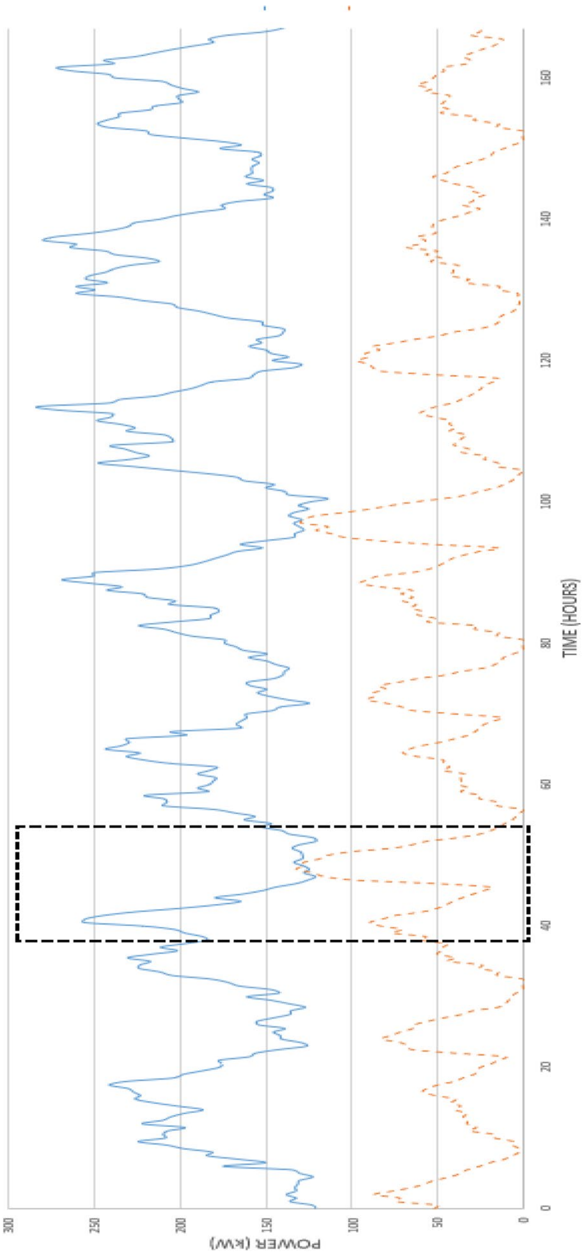

Fig. 7 Controlled charging nature of EVs

D_{ei} is the distance traveled by electric vehicle, D_i is the total distance traveled by vehicle i. N is the number of vehicles, Higher the AER more miles are driven using electricity. A UF of 1 therefore denotes that all miles traveled are powered by electrical energy.

2. Electric range utility factor: the ratio of actual miles driven on electricity to the total miles traveled on electricity is known as the electric range utility factor (ERUF) [25, 26].

$$\mathrm{ERUF} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{D_{ei}}}{\mathrm{N} * \mathrm{k}} \tag{4}$$

D_{ei} is the distance traveled by electric vehicle. N is the no. of vehicles. k is the AER of PHEVs.

3. State of charge (SOC): the amount of charge left in the vehicle when it arrives is known as the state of charge (SOC). Based on distance travelled and the PHEV's AER, one can calculate a vehicle's SOC. The proportion of the total charge used to represent SOC [27–29]. Figure 8 shows the nature of the state of charge for four with respect to electric vehicles, charging time is increasing because the voltage is increasing, and then it becomes constant. The current is also constant for a while, and then it gradually decreases to zero.

Assume PHEV-k is completely charged and has travelled x miles, the SOC of the vehicle is computed as follows:

$$SOC = \begin{cases} 100 * \left(\frac{k-d}{k}\right) & d \le k \\ 0, & d > k \end{cases} \tag{5}$$

Chargers for electric vehicles must be always accessible at all times during the 24-h periods. Therefore, charging infrastructure for EVs battery charging for public location, home and work place is essential [30]. Due to electric vehicle charging load, objective function for optimization of power system demand shows in Eqs. (9), (10), and (12).

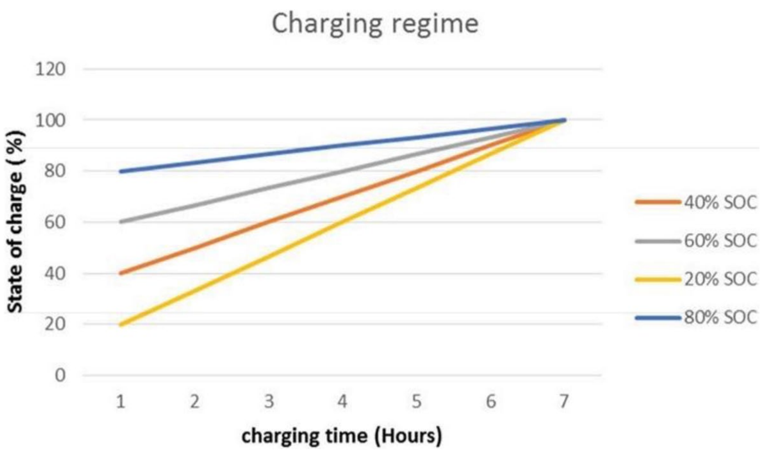

Fig. 8 Variable nature of charging rates for four EVs

$$\text{Max.EV for charging} = \sum_{t=1}^{24} \left\{ \text{EV}_{\text{HOME}}(t) + \text{EV}_{\text{WORKPLACE}}(t) + \text{EV}_{\text{ROAD SIDE}}(t) \right\} * \text{EV}_{\text{PENETRATION LEVEL}} \tag{6}$$

$$\text{Power req.for charging max.EV} = \text{Max.EV for charging} \times \text{Power required for charging Single EV} \tag{7}$$

During period of light load, we can ignore workplace power so Eq. (9) becomes:

$$\text{Max.EV for charging} = \sum_{t=1}^{24} \left\{ \text{EV}_{\text{HOME}}(t) + \text{EV}_{\text{ROAD SIDE}}(t) \right\} * \text{EV}_{\text{PENETRATION LEVEL}} \tag{8}$$

Issues in electric vehicle's integration on distribution grid and their mitigation measures

Voltage unbalance mitigation in electric distribution system with EVs

A phase reconfiguration strategy is another way to reduce the voltage imbalance factor. In [31], the financial implications of a phase reconfiguration to lessen the negative effects of the unbalanced EVs on an LV distribution system have been evaluated. The findings confirmed that a phased reconfiguration strategy could reduce the imbalance impact of EVs by utilising the time-of-use tariff. Additionally, managing EV charging and discharging can lessen the phase unbalance issue [32]. A system's voltage can be balanced by making the best choice possible for connecting points (phases a, b, or c), charging and discharging power rates, and charging and discharging status. A control mechanism is being developed to coordinate all electric vehicles' smart charging and increase the load profile of the electric vehicle linked to the electrical grid network [33]. The communication system that enables this coordination of charging between the electric vehicles and the aggregator collects and transmits data. In order to standardize the voltage profile, the load profile is smoothed. Voltage regulators can be used to reduce a network's imbalance index. The PQ for voltage imbalances and variations is improved using energy storage devices, feeder capacitors, and D-STATCOM [34]. Though some EVs would occasionally achieve higher peak voltages. The decentralized controller, unlike the central controller, charges the electric vehicles locally [35]. The use of less communication infrastructure reduces the cost of this dispersed control.

The neutral current that flows as a result of the phase voltage imbalance is not considered by the electric vehicle current charger. Because the input from distributed energy resources is likewise dynamic, the distributed energy resources require coordination in addition to the electric vehicle. While the distributed energy resources and electric vehicles are linked to the distributed network, neutral current and voltage unbalance must all be regulated [36, 37]. The benefits and drawbacks of both the centralized and decentralized EV charging coordination models are examined. For smart charging in the electrical distribution system, active power balancing can be achieved using the droop controller topology. Although the reactive power delivered into the dispersed network by power electronics equipment such as rectification and switching converters adds to the burden on the distribution network, a droop controller-based controller is described in [38] for a balanced system, and reactive power correction is achievable using the auxiliary equipment specified in [39]. To reduce the voltage unbalance, zero and negative sequence voltages are generated.

Harmonics impact and its mitigation technique in distribution grid

Harmonics are the sinusoidal component of a periodic waveform whose frequency is a multiple of the fundamental power frequency's integer [40]. Harmonic power-waveform distortion occurs when there is a mixing of the first, second, third, and other harmonics. Non-sinusoidal voltage and current waveforms are given in Eqs. (12) and (13).

$$V(t) = v_{DC} + \sum\nolimits_{H=1}^{H_{max}} v_{rms}^{H}(cosHw_0t + \phi_h) \tag{9}$$

$$I(t) = i_{DC} + \sum_{H=1}^{H_{max}} i_{rms}^{H}(cosHw_0t + \phi_h) \tag{10}$$

Where, H is the harmonic order, w_0 is the fundamental frequency, ϕ_h is the phase shift of voltage and current for harmonics.

The total harmonic distortion (THD) components, which calculate the effective value of the harmonic contents of a distorted waveform, can be used to quantify the harmonic components of distorted waveforms [41]. THD can be stated as a percentage for voltage and current.

$$THD_V = \frac{\sqrt{\sum\nolimits_{H=2}^{H_{max}} {v_H}^2}}{v_1} \tag{11}$$

$$THD_I = \frac{\sqrt{\sum\nolimits_{H=2}^{H_{max}} {i_H}^2}}{i_1} \tag{12}$$

Harmonics are injected by nonlinear devices, i.e., EV chargers, as shown in Fig. 9. Because of the inverter's semiconductor switches, PV systems are harmonic sources. The inverter technology, solar radiation, temperature, and network parameters all affect total harmonic distortion [42, 43]. The low penetration of EVs and the slow charging rate have little effect on the network's PQ harmonic distortion. Fast charging rates and the increasing penetration of EVs, however, could cause significant voltage and current harmonic distortion. Furthermore, the author discovered that the charging of arbitrary EVs may deviate from the normal level of the voltage harmonic.

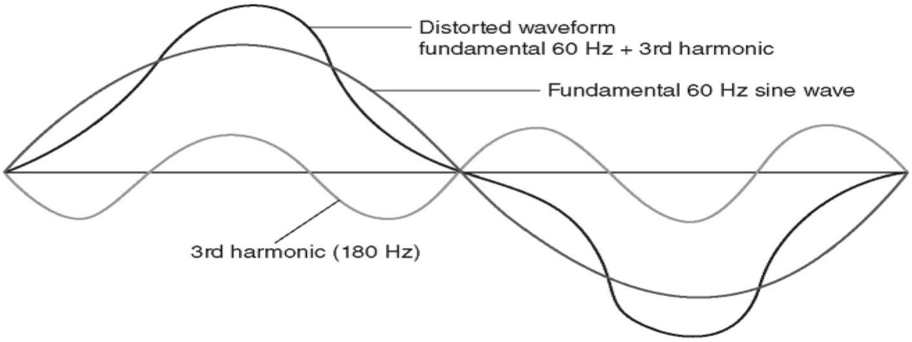

Fig. 9 Harmonic distortion where the waveform composed of 3rd and fundamental

Power filter design and control are often part of the grid-tied converters' harmonic mitigation methods. Modulation techniques (SPWM, SVPWM, DPWM, SHE, interleaving, and power filter design (L-, LCL-filter, etc.) are typically used to reduce switching frequency noise [44]. Current harmonic amplification most likely results from the employment of a shunt active power filter. Through the absorption or injection of harmonic currents into or out of the network, other research studies like [45] have deemed EVs to be harmonic compensators. EVs can also engage in the marketplace for ancillary services related to harmonic and reactive power.

On an electrical distribution system, the combined impacts of photovoltaics and electric vehicles on voltage profiles and harmonic distortions were investigated [46]. The findings indicated that while photovoltaic and electric vehicles increase the total harmonic distortion of voltage, they are still able to reduce voltage fluctuation [47].

The influence of current and voltage harmonics produced by photovoltaic systems has been addressed using a variety of strategies. The two most common ways to eliminate harmonics in a system are passive and active filters. However, more compensators are needed for the power system [48]. Utilizing inverter control mechanisms is another strategy for harmonic compensation.

Several techniques, including modelling approaches, system conditions, and solution approaches, can be used to solve the harmonic power flow problem. The two types of solution approaches are coupled and decoupled. Nonlinear systems with strong couplings between harmonics can be accurately solved using a coupled solution approach. Convergence issues may occur in big power systems with numerous nonlinear loads, despite the fact that Newton-based harmonic power flow offers an accurate solution because it incorporates harmonic couplings at all frequencies.

A more uniform load demand profile can result from implementing an off-peak charging plan. In order to deal with the effects of electric vehicle charging on secondary service voltages and transformers, an infrastructure improvement strategy is suggested in [49]. Infrastructure improvements are required for this approach. With this method, the service transformer's kVA rating is increased, and the secondary circuit is rearranged using a second service transformer.

Impacts of transformer in EV charging and its mitigation methods

EV power demand, Plug-in and plug-out time, however, they did not assess the future electric vehicle demand and the possible mitigation by EV demand flexibility or quantify the peak load of the transformer. The future of electric vehicles would greatly benefit from the adoption of solid-state transformers [50]. Its ability to interface with an AC or DC grid system and simplicity of dynamic control are the reasons behind this. As a result, these characteristics would make it simple to integrate DERs like electric vehicles (EVs), high-penetration solar panels (PVs), energy storage, etc. The SSTs have the capacity to enhance communication, protection, and power quality. The medium- and low-voltage transformers on which the charging load is expected are selected based on the parking areas. Since the economics of such a big change are frequently impractical, upgrading the transformer in response to demand is not a good strategy.

By using demand-side control, EV charging can be delayed. EVs with fully charged batteries shouldn't needlessly be charged. To obtain a transformer overloading mitigation effect, those EVs must be encouraged. It is clear that transformer degradation is a result of the system's increased EV penetration.

Current harmonics produced by electric vehicles can result in increased transformer load loss, a rise in temperature, and decreased transformer lifetime [51, 52]. Transformer losses are classified as either no load loss or load loss.

Transformer load loss consists of copper loss, eddy current losses, and stray losses caused by stray electromagnetic flux in the windings.

$$P_{\text{LOAD LOSS}} = P_{\text{COPPER LOSS}} + P_{\text{EDDY-CURRENT LOSS}} + P_{\text{STRAY LOSS}} \tag{13}$$

$$P_{\text{TOATL LOSS}} = P_{\text{LOAD LOSS}} + P_{\text{NO LOAD LOSS}} \tag{14}$$

Figure 10 depicts the variation of transformer hourly load demand with respect to time, i.e., the duration of 24 h.

A rule-based system that regulates the charging time in accordance with the client's preferences, including whether to charge electric vehicles during peak demand or not, reduces loss in the transformer in the electrical distribution network [53, 54]. An optimization technique with the goal of reducing voltage and heat stress on the transformer is described as an objective function in [54]. The algorithm evaluation is based only on the EV batteries' state of charge (SOC), not the preferences of the client. The algorithm is to be evaluated based on the state of charge (SOC) of the electric vehicle's batteries, not the customer's preferences [54]. Even though the objective function only considers thermal stress and voltage, the optimization objective also takes failure hazard into account. The distribution transformer's ageing factor [55, 56] is as follows:

$$\text{Aging acceleration factor} = \exp\left(\frac{15000}{383} - \frac{15000}{\alpha_H + 273}\right) \tag{15}$$

$$\text{Insulation}_{\text{life}}\text{of Transformer} = 9.8 \times 10^{-18} \exp\left(\frac{15000}{\alpha_H + 273}\right) \tag{16}$$

Distribution transformer loss of life (DTLL) given in Eq. (20)

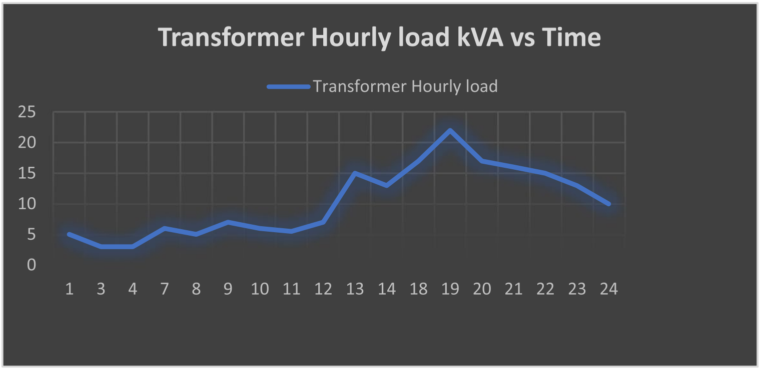

Fig. 10 Transformer hourly load vs hours graph

$$\mathrm{DTLL} = \frac{\text{Aging acceleration factor} \times \text{time}}{\text{insulation\_life}_{\text{normal}}} \tag{17}$$

PEV penetration levels as low as 10% may cause distribution transformer overloading [57]. Two residential distribution circuits, and predicts that with significant (60%) PEV deployment, distribution infrastructure costs might rise by 19% and energy losses could rise by 40% [57, 58]. Using the performance indicator, the advanced controller serves as the decision-making mechanism for resolving distribution transformer failure. Decision-making considerations include the battery's SoC, the SoC needed for the subsequent trip, the amount of time left before departure, and the needs of the EV owner [59].

Power quality issue due to power electronics devices and its mitigation measure in grid

EV chargers convert alternating current to direct current, allowing EV batteries to be charged. Harmonics are introduced into the grid during this power conversion process by high-frequency switching converters used in power electronics, which lower the power quality of line current in the grid as shown in Fig. 11. Such harmonic injection shortens the lifespan of distribution transformers by overloading them electrically and thermally. Other issues include overusing the grid's current capacity, an imbalance between supply and demand in the utility grid, grid voltage, etc. [60, 61].

Both the grid structure and the location of the PV capacity inside the grid have an impact on voltage fluctuation. Inconvenient or seeming light flickers may increase in frequency over time due to the rise in EV usage. The voltage profile is improved during fluctuation transients by the algorithmic method described here [62]. Half of the input DC link voltage is used to reduce the switch voltage stress. The connection of large residential loads, the integration of sizable loads like EVs themselves, heat pumps, or unforeseen circumstances like distant problems are a few of the main factors that could result in voltage reductions. Usually, the transformers in low-voltage distribution grids only have offload tap-changers, which allow a voltage drop on the high-voltage side to spread to the low-voltage part.

Flexible ac transmission systems (FACTSs) and voltage-source converters with intelligent dynamic controllers are becoming more common in order to improve power quality. Additionally, distributed FACTS have a significant impact on power quality, energy efficiency, and power factor [63, 64].

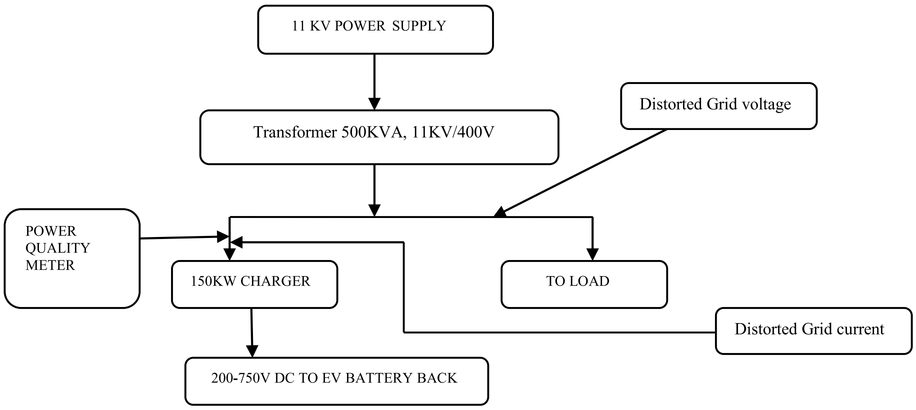

Fig. 11 Electrical vehicle fast charging station 150 KW

A two-stage battery charger is used, with the first stage, the AC-DC stage, being controlled by sinusoidal pulse width modulation and the second stage, the DC-DC stage, being controlled by a predictive duty cycle. Utilizing predictive control, which eliminates the DC bias from the transformer current by managing its peak value, it is possible to quickly control a battery current. At the source of DC-DC converters, power factor correction (PFC) adjustment is possible [65, 66]. The charge efficiency is increased by a proposed bridgeless CUK converter that functions as a PFC-based converter. Total harmonic distortion is decreased in accordance with the regulations, and an improvement in power quality is confirmed by the power quality index. The approach exhibits satisfactory charging efficiency. In the electric vehicle-linked dispersed system, the PFC uses an interleaved converter [67]. Together with the output voltage harmonics, the input current harmonics are also decreased.

The load profile, voltage variation, harmonics, power losses, voltage, frequency, and number of EVs charging meet the criteria for oscillatory stability. These effects could be controlled by the application of a feeder capacitor bank, tap transformer replacement, energy D-STATCOM, a filter for the charging station, coordination, and storage, using a distributed generator, charging, and time-of-use (ToU) tax, and so forth [68, 69].

The oscillatory stability of the grid is anticipated to be impacted by the widespread integration of EVs into the power grid. However, because the characteristics of EV loads differ greatly from those of traditional constant impedance, current, and power (ZIP) loads, it is crucial to model EV loads in detail in order to examine their effects on the oscillatory stability of the grid. An EV charging system load model that combines a constant power component and a voltage-dependent negative exponential component has been established, and it includes an AC-DC converter, a DC-DC converter, a filter, and associated control devices.

Calculation of power quality parameters of supply system

Voltage unbalance calculation

Voltage unbalance occurs when the three phase voltages are mismatched in magnitude and/or do not differ in phase angle by 120°, according to IEEE Standards (1995). In a three-phase network, voltage unbalance can be seen as a relationship between negative and positive sequence voltages. The voltage imbalance percent is computed as [20, 21]:

$$\text{Voltage unbalance (\%)} = \frac{\mathrm{v}_2}{\mathrm{v}_1} * 100 \tag{18}$$

$$= \sqrt{\frac{1-\sqrt{3-6\Upsilon}}{1+\sqrt{3-6\Upsilon}}} \tag{19}$$

$$\Upsilon = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{\left(V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right)^2} \tag{20}$$

Where, v_2 is the negative sequence voltage and v_1 is the positive sequence voltage, respectively.

Based on (PEA, 2009), the acceptable voltage unbalance is limited to 2%.

Voltage deviation calculation

A bus voltage magnitude may differ from the rated value. Small percentages of these variations are frequently accepted, but if they exceed specified thresholds, they are regarded as disturbances.

$$\Delta V_d = \frac{RP_1 + XQ_1}{V_1} = V_1 - V_2 \tag{21}$$

The voltage deviation of a line is represented by Eq. (6). It shows that voltage deviation is highly dependent on the reactive power of inductive lines [70, 71]. Because of the lower reactance and resistance ratios, voltage deviation of distribution lines is affected by both active and reactive power. The IEEE 1547–2003 standard recommends that voltage deviation should not be greater than around the base value.

Distribution network parameters

The three most important operating criteria for the distribution network are voltage stability, power losses, and reliability. In this part, the methodology for calculating the distribution network's voltage stability, power losses, and reliability is explained in more detail.

Voltage stability

Voltage stability is the capacity of the power system to maintain consistent, acceptable voltages for all buses when external disturbances occur [72, 73]. When voltage instability occurrences occur, the network's bus voltage gradually drops. Sudden disturbances, fault circumstances, and line overloading can cause the system to become unstable. The voltage of all system buses must be within acceptable limits, which is a voltage stability requirement utilized in many stability studies.

Based on the estimation of the voltage stability factor (VSF) from the PV curve, the voltage stability is examined. Active power and voltage are graphically represented by the PV curve in Fig. 12. It shows changing voltage with rising active power; finding

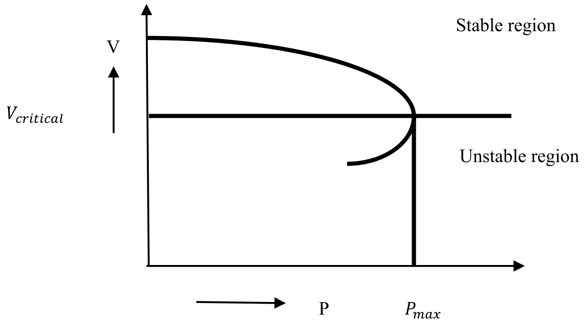

Fig. 12 PV Curve

the voltage of each bus in the distribution network is the first step in designing the PV curve. The Newton–Raphson method and other common load flow analysis techniques have major drawbacks when used to determine the voltage of radial distribution networks due to their large R/X ratios. Compared to transmission systems, the R/X ratio is highly prominent in distribution systems. When analyzing the voltage stability of distribution networks, all buses' voltages must fall within an acceptable range (6% of their nominal value).

Mathematically it is expressed as:

$$\mathrm{VSF} = \frac{|dv|}{|dP|} \forall \mathrm{P} < \mathrm{Pmax} \tag{22}$$

Power losses

Distribution network power losses are $i^2 r$ losses of the line. The mathematical expression for calculating the line losses for the two-bus system shown in Fig. 13 is as provided in Eq. 23.

$$P_k = i^2 r \tag{23}$$

and total power losses are represented in Eq. 24

$$P_t = \sum\nolimits_{k=1}^{n} P_k \tag{24}$$

Reliability

Power system reliability analysis has become a challenging area of study. The reliability of generation, transmission, and distribution are all key considerations in power system reliability analysis. Data on the failure rate, repair rate, average outage time, and outages are statistically significant for evaluating the distribution network's reliability indices [74]. The reliability indices of the distribution network are broadly divided into customer- and energy-oriented, as shown in Fig. 5. The three main subcategories of customer-oriented reliability indices are the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI). The energy-oriented reliability indices are further divided into energy not served (ENS) and average energy not served (AENS). The correlation between SAIFI and SAIDI depends on how frequently and for how long interruptions occur. Customer dissatisfaction due to

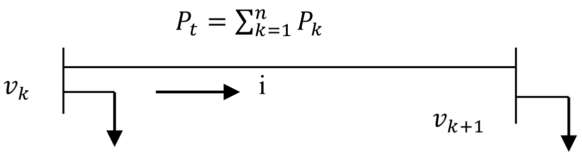

Fig. 13 Two-bus system single line diagram

interruption is quantified by CAIDI. AENS is the average load curtailment index as a result of service interruptions.

Approaches to mitigate impact of EV on power quality

The current electric vehicle charging station faces several challenges that must be overcome to provide reliable, high-quality electricity as shown in Table 2, and positive impacts and control features of different type of facts devices in power quality and electric vehicles system as shown in Table 3. Flowchart for power quality issues mitigation and bidirectional converter controlling was created as shown in Fig. 14.

With a three-phase, three-level rectifier/inverter, the three-phase grid voltage is rectified to a DC voltage (see Fig. 14). The EV-side controller, the grid-side interface controller, and the centralized charging controller level make up the charging station control system. Phase currents and utility voltages are converted from a-b-c coordinates to a d-q frame using the Park transformation, which is then produced by the PLL. A reactive power controller creates the q-axis current reference in the reactive power support mode. However, the PCC voltage controller produces the q-axis current reference signal and voltage support for the AC system. EV is charged and discharged at the EV-side controller using a DC/DC power converter to handle the charge and discharge of the EV batteries. The three-level AC/DC inverter/converter is regulated at the grid-side controller by maintaining a constant DC-bus voltage and managing the reactive power sent to or received from the grid by the three-phase three-level (TPTL) rectifier. The primary connection between the grid and the EVs is the bidirectional AC-DC power converter.

Table 2 Approaches to mitigate impact of EV on power quality

Impacts	Mitigation techniques	Description
Impact on power losses	Coordinating EV charging/discharging and with distributed generators	Optimal coordinated operation and scheduling of EV charging in low voltage distribution line and to minimize power loss, EV charging demand can be synchronized with distributed and RE sources [75–77]
Impact on voltage unbalance	Phase reconfiguration technique, voltage regulators, Management of EV charging and discharging	Optimization of EV and phase reconfiguration technique to mitigate voltage unbalance. Flywheels, super capacitors, battery storage systems (BES), capacitive energy storage system (CES) and super conducting magnetic storage system (SMES), DVR, DSTATCOM can be used to reduce voltage unbalance [78, 79]
Impact on voltage fluctuations	Charging management, voltage regulators, active and reactive power control strategy	Transformer tap changes, capacitor bank can be used to reduce voltage fluctuations. Coordinating EV charging used in a control manner to regulate network voltage to reduce voltage fluctuations [78, 80, 81]
Impact on harmonics	Filters, absorb or inject harmonic current	Shunt filter, series filter, resonance filter and hybrid filter, and harmonic analyzer can be used to mitigate harmonics distortion in distribution network. EVs can take part in harmonics and reactive power ancillary services [82, 83]

Table 3 Fact devices and their impacts on power quality and electric vehicle charging system

S. no	Filter and fact devices	Features	Drawbacks	Positive impacts and control features in power quality and electric vehicles system
1	Hybrid LC filters [84–86]	Efficient, low ripple factor, reliable, high gain, bleeder resistance improves voltage regulation and filtering action	Require tuning of LC circuit, limited standard sizes, L filter is bulky, Low output DC voltage	Reduction in DC ripple, AC side harmonics, reduced filter VA rating, prevent injection of low order current harmonics into ac mains, reduce electromagnetic interference problem in EV system
2	Dynamic voltage restorer (DVR) [87–89]	Small in size, more energy capacity compared to UPS, less cost, higher capacity, less maintenance, voltage balancing capability	Difficult to protect the devices during short circuit due to connected in series, no battery	Very fast response, Precise voltage regulation, Improve and correct short voltage reductions, controlled real and reactive power at load side, compensate power quality issues, i.e., voltage sag and swell when integrated with energy storage devices in EV charging system, absorb harmonic current, controlled charging
3	Multilevel Inverter [90–92]	Less no of components, power easily scaled, better electromagnetic compatibility, lower switching loss, boost voltage, reduce voltage stress, THD is low, simple control of active and reactive power	Capacitor and clamp diode is in large number, i.e., system bulky, efficiency poor, high cost, capacitors voltage unbalance	Staircase waveform quality, reduced harmonic distortion, reduce electromagnetic interference problem in EV system, less voltage distortion, operate in bidirectional way in EV system, Increase reliability
4	Interline power flow controller (IPFC) [93–95]	Extension of UPFC, combination of series controller and unified controller, control power flow of multiple lines, switches off capacitor bank, current, voltage when excess, control and optimize of transmission line	More no of series converter makes system bulky, less control of capacitor voltage,	Increase stability of grid using Internet of things, improved voltage profile, reduced power loss, enhances dynamic response when combine with superconducting magnetic energy storage (SMES), robustness, reactive power control, damp oscillation
5	STATCOM without storage [96–98]	Component smaller than SVC, faster response time, dynamic voltage control, better characteristics, robust and simple, flexible algorithm	More losses, high cost, no harmonic suppression	Controlling voltage, VAR compensation, damp oscillation, dynamic stability, minimize total real power loss, power factor correction
6	STATCOM with storage [98]	Wide operating range, lower rating than SVC, dynamic voltage control, better characteristics, robust and simple, flexible algorithm, component smaller than SVC, faster response time	More loss, high cost, large DC source required to charge the capacitor, no harmonic suppression	Interface with real power sources, like battery, fuel cell or SMES, controlling voltage, VAR compensation, damp oscillation, automatic gain controller, provide smooth integration of renewable energy, minimize total real power loss and power factor correction in EV system
7	Static VAR compensator (SVC) [99–102]	Improve transient, Smoother control, faster response due to no inertia, improve system capability	Slower than STATCOM, Not interface with energy storage sources, expensive, limited overload capability	Control reactive power, overvoltage and dynamic performance of grid, reduce fluctuation on grid voltage, stabilize system, minimize energy loss, improve voltage deviation
8	Static VAR Generators (SVG) [103, 104]	High reliability, low maintenance, improve transient stability, faster response, static operation	Large DC source required to charge the capacitor, no harmonic suppression	Control damping oscillation, Interface with real power sources, like battery, fuel cell or SMES, controlling voltage, VAR Compensation

Table 3 (continued)

S. no	Filter and fact devices	Features	Drawbacks	Positive impacts and control features in power quality and electric vehicles system
9	Unified power flow controller (UPFC) [105-107]	Combination of STATCOM and static series compensator, high level of voltage and current achieve, redundancy is possible, bidirectional flow capability, real time control, flexible, capacity expansion possible	System cost high, control complexity when DC linked separated, interruption in voltage not possible, required large number of diodes, inverter and capacitor which makes system bulky, conduction and switching loss high	Control voltage, current, phase and power flow, Control active and reactive power, VAR compensation, damping oscillation, transient and dynamic stability, better voltage regulation than SSSC, minimization of losses, voltage stability, improves dynamic stability of system
10	Distributed Power flow controller (DPFC) [108, 109]	Provide reactive power compensation, power flow control, System impedance control	Phase shift error increase due to linearization	Transient and dynamic stability improvements, better voltage regulation, improves power transfer capability, Power compensation and low frequency power oscillation, Enhances system load ability
11	Static synchronous series compensator (SSSC) [110, 111]	Connected in series with transmission line through transformer, eliminate bulky passive component capacitors and inductor, injected voltage managed independently, satisfactory work with high load and low load, increase or decrease transferable power	Expensive, costly, mal operation of relay if degree of compensation and location is not proper	Power factor correction, load balance, reduce harmonic distortion, Series voltage sag compensation, regulate power flow, limit short circuit current, mitigate sub synchronous resonance oscillation in grid
12	Thyristor controlled Series compensator (TCSC) [112, 113]	Improve system stability, provide nonlinear switching behavior of thyristors, decrease dc offset voltage, improve voltage profile	High level of harmonics due to non-symmetrical harmonics, heating, and additional power losses issue	Control active power flow, suppress oscillation, decrease Dc offset voltages, control power flow, improve the transient stability, limit fault current, mitigate sub synchronous resonance
13	Thyristor controlled series reactor (TCSR) [114, 115]	Compensate, regulate and damp oscillation power system, decrease dc offset	Heating issue, power loss, switching and conduction loss, costly	Control current, improve transient and dynamic stability,
14	Series active power filter [116, 117]	Connected in series with grid system, easier to tune, smaller in size, harmonic isolation and harmonic damping, reduce power loss, reliable operation, less dependency on inductors	Large DC power supply require, oscillation, expensive, not handle large amount of power, handle low and moderate frequency	Reactive power compensation, control voltage, mitigate current unbalance, Sag, swell, reduce current harmonics, mitigate harmonic distortion in distribution network, reduce dc ripple, ac side harmonics, and filter VA ratings
15	Shunt Active power filters [118, 119]	Connected in parallel with grid system, compensate unbalance current and fluctuating current, easy installation, easy to connect parallel line, low implementation cost	Not applicable for high order harmonic, large DC power supply require, large capacitor makes system bulky and expensive, smaller inductor increase ripples	Reactive power compensation, mitigation of current unbalance, reduce harmonic propagation, and interharmonic, improve system performance, i.e., reduce current and voltage distortion in distributed grid
16	Virtual Coordinate System [120]	Combine effect of phase locked frequency multiplier and instantaneous reactive power theory improve charging quality of electric vehicle, reliable operation, response increase	Typical have fast locked problem in PLL multiplier, overshoot and instability, power dissipation in PLL, not accurate under high bandwidth condition, Sensitive to harmonics	Reduced impact of volatile energy, reduced distortion and fluctuation of charging current, improve charging quality of electric vehicle, reduce fluctuation of output voltage, reduce distortion of access current, enhances life of battery and charging components of electric vehicle charger

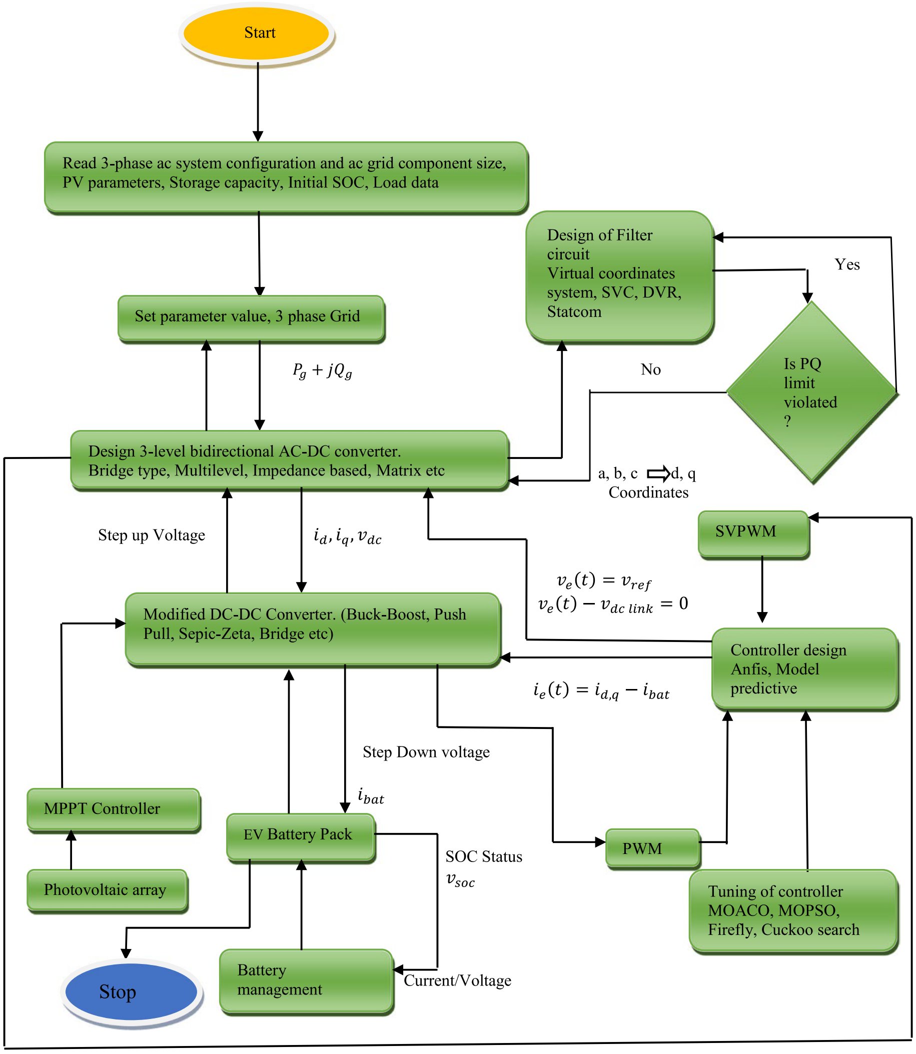

Fig. 14 Proposed flowchart for Power quality issues mitigation and bidirectional converter controlling

This converter functions as a rectifier in the EV charge mode, changing the utility's AC voltage into the DC bus voltage. When operating in V2G mode, it performs the function of an inverter, converting DC voltage to AC voltage and redistributing electricity to the grid. The EV battery will be charged and discharged using the suggested bi-directional PWM DC/DC converter. Because of the short duty cycle and the lower output power, the current ripple in the inductor will grow in this scenario. Likewise, the converter efficiency will be poorer. It is clear that the TPTL converter performs more effectively in boost and buck operation modes. But after comparing every aspect of these two converters, it becomes clear that the three-level DC/DC converter performs better in almost all areas.

Due to the voltage imbalances in the electric grid and other power quality issues, the cost of voltage correction devices may rise. Switching losses in the AC-DC converters of the electric vehicle charging station account for a portion of the power loss [75–83].

Due to the non-linear nature of EV chargers and distribution networks, an effective controller must be used in place of a standard control technique. Using the current references Id and Iq, the regulator determines the necessary reference voltages for the inverter (reactive current). In the case of G2V mode, the Iq reference is set to zero, while in the case of V2G mode, it has a predetermined value. The current regulator's necessary active current Id reference is established.

To increase the lifespan of the EV battery and keep the battery operating at a higher performance level, a corresponding battery management strategy of charging or discharging should be pursued and created. The procedures of CC and CV charging are combined during the process of charging a battery [27–29]. CC charging is typically used to charge an EV battery until it reaches the charge voltage level. Then CV charging is used, enabling the charge current to taper until it is very low.

Some others power quality issue

Phantom loading effect in power quality

After the initial data gathering phase, it was discovered that some of the charging stations were using energy even when there were no EVs attached to those stations, which was an oddity. There turned out to be two types of this "phantom" loading [77, 78]. The digital circuitry, LCD panels, and indicator lights present in most of charging stations are responsible for a modest degree of phantom loading. Whether an EV is charging at the station or not, these ancillary circuits always use a small amount of power. Level 3 DC rapid chargers with a battery bank are the second type of phantom loading. The battery bank, which is separate from the charger at the site, allows the charger to direct power from both the utility and the battery bank, reducing current surges on the utility feeder.

Load imbalance and DC charger

Systems are often created with the loads distributed evenly among the three phases. By balancing the loads, the terminal voltages produced on each of the three branches and the current in each are about equal. The system was found to be loaded substantially heavier for one phase or the other depending on which units were in operation at any given time at electric avenue due to the vast number of level I and II charging stations, which are single-phase equipment [79]. Currents might flow through the neutral line as a result of unbalanced loading. In severe situations, these neutral currents can result in excessive heating since neutral lines frequently have smaller diameters than hot lines. A voltage imbalance brought on by a load imbalance might cause issues for three-phase loads reliant on equal phase voltages. The size of the negative sequence component divided by the magnitude of the positive sequence component, stated as a percentage, is the ratio that characterizes an unbalanced three-phase system (IEEE Std. 1159–1995). It was discovered that the system's voltage imbalance never went above 1% at any given time. This is far less than the IEEE's suggested maximum of 3% [80].

DC offset in power quality

Due to a rise in transformer saturation and the resulting heating, additional stress on the insulation, and other negative effects, DC in AC networks can be harmful (IEEE Std 1159–1995). Many of the charging events occurred at varied times during the cycle, and in all three cases, the DC offset was comparable [81].

Discussion

In this paper, we analyzed the power quality issue and its mitigation approach. From the simulation graph of Fig. 3, which shows the graph of EV charging on peak load with respect to time. The load curve is studied throughout the entire week and it is suggested that EV charging can be accomplished when the load is around 50% of the peak load demand during the hours of midnight to 3:00 a.m. At different times during the day, the voltage drop on the grid exceeds the permitted limit of 0.93 pu, which leads to a voltage imbalance between the system's three phases. It could be analyzed from the result amount of voltage drop mostly occurs during peak load. A comparison of all the levels of AC and DC charging shown in Figs. 3 and 4 with respect to voltages and current.

A simulation graph of Figs. 6 and 7, which show a typical daily demand profile with base and intermediate loads supplying enough generation to meet most of the demand. This graph shows that with these peak alignments, once the two demands are added up, the present peal would be amplified. This gives information on how well the controlled charge scenario levels the demand profile, which is important if the network operator depends on grid imports to meet demand. The uncontrolled weekly total electrical demand is shown in the graph with 100% EV adoption.

Issues in electric vehicle's integration on the distribution grid, such as voltage unbalance issues, harmonic impact issues, transformer impact, and issues related to power electronic devices are analyzed in this paper. Voltage imbalances and variations are improved using energy storage devices, feeder capacitors, and D-STATCOM. Phase reconfiguration strategy and droop controller-based controller etc., improved the voltage unbalance problem on the distribution grid. Variation of transformer hourly load demand with respect to time as shown in Fig. 10. In order to enhance power quality, flexible ac transmission systems (FACTSs) and voltage-source converters with sophisticated dynamic controllers are becoming more widespread. Furthermore, distributed FACTS significantly affect power factor, energy efficiency, and quality of power.

An increase in industrial and commercial consumption, the Morning Peak, which occurs between 8 and 9am, follows the Night Lean at 4am to 5am. Daytime leaning can be categorized as occurring between 1 and 2 pm, with evening peaking occurring between 5 and 8 pm. Hence, it may be concluded that India has a peak in the evening (5 pm–7 pm, approximately), about 225,034 MVA at 9 pm. Residential lights, HVAC, and manufacturing industries' usage make up a sizable portion of this, but commercial consumption is essentially at a standstill at this time. In order to enhance power quality, flexible ac transmission systems (FACTSs) and voltage-source converters with sophisticated dynamic controllers are becoming more widespread. Furthermore, distributed FACTS significantly affect power factor, energy efficiency, and quality of power.

A proposed flowchart presents the bidirectional control, mitigation of power quality issues, MPPT technique and battery management system using a three-level converter on both the grid and EV sides. At the grid interface point, or the point of common coupling (PCC), the three-level grid side converter (GSC) can take part in reactive power support. It is necessary to create an efficient controller that can implement the transformer disturbance controller, harmonic reduction, and voltage imbalance management. Future implementation must move towards the efficient controller because it is feasible at the EVSE end. A comparison is made between the facts devices as shown in Table 3. which shows their benefits, drawback, and control features in power quality and electric vehicles.

Conclusions

This paper's context effectively covered a variety of power quality problems that arise from the integration of EVs in electric distribution networks and mitigation strategies. From this review, it is evident that high penetration of EVs can have a negative effect on the grid's stability and power quality because energy sources are intermittent and EV loads are unpredictable. These negative effects on power quality and grid stability, however, can be mitigated by coordinating or combining the operational strategies of integrating EV systems. Large-scale EV loads are also considered significant participants in the future energy market because of their high penetration and potential to influence the price and outcome of the wholesale energy market in the future smart grid. Utilizing strategies for battery charge scheduling, supporting renewable energy sources, and a few other techniques, the voltage unbalance issue is reduced. A composite controller is designed that can implement transformer disturbance, harmonics reduction, and voltage imbalance management. Active harmonic filters and fact devices can be designed and put into use in addition to EV integration to reduce harmonics produced by nonlinear devices and supply highly reactive power that satisfies the specifications. Due to their ease of refit and scale, as well as their direct efficacy in reducing the harmonic voltage, parallel-coupled active harmonic filters have various benefits. The offered active filters provide dynamic reactive power adjustment and can filter harmonics up to the 50th order. To reduce the loss of transformer life, the ant colony optimization, particle swarm optimization, and Firefly algorithm's optimization problem can be expanded.

Abbreviations

EV	Electric vehicles
G2V	Grid to vehicles
V2G	Vehicle to grid
PQ	Power quality
THD	Total harmonic distortion
PV	Photo voltaic
AER	All electric range
ERUF	Electric range utility factor
ToU	Time of use
VSF	Voltage stability factor
BES	Battery storage system
DVR	Direct voltage restorer
SVC	Static VAR compensator

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Authors' contributions

AS carried out the studies, collected and analyzed the data, and drafted the manuscript. MM and RKD revised and contributed to the final manuscript. All authors have read and approved the manuscript.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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