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A review on power quality issues in electric vehicle interfaced distribution system and mitigation techniques

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ABSTRACT

Electric vehicles (EV) penetration in the distribution systems is evident and intended to grow day by day. Power quality issues pop up in the distribution system with an increase in EV penetration. Distribution networks need to consider the power quality issues developed due to the penetration of EVs for planning and designing the system. The power quality issues, including voltage imbalance, total harmonic distortion, distribution transformer failure, and related issues, are anticipated due to EV penetration in distribution systems. Detailed review of power quality issues and mitigation techniques are detailed in this paper. Discussion on the effect of these power quality issues on the distribution systems and corresponding mitigation measures are detailed. Power quality impact mitigation techniques have been discussed recently, which exploits the bidirectional power flow of vehicle to grid vehicle to grid (V2G) and grid to vehicle grid-to-vehicle (G2V). Methods and methodologies that mitigate power quality problems in the EV penetrated distribution system is discussed. Bidirectional power flow during EV charging and discharging and power quality issues in this topology is detailed in this review paper. A discussion on future trends and different possible future research paradigms is discussed as the review's conclusion.

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1. INTRODUCTION

In the Indian perspective, electric vehicles (EVs) and related fields have an enormous development scope. Electrical vehicles and related research are becoming a relevant subject of research nowadays. Although EVs are most sought for transportation it introduces power quality issues. Faster adoption and manufacturing of hybrid & electric vehicles, 2015 (FAME) and national electric mobility mission plan (NEMMP) are the regulators of the electric vehicle technology in India. These regulatory bodies propose an expected growth of around 3.8 million EVs in 2020. Charging infrastructure also grows at the same pace. Battery charging system is the important power electronic device that introduce non-linearity in the system causing total harmonic distortion (THD) of the grid side voltage or current. Unregulated connection and disconnection of the EVs in the grid creates the voltage imbalance issues. The cost for voltage compensation devices may increase due to these voltage imbalances in the grid. Switching losses in the alternating current and direct current (AC-DC) converters of the electric vehicle supply equipment (EVSE) contribute a chunk of the power loss. Since EVs travel from one locality to another the traffic of EVs in any area is unpredictable. Apart from overloading, transformers also encounter wear and tear due to harmonics. EVs charging electronics are a definite source of harmonics if multiple EVs are simultaneously connected. The distribution transformer is the most vulnerable grid component that gets affected by the introduction of EVs in the grid. An EV can vary the harmonic level from 3% while at the start of charging to around 28% at the end of charging. This paper answers these three questions to a more considerable extent. Will there be any impact on the grid if EVs are introduced to the distribution system? What parameters are getting affected in the grid? What are the measures that can be taken to nullify or to reduce the effect? These questions arise since the EV interface devices engage power electronics converters and different pulse width modulation (PWM) techniques. This paper details the causes of the power quality issues in the distribution system (DS) due to the EVs. Then amount of power quality damage that EV penetration in the grid is detailed. Possible mitigation techniques that the distribution Companies DISCOMS must follow to get rid of these power quality issues are discussed with more light on the distribution transformer protection. Loading in the network, imbalance in phase, voltage profile, power quality issues are to be assessed since higher penetration EVs are evident soon.

2. VOLTAGE IMBALANCE IMPACT IN DISTRIBUTION NETWORK BY EV CHARGING

The voltage imbalance issue occurring in the DS can be understood by knowing in detail about different levels of power that is inherent in types of charging. The slow charging outlets are not going to affect the DS whereas the fast-charging outlets primarily affect the DS. According to the power level and type of power classification of charging mechanism is as given in SAE J1772 in 2017 [1]. Two DC levels and two AC levels of charging is defined as: Charging the electrical vehicle at home with the 16A outlet with the voltage level of 120V is referred to as AC level 1. Charging the vehicle with 80 A and 208-240 V that accounts to around 19.2 kW (max) is referred to as AC level 2. Charging at workplace, parking place and public charging outlets sometimes uses the AC level 2. DC level charging charges the battery directly while the AC level charging is carried out only if the on-board chargers are available in the vehicle. DC level charging with the voltage range of 50-1000 V DC and about 80 A is referred as DC level 1. Another DC level follows same voltage level as DC level 1 while the current range reaches to 400 A. This is called DC level 2 charging methods. Single phase power from the electric vehicle supply equipment (EVSE) supplies the both the AC types while DC levels utilizes single phase as well as three phases. Another standard for the charging discussed as SAE J1772, SAE J3068 during 2018 recommends three phase utility power. At high power levels the utility if supplies a symmetric load the grid stability gest enhanced. SAE J3068 standardizes the heavy-duty vehicle charges with three phase supplies. Digital control protocols and charging coupler are used for power sufficiency and reliability [2]. Communication between the EV and EVSE via single wire baseband signaling controls reliable EV charging. This bidirectional communication between EV and three phase EVSE provides less complex, reliable, low-cost power. Getting support from distributed energy resources (DERs) these EVSEs can provide both the AC and DC output, if customer prefers, simultaneously supporting the grid. Renewable energy integration to the grid is standardized providing best maintenance and safety practices, reliable operation performance and testing capability using these standards. Thus, making sure the cascading failure is avoided while interconnecting the renewable sources [3]. Major blackout in South Australia due to wind farm tripping in 2016 affecting 650,000 customers is an example [4]. Apart from using the traditional EVSEs there must be a consideration for the renewable energy integration with the grid with relevant standardization. Since the effect of the voltage imbalance is dependent on the power range of EV charging, an idea about the power usage for the charging types is given in the following subsection.

2.1. Power range in EV charging

An increase in EV connected to the distribution system affects the voltage profile in the system. Single-phase on-board charging starts with 1.6 KW at households and to the highest by the, DC level 2 charging with tens of KW for fast charging [5]. If there should be an occurrence of charging an EV at home shows insertion of substantial single stage loads in the private low voltage (LV) distribution systems. In any case, higher penetration of EVs may adversely influence distribution networks diversely based on their electrical energy demand. It might prompt undesirable peaks in power usage, resulting in power quality issues like voltage drop, transformer overloading, harmonics, and voltage unbalance [6], [7]. As of late, a few contemplations that limit the power systems for EVs charging [8]-[15] is discussed. These limitations apply technical and economic constraints to the power system and equipment failure.

Incentive-based and constant Tariff in EV charging,

$$SOC_{bat} = \begin{cases} \left(1 - \frac{d}{AER}\right) d \leq AER \\ \\ 0 \; d \leq AER \end{cases} \tag{1}$$

electric vehicles must be able to charge at any point in the 24 schedules. Thus, the infrastructure for charging at home, workplace and public spot is required. Considering a provided infrastructure total number of EVs that can be charged in a charging point is as given in (2).

$$EV_{Nrmax} = \sum_{t(h)=1}^{24}(EV_{C_{t(h)}}^{HS} + EV_{C_{t(h)}}^{WP} + EV_{C_{t(h)}}^{PP})XEV_{PL} \tag{2}$$

At any hour h EV_{Nrmax} is the maximum number of EVs that can be connected for charging. $EV_{C_{t(h)}}^{HS}$, $EV_{C_{t(h)}}^{WP}$ and $EV_{C_{t(h)}}^{PP}$ are EV that is charged at home, work space and public place at any hour h respectively. And EV_{PL} is the EV penetration level. In (3) defines the power consumed from the LV utility EV_{Nrmax} . $P_{C(h)_{EV}}$ is the power required for charging a single EV,

$$PEV_{Nrmax} = EV_{Nrmax} * P_{C(h)_{EV}} \tag{3}$$

in (4) is the approximation of the (2) with workplace power ignored.

$$PEV_{Nrmax} = \sum_{t(h)=1}^{24}\{(EV_{C_{t(h)}}^{HS} + EV_{C_{t(h)}}^{PP}) * P_{C(h)_{EV}}\} * EV_{PL} \tag{4}$$

The total power required charging the EV_{Nrmax} number of EVs and any hour h. While grid working condition is stable the EV charging is considered. If EVs are allowed to charge and discharge anytime then it is called uncontrolled charging. Power quality issues when plug-in hybrid electric vehicles (PHEV) is introduced in grid is detailed [16]. Details of the penalty and the incentives that is charged on the client during the peak and the valley hours enable them to decide whether to charge the EV vehicle or to wait. Ideal working condition of charging versus the EV driver's eagerness decides the cost of the charging power. Objective function enables the charging of the vehicle during the non peak load period. While implemented the cost is higher during the time ranging between in this 13:00 and 20:00 h of a day and other time of the day will be charged with reduced tariff [17]. Benefit od low tariff is contingent upon the eagerness of the EV driver hour h. Power needed for all EVs at residential and public points are as given in (5) to (6) and power drawn from a LV network for charging is given in (7).

$$PEV_{C_{t(h)}}^{HS} \leq \sum_{t(h)=1}^{24}(EV_{C_{t(h)}}^{HS} * P_{C(h)_{EV}}) * EV_{PL} \tag{5}$$

$$PEV_{C_{t(h)}}^{PP} \leq \sum_{t(h)=1}^{24}(EV_{C_{t(h)}}^{PP} * P_{C(h)_{EV}}) * EV_{PL} \tag{6}$$

$$PEV_{Nrmax} \leq \sum_{t(h)=1}^{24}\{(EV_{C_{t(h)}}^{HS} + EV_{C_{t(h)}}^{PP}) * P_{C(h)_{EV}}\} * EV_{PL} \tag{7}$$

Although the economic signal is provided to the consumer, if more EVs are connected to the system, the distribution system would cross the normal loading conditions [18].

2.2. Voltage imbalance problem

Voltage unbalance is defined in different ways. The definition of the voltage unbalance is as defined in this section with the essential guidelines. Ratio of the three-phase negative and the positive sequence voltage is defined as the voltage unbalance factor (VUF) [19]. Mathematically it is given in (8).

$$Voltage\ unbalance\ factor(\%) = \frac{V_2}{V_1} * 100$$

$$\approx \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}}$$

$$\beta = \frac{V_{ab}^4+V_{bc}^4+V_{ca}^4}{(V_{ab}^2+V_{bc}^2+V_{ca}^2)^2} \tag{8}$$

Ratio of positive sequence voltage 'V1' and negative sequence voltage 'V2' defines the voltage unbalance factor. As EVs charging load isn't equally distributed on the three phase's power system, it might increase the difference of loads among each period of the system.

2.3. Mitigation of voltage imbalance in distribution networks with EVs

A large portion of research works [20]-[29] facilitates EV charging using the centralized or decentralized methodology. Both economic and technical performance of the distribution system is improved by introducing the suggestions that is controlled by (a) EV charging and discharging, scheduling the time of utilization (ToU), and (b) Rate at which the EV can charge or discharge. To obtain these controls using the communication capability, the cost of getting the desired target is higher. Unbalance are introduced between phases of the distributed system by adding unequal number of EVs in each phase [5]-[14]. EVs capability to improve the distribution system performance is uncertain since the time commitment by the EV to supply the power from vehicle to grid is dependent on human error [30]. Failure in the charging devices, charging timetable mismatch and other problems are evident in using the EV capability in supporting the distributed system. Most of the research work centers around lessening power loss and improving the voltage.

A coordinated EV charging called as electric vehicle charging coordination (EVCC) mitigates voltage imbalance [26]. EVCC does not consider the neutral current that flows due to the imbalance voltage between the phases. Along with the EVs the DERS also need the coordination since the input from DERs are also dynamic in nature. Voltage imbalance, power loss and neutral current all three needs to be controlled while the DERS and EVs are connected to the distributed network. A coordinated control of the DER and EVs enable the voltage imbalance mitigation in the EV connected distributed system. Advantages and the disadvantages of both the centralized and decentralized coordination model of the EV charging is discussed in [31]-[33].

A case study that discusses about the emission benefits for both centralized and decentralized smart charging till the year 2030 is discussed [34]. A control methodology that coordinates the smart charging of all the vehicles that improves the load profile of the EVs connected to the distributed system is developed. The communication system involved in realizing this charging coordination collects and transfers data between the EVs and the aggregator. The load profile is smoothened in order to have this voltage profile normalized. Though some EVs would obtain higher peak voltages at times. Unlike the centralized control the decentralized controller charges the EVs locally. The reduced communication equipment that are used in this decentralized control reduces the cost involved. It is adaptable to changes and has a reduced computational complexity [35]. The decentralized controller looks advantageous to the centralized controller while the individual EV client controls the charging cost of the EVs. Decentralized coordination is best while the cost and the robustness is considered. That is why at some situations the decentralized control is preferred since there is no dependency on the neighboring vehicle or communication devices [33], [35]. However, another classification of EV charging is single phase-based and three phase-based charging [35].

The active power balancing is possible using the droop controller topology for the smart charging in the distribution network [36]-[38]. But these controllers will not bother to charge an EV satisfying the client fully. Although the reactive power that is introduced in the distributed network due to the power electronics devices like rectification and switching converters is an additional burden for the distribution network [39], [40]. Droop controller-based controller is defined in [36] while the reactive power compensation is possible using the auxiliary equipment described in [41], [42] for a balanced system. Negative and zero sequence voltages are generated to decrease the voltage unbalance in the three-phase supply [43]. Low voltage network load voltage profile is improved by adjusting the network loads in [44], [45]. For this situation, the procedure likewise requires a reactive power capability, which is constantly restricted by the rated power of the charger.

2.4. Impact of voltage imbalance in distribution networks with EV charging

The charger injects the harmonic current in the network that is clear in the harmonic model. The harmonic current and its corresponding phase angle is given in (9). This harmonic model is defined in [46], where the harmonics, when charging, create power electronics switching oscillations and harmonics is injected in the distributed system. These current harmonics are resolved by using the 60Hz power flow results.

$$I_h = I_1 \times \frac{I_{h-spectrum}}{I_{1-spectrum}}$$

$$\theta_h = \theta_{h-spectrum} + h \times (\theta_1 - \theta_{1-spectrum}) \tag{9}$$

The harmonics flow from the non-linear apparatus and power electronic devices are as shown in the equation. The PHEV chargers are bound to draw the harmonics frequently from the charging action. The deterministic angular variation is also defined in the equation.

3. COMPACT FLUORESCENT LAMP (CFL) EFFECT AND NEUTRAL VOLTAGE RISE

Compact fluorescent lamp (CFL) index is one measurement index that is equivalent to the power used by the CFL and multiplied by the number of CFLs [47]. Harmonics introduced in the system due to the harmonic current injection is quantified by the power each CFL uses and multiplied by the number of CFLs. The measurement is facilitated due to the availability of CFL in every household [48]. It is predicted that the penetration level of the EVs in 2020 will be 0.2 per home [49]. The voltage increase will transcend to up to 1.0 V in neutral voltage [50], [51]. If the ground condition is improper, the voltage will increase from 2 V to 4 V. This rise in neutral voltage due to harmonics is a tiny problem today, but during 2022 it is thought to be higher. The voltage increase will transcend to up to 1.0 V in neutral voltage [50], [51]. If the ground condition is not proper, the voltage will increase from 2 V to 4 V. This rise in neutral voltage due to harmonics is a tiny problem today, but during 2022 it is thought to be higher.

4. HARMONIC MITIGATION TECHNIQUES IN EV CHARGED DISTRIBUTION SYSTEM

The fast-charging stations [52]-[56] apply centralized coordination implementation with different DC-DC stages for better harmonic mitigation. The DC distribution system is a primary variation in the charging station that can reduce the harmonic effect in the EVSE. The points that strengthen the idea of DC distribution is that, (a) The rectifier and inverter stages can beeliminated, (b) only one point of coupling with the grid, (c) storage and renewable integration very simple, and (d) Energy management must be streamlined. The average power demand is very high compared to the average demand as in [52]. The range of power used for the fast charging is in the range from 1.1 MW and 20 Kwh in dc side storage unit and for fast charging it ranges to 240 kW [52]. The quick chargers are using the 12 pulse rectifiers in order to be able to maintain good harmonics and different models are defined in [53]-[56]. Although cost is high when 12 pulse implementations is carried out the harmonic reduction is a bigger advantage than the cost. The low ac harmonics are maintained by the triangular current form as defined in [57]. The low ac harmonics are obtained due to the reference triangular form as defined in [57]-[62]. The rectifier output is molded to obtain the triangular wave to reduce the ac side harmonics. But in the literature [63] instead of using the triangular form the letter of credit (LC) filter is used to obtain the harmonic reduction.

5. IMPACT OF TRANSFORMERS AND MITIGATION METHODS

Due to higher penetration of EVs the transformers are exposed to ageing issues. Failure due to thermal stress and accelerated degradation of the transformer is evident [64]. The up-gradation of the transformation according to the demand is not a practical solution since the economics of that significant change is unfeasible most of the time. Thus, the demand side management is the alternative that fits the EV integration in the distributed system. Charging of the EVs can be postponed carrying out demand-side management. EVs with full batteries should not be charged unnecessarily. Thus, those EVs must be incentivized to obtain a mitigating effect of the overloading in transformers. Transformer degradation due to increase in the EV penetration in the system is evident in [65]. Numerous papers investigating the distribution transformer and residential grid impact due to high EV penetration is detailed in [65]-[67]. Economic impacts are also detailed. Photovoltaic (PV) arrays mitigate the transformer degradation impact in the EV penetrated grid [68]. It is discussed that 10% penetration of the EV in the distribution system causes a considerable impact on the transformer degradation [69]. PV array generation and battery energy storage system (BESS) effectively mitigate the transformer loss mitigation using the optimization paradigm [70]. Computational complexity and the expenses due to the equipment's bought introduce the feasibility issue [70]-[74]. A rule-based implementation that manages the charging time according to the client's preferences whether to charge in peak hour or not helps mitigate the transformer loss in the distribution system [73], [74]. Optimization algorithm with the thermal and the voltage stress reduction on the transformer as the objective function is adopted [75]. The customer preference is not considered but only the state of charge (SoC) of the EV batteries are supposed to evaluate the algorithm [75]. Although the objective function considered in the only considers the voltage and thermal stress, the failure hazard is considered for the optimization objective in [76]. Fuzzy logic controller (FLC) acts as the decision-making algorithm for solving the transformer failure using the performance index called the distribution. Factors involved in the decision making are SoC of battery, SoC required for next trip, time remaining for departure and EV owner's requirement.

6. POWER ELECTRONICS DEVICES BASED POWER QUALITY ISSUES AND MITIGATION TECHNIQUES

Reducing the switch stress, current and voltage ripple, and the filter size reduction is exhibited in the topological variation developed in the onboard chargers. Power quality indices that are measured at the source that depends on the power factor and the THD are considered the objective. The onboard charger topology includes the three level DC-DC converter that gets the DC input from the controlled rectifier from the distribution system. The reduced size in the filter elements makes this implementation advantageous to other topologies [77]. Power factor correction (PFC) correction at the source of DC-DC converters is available. Proposed bridgeless cuk converter that acts as a PFC based converter improves the charge efficiency. THD is reduced according to the standards and power quality improvement is validated by the power quality index. A satisfactory charging efficiency is observed in the method [78]. Interleaved lands man converter is used for the PFC in the EV connected distributed system. Input current harmonics is reduced along with the output voltage harmonics. Current control is intact in both the constant current and constant voltage charging of the battery [79]. Voltage regulation, power factor improvement and neutral power compensation is developed in the controller. Active power regulation is also evident in the controller, thus providing overall power quality control [80]. The voltage fluctuation depends on the grid configuration and the location of the PV capacity in the grid system. The light flicker that are visible or annoying can occur in future considering the expansion of the EV usage. The method discussed in the algorithm improves the voltage profile during the fluctuation transients [81]. Vehicle to grid vehicle to grid (V2G) operation with voltage dip in the grid and related power quality issues are detailed [82]. Active power supply using the active power filter powered using the grid integrated PV with large battery capacity is discussed in [83]. Power compensation and harmonics suppression is evident in the implementation. With minimization of VUF as the optimization objective function the charging and discharging of the PHEVs are applied with and without PHEV incorporation in the implementation. Both coordinated and uncoordinated charging is applied in the scenarios [84]. Droop characteristic-based voltage stabilizing is applied in the grid-operated EV charging scenario's load models [85]. This article also presents an adaptive control and DC charger technique to demonstrate how basic PV/charger functions together with immunity to solar irradiance’s intermittent nature can be achieved [86]. A two-stage battery charger, in which the first stage i.e., AC-DC stage, which is controlled by sinusoidal pulse width modulation (SPWM) control, and a predictive duty cycle control method is used for the second stage i.e., DC-DC stage is adopted. The fast control of a battery current is achieved by using predictive control, which removes the DC bias from the transformer current by controlling its peak value [87].

Additionally, switch voltage stress is reduced to half of the input dc link voltage. Some of the primary reasons that could cause the voltage drops to include the connection of large household loads or the integration of sizeable loads like EVs themselves, and heat pumps, or contingencies like remote faults. Typically, in low voltage distribution grids (such as the one studied in this work), the transformers possess only offload tap-changers, where a voltage drop at the high voltage side could propagate to the low voltage section [88]. Measurement of power quality issues needs more technical expertise in measuring parameters that decide the existence of power quality issues in distribution systems due to EV penetration. A series of field measurements is conducted to obtain the harmonic component in the current of the distribution network is observed [89].

7. FUTURE RESEARCH DIRECTIONS

A composite controller that can implement the voltage imbalance control and the THD reduction and transformer disturbance controller needs to be developed. Since the composite controller is possible at the EVSE end, future implementation needs to be towards the composite controller. EVSE that can charge the EV customer with higher tariff while in supplied from the grid and lower tariff while supplied from the renewable source can be developed for efficient resource utilization.

8. CONCLUSION

A detailed review of the power quality issues that pop up while the EVs are introduced in the Distributed system is discussed. Mitigation procedures that are helpful in the improvement of the power quality in the distributed system is elaborated. The voltage unbalance problem is mitigated using the battery charge scheduling methods, using renewable energy support and other few methods. The harmonics elimination techniques are used to reduce the harmonic levels in the system. The transformer degradation algorithm is decreased also using renewable energy and battery charging scheduling methods. Future research directions on power quality improvement while EV is introduced in the distribution system is suggested as a concluding remark.

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