VOL. 24, NO. 3, 2025, 237-246
elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

The Impact of Electric Vehicle Charging Stations on Power Quality

Ronald Kibenge[1], **Dalila Mat Said** *[1,2], **Immaculate Babirye**[3], **Nasarudin Ahmad**[1]

[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.
[2]Centre of Electrical Energy Systems, Institute of Future Energy, Universiti Teknologi Malaysia.
[3]College of Engineering, Design, Art, and Technology (CEDAT), Makerere University, Kampala, Uganda.

*Corresponding author: dalila@utm.my

Abstract: Electric Vehicle Charging Stations (EVCS) have become a critical component of modern energy infrastructure as the adoption of electric vehicles (EVs) continues to grow rapidly. While these stations are essential for facilitating the transition to sustainable transportation, their widespread integration into the power grid presents significant challenges related to power quality. Given the increasing number of EVCS installations globally, the paper highlights the need for comprehensive studies of their impact on the existing power grid and mitigation strategies to ensure that power quality standards are maintained to support the seamless integration of EVs. Unlike other reviews that focus on a specific power quality like harmonics, this review makes a distinct contribution to the literature by providing a comprehensive analysis of the six major power quality disturbances with EVCS, such as harmonics distortion, voltage sags, transformer loading, voltage fluctuations, power factor, and phase imbalance. The paper also delves deeper into the variation of power quality disturbances with the EV penetration levels, the power quality disturbances, particularly transformer loading increases with the power of the EV charger, higher derating of the transformer required to accommodate a higher number of EVs, and voltage sags increase more during the peak hours and increase with the penetration level of EVs. Finally, mitigation strategies are proposed in the discussion section of the paper, such as the adoption of vehicle-to-grid technologies, integration of energy storage systems, and integration of distributed renewable energy sources to reduce the negative effects of EVCS on power quality while ensuring a smooth transition to an electric transportation future.

Keywords: Electric vehicle, power quality, harmonic distortion, voltage sag, power factor

Article History: received 14 November 2024; accepted 13 June 2025; published 22 December 2025
Digital Object Identifier 10.11113/elektrika.v24n3.639

1. INTRODUCTION

The increase in average atmospheric temperature of Earth's near-surface air and oceans since the mid-20th century defines global warming. Global warming is caused by the increasing concentration of greenhouse gases (GHG) mainly carbon dioxide (CO2) and methane [1]. The increase in the global temperature attracted the attention of one hundred ninety-three (193) countries under the sustainable development agenda to mitigate the temperature increase. This is highlighted in sustainable development goal thirteen which focuses on taking action to combat climate change and its associated impacts by keeping global temperature rise well below the 2 degrees Celsius of pre-industrial levels [2].

The GHGs that greatly contribute to global warming are mainly produced by the burning of fossil fuels [3]. The transport sector is responsible for 15% of anthropogenic GHG, 23% of global energy-related, and 8.7 Gt CO2-eq emissions [4]. According to the 2017 edition report of the International Energy Agency (IEA) [5], transportation directly contributed 836.6Mt of carbon dioxide, translating to 9% of China's total carbon dioxide emissions in 2015.

Therefore, transport has been seriously considered in mitigating global warming being one of the leading contributors to GHG emissions. The combustion of fossil fuels in the internal combustion engines of vehicles and turbines, such as gasoline and diesel, releases carbon dioxide into the atmosphere [4, 6]. The production and distribution of fuels also contribute to GHG emissions [7].

Concerns about the necessity of finding practical ways to cut CO2 emissions and move toward the decarbonization of the transportation sector have been expressed considering anticipated increases in demand for transportation services in the future [8].

In response to the increasing emission of greenhouse gases and associated climate change, the transport sector is shifting from fossil-fueled internal combustion engine vehicles to Electric Vehicles (EVs). Cars, buses, small trucks, and sport utility vehicles (SUVs) can be electrified by renewable energy sources and batteries to combat emissions from fossil-fueled cars [8]. This shift guarantees clean transportation with low emissions and improved air quality [9]. EVs, such as electric cars, trucks, and buses, produce no exhaust pipe emissions and are therefore considered environmentally friendly compared to conventional vehicles. Therefore, the adoption of EVs is a viable solution to the reduction of emissions by the transport sector. In addition, with a goal for sustainable cities and a clean and healthy environment, cities are adopting EVs to achieve a net zero emissions target [10]. It is thus important to consider the adoption of EVs.

1.1 Electric Vehicles (EVs)

Electric vehicles, contrary to internal combustion engine vehicles (ICEV) utilize the energy stored in a battery or other storage means and are operated by electric motors [11]. With different models, EVs mainly consist of batteries, electric motors, charging systems, EV chargers, and energy sources. Types of EVs include battery electric vehicles (BEV), hybrid electric vehicles (HEV), plug-in hybrid EVs (PHEV), and fuel cell electric vehicles (FCEV) [11, 12]. EVs are categorized as light-duty and heavy-duty EVs. Light-duty EVs consist of electrics while heavy-duty EVs consist of electric trucks (SUVs) and electric buses [13].

1.2 Adoption of EVs

Many scholars have written literature about the adoption of EVs in the world. Many factors affect the adoption of EVs; the consumers' perception of EVs in terms of incentive policies and environmental benefits, and the impact of symbolic meanings of EVs are discussed by authors [14]. Also, different models and frameworks to analyze the adoption of EVs have been documented. [14] discusses the theoretical reflections of consumer behavior in the adoption and non-adoption of EVs. [15] systematically reviews direct and indirect factors affecting the adoption of EVs in France. Direct factors reviewed include technical readiness, difference in total cost ownership, word-of-mouth effects, and environmentally friendly image. Indirect factors that affect EV adoption include government subsidies, green energy ratio, taxes, and policy intervention [15]. The causal loop diagram (CLD) model to represent the adoption of people in France to EVs is also discussed in [15].

In India, the government implemented the faster adoption and manufacturing of electric vehicles (FAME) in 2015 to accelerate the adoption of EVs targeting 30% EVs by 2030 [16]. [16] also analyzes the adoption of EVs in India using the technology acceptance model.

Challenges to the adoption of EVs in countries like Ghana, India, Bangladesh, and Turkey include the lack of technical support for maintenance, high cost of EVs, lack of awareness, high battery price and low capacity, high charging cost and time, lack of charging stations, quality of roads, low speed of EVs among others impede the adoption of EVs [8, 10, 12, 17].

IEA provides the number of EVs on the road and associated sales per year. EV sales in 2019 reached approximately 2.1 million, totaling 7.2 million EVs globally, which accounted for 2.6% of global car sales and 1% of global car stock [18]. In 2022, over 26 million electric cars were on the road (a 60% increase relative to 2021) with China accounting for over 60 % of total EVs over the globe followed by Europe and the United States in the third place. In 2021 electric car sales were less than 5%. In 2021, it was around 9%. However, in 2022, the percentage increased to 14 % of the total car sales in the world [13]. Figure 1 shows the number of EVs sold in millions from 2010 to 2022.

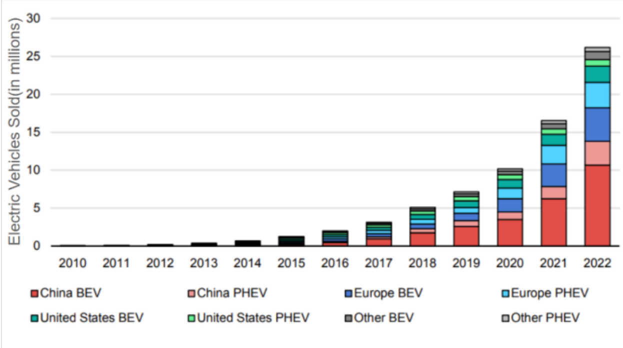

Figure 1. Global electric car stock in selected regions, 2010-2022 [14]

1.3 Power quality

An electrical grid is a network of synchronized power providers and consumers that are connected by transmission and distribution lines and operated by one or more control centers. An electrical grid consisting of a wide range of electrical devices such as appliances, meters, and renewable energy resources, can be defined as a smart grid [19].

Power quality is one of the latest branches in power system research. It refers to maintaining the amplitude and frequency of the distribution bus voltage and current as the rated value and the waveform is like the quality of the sine wave. Power quality problems occur in actual load equipment and components or transmission and distribution subsystems, which is not conducive to the normal operation of various equipment and power systems, affecting the stability, continuity, and reliability of the power system [20]. An adequate power quality guarantees the necessary compatibility between all equipment connected to grids. It is therefore important for the successful operation of the existing grids and even the future grids.

Studying the impact of Electric Vehicle Charging Stations (EVCS) on power quality is crucial for understanding power quality problems. As more charging stations and powerful electric cars come into existence, issues like flickers, swells, sags, harmonics, and other problems happen. These harm the power grid and make electrical equipment fail to work as expected. Different ways to connect EVCS to the power grid have been suggested and a study of how they affect power quality has been done. Problems like harmonics have been considered and the best way to set up the equipment is suggested [21].

Power quality problems, such as changes in voltage, interruptions in power, and other issues, can make electricity bills higher, wear out equipment faster, and strain the power system's stability and reliability [22]. A study of how to model EVCS connected to the power grid and how different control strategies can affect power quality has been done [23]. From the different studies, it is important to put EVCS in the right places in the power system to keep them working well [24].

There is a shift towards more sustainable mobility systems, with a focus on increasing electrification of the road transport sector. This shift is driven by the need to reduce carbon emissions and comply with global climate goals. According to Global EV Outlook 2023, the sales of EVs, including Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), reached USD 10.5 million. Additionally, it is projected that by 2030, EVs will represent more than 60% of vehicles sold globally. This significant increase in the number of EVs on the road will lead to an expansion in the number of public charging points and products available for charging vehicles. As a result, the integration of several EVs into the grid could potentially lead to voltage imbalances, decreased transformer efficiency, and an increase in the Total Harmonic Distortion (THD) of the grid. The impact will depend on factors such as the number of EVs being charged at the same time, their location, and their charging rate. Studies have found that the primary concern for power quality is harmonic distortion, and the higher the EV share, the higher the THD [25].

2. TYPES OF EV CHARGING STATIONS

EVs come in various types, including battery-electric vehicles (BEV), hybrid-electric vehicles (HEV), plug-in hybrid-electric vehicles (PHEVs), and fuel-cell electric vehicles (FCEV) [11, 12]. EVs use motors that are powered electrically instead of internal combustion engines. As such EVs (BEVs and PHEVs) use rechargeable batteries as the main source of electricity to store and supply the electricity needed to drive the motors instead of internal combustion engines except FCEVs [13]. Therefore, charging is a very important factor to consider while using EVs. EVs are charged using different types of charging methods that include portable and non-portable charging, slow charging, fast charging, and wireless charging.

Charger systems for EVs are also categorized as off-board and on-board chargers, conductive and inductive charging systems, and uni-directional and bi-directional chargers. Additionally, there are different power levels for charging, such as Level 1, Level 2, and Level 3 charging [14, 15]. Figure 2 shows a typical connection of an electric vehicle charging station from the point of common coupling to the EV battery.

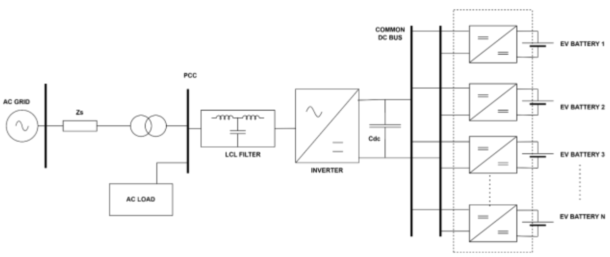

Figure 2. Diagram of a typical electric vehicle charging station

Level 1 EV charging is the lowest power rating for charging electric vehicles from the grid, typically done using a standard residential socket. Level 1 charging is simple, portable, and cheap since there is no need for infrastructure. Complete charging takes between 8 to 12 hours for a fully drained battery. Level 1 charger is built into the vehicle and provides AC voltage of 120 - 240V with a maximum current of 15A and a maximum power of 3.3kW [15]. Therefore, level one is suitable for overnight charging applicable to home or office vehicles that park for an extended period.

Level 2 is designed on a similar technology as Level 1 but can accept a more powerful 240V polyphase AC input line at 15A-80A. Level 2 charging involves the use of a dedicated charging station with higher power output, usually ranging from 3.3 kW to 22 kW. It involves the use of a dedicated circuit that can support the current for charging the EVs which is about 60A according to Texas instruments with [15, 16]. The procedure of charging is like that of level 1 and the same connector location for level 1 can be used [15]. The charging takes about 6 to 8 hours to charge a fully depleted battery, depending on the type of battery. Therefore, level 2 chargers can be used in residential places, public parking areas, and commercial buildings. Figure 2 shows an example of a level 2 charging station.

Figure 3. Level 2 charging station [26]

Level 3 chargers differ from level 1 and level 2 in that a high direct current can be applied directly to the battery to shorten the charging time of the battery and support long-distance trips. Supplying DC eliminates the use of EV onboard chargers [15]. Figure 3 shows a typical level 3 charging station.

Figure 4. Level 3 charging station [27]

Level 3 chargers also known as DC fast charging can supply between 300V up to 920V at a maximum of 500A. The charging time is about 10- to 30 minutes depending on the energy level and the type of battery [14]. Therefore, level 3 EV chargers bring more complexity and cost and thus DC fast charging can be found in public charging points. DC fast charging is more efficient and with reduced charging time the overall impact of emissions from EVs connected to a grid dominated by fossil fuel sources is reduced [17]. It is important however to note that fast charging can also be supplied from an AC power bus or hybrid AC and DC power buses on top of DC only [18].
The different types of charging stations, including level 1 (residential), level 2 (workplace, public), and level 3 (DC fast charging stations), contribute to the overall load demand on the power system. The pattern of load demand varies based on the type of charging station, location, and the availability of infrastructure. For example, around 50% to 80% of all plug-in events occur at home, 15% to 25% at work, and around 5% at public or corridor charging stations. The availability of public charging infrastructure and the possibility of installing residential chargers are key determinants of consumer decisions affecting the shape of the charging load [19].

Electric vehicle chargers cause harmonic distortion. Charger power electronic components produce nonlinear time-varying loads, resulting in harmonic voltages and currents injected into the distribution system. This harmonic distortion causes power quality issues and influences the operation of critical distribution equipment. The impact of EV charging on power quality is particularly significant in developing countries with underdeveloped power quality standards, a lack of maintenance, and specialized human capacity in power system maintenance [19]. For instance, integrating EV charging stations on Nigeria's low-voltage distribution network requires support from distributed wind/PV generation to balance generation and the power demand [20].

The impact of the workplace charging station on power quality depends on the service policy implemented as illustrated in [21]. Under the "dumb service" policy, severe voltage drops occur, while under the impact-aware service policy, the impact is minimized but the voltage drops may last longer [21].

The statistics on the arrival and departure times of electric vehicles (EVs) at residential charging stations as illustrated in Figure 4.

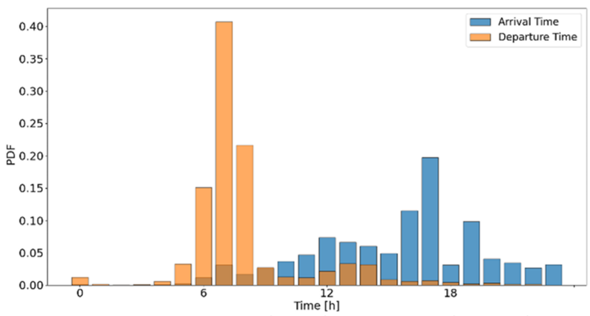

Figure 5. Discrete PDFs of the arrival (in blue) and departure (in orange) times at the residential charging stations [28]

It shows that almost 60% of the simulated EVs leave the residential charging stations by 7 AM, with an average connection time of 15 hours. The data also indicates a higher dispersion in the connection time, with most EVs being connected to the charging stations between 4:30 - 8 PM. This variability in connection times leads to a steep variation in power absorption, potentially causing operation network criticalities [22].

A study conducted using the Chiang Mai 4 substation and DIgSILENT Power Factory simulation tool showed various impacts of the public charging station on the power distribution system [23]. The load profiles of the substation showed that the addition of charging station loads leads to an increase in demand for power during specific periods. The study also shows that the peak load time changes with the addition of charging station loads. The study confirms that voltage stability is maintained, but it also notes that the addition of charging station loads leads to variations in the voltage profile at different times of the day. The study examines the total harmonic distortion of the voltage (%THDv) and finds that the charging station loads cause an increase in THD as shown in Figure 6 below. The %THDv profile shows higher value during specific periods, especially in the morning hours. However, the study also notes that the %THDv remains within the limit of the planning level of the Provincial Electricity Authority (PEA) [23].

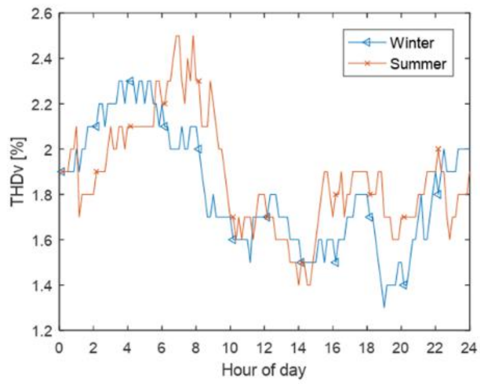

Figure 6. Total harmonic distortion of voltage (%THDv) profile of substation [24]

The impact of integrating large-scale high-power fast charging stations (HPFCS) on power quality in distribution systems is illustrated in Figure 5. It focuses on harmonics, supra-harmonics, and voltage fluctuation caused by HPFCS and electric vehicles (EVs). The results show that chargers from different manufacturers and different vehicle types affect harmonic distortion levels, supra harmonics emissions, and voltage flickers. The study highlights the need to quantify the impact of HPFCS on power quality and provides valuable insights for the integration of EV charging infrastructure [24].

Therefore, the adoption of EVs all over the world necessitates an increase in the number of EV charging stations to enable seamless use of EVs. Just like any other loads, EVCSs have an impact on the power quality and thus on the existing power infrastructure, from power demand to power quality. Aspects of power quality include voltage sag/swell, harmonics, voltage imbalance, voltage fluctuations, power factor, and frequency variations. These power quality issues can severely impact the power transmission and the power grid at large. For instance, an increase in the harmonics can result in reducing the lifespan of transformers, motors, cables, and neutral conductors [25].

3. THE IMPACT OF EV CHARGING STATIONS ON THE POWER QUALITY

The impact of electric vehicle charging stations (EVCSs) has been categorized into six disturbances i.e. harmonics, voltage sags, voltage fluctuations, power factor, transformer loading, and phase imbalance.

3.1 Waveform Distortion/ Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency. Harmonics distort the sinusoidal waveforms, which can cause malfunction of power system components if not limited. The waveform distortion can be quantified using individual harmonic distortion (IHD), total harmonic distortion (THD), and total demand distortion (TDD). IHD reveals the contribution of each harmonic order to the overall distortion of the sinusoid waveform. Whereas THD and TDD reveal the net distortion caused by all the harmonics in the system, THD is calculated based on the peak demand current of the system.

The use of power electronic devices in EV chargers, such as rectifiers and inverters, introduces non-linear loads into the grid, resulting in harmonic distortions: In systems where six-pulse rectifier chargers are used, up to 70% Total Harmonic Distortion (THD) can be generated, while 12-pulse rectifier chargers create around 15% THD [29]. Harmonics in EVCs are particularly problematic because they can exceed the allowable limits set by standards such as IEEE 519, which caps THD at 5% for grid integration [29].

Based on the MATLAB/Simulink design of the EV charger, authors [30] conclude that connecting one EV to the grid results in a THD of 20.30%, 27.67% when three EVs are connected, and 34.19% THD when 5 EVs of similar specifications are connected to the grid. Therefore, considering the IEEE 519 -2014 standard, the results violate the standard for the 69kV system. According to the standard, the THD must be limited to only 5%.

The harmonic analysis was performed by [31] to establish the impact of EVCSs on the power quality in the distribution network. 20 charging piles on a 380V bus are used in simulation. From the simulation of the different topologies of the EV chargers, it is observed that the harmonic content (measured based on the total harmonic distortion of the bus voltage) exceeds the national power quality standards after 13 charging piles made of three pulse rectifiers are connected to the bus, 15 piles made of six pulse rectifier and 10 charging piles made of twelve pulse rectifiers. When the number of charging piles exceeds 20 on the same bus, the total harmonic distortion remains fairly beyond the standard at 2.45%.

Authors [32] explain transformer loading, harmonics, and voltage unbalance as the notable effects of the EVCSs on the power quality in the electricity distribution network. Further insight is gained from the simulation of the charger for a 5kWh battery. Results indicate that when one EV is connected to the system, the harmonics introduced are within the range acceptable by IEEE 519 standard. However, when 3 EVs are connected, the THD rises to 14.07% and 23.55% for 5 EVs which violates the acceptable standards. In the case of [33], the THD for current increased from 2.06% at the beginning of charging to 8.47% while the THD for voltage increased from 2.09% to 2.47% during the charging of one EV and operation of the PV source on the grid.

In the study detailed in [34] emission of harmonics from smart EV charging was profiled. The charging current for both single-phase and three-phase chargers was reduced gradually while charging mainstream EVs, which included Peugeot e 208, Nissan LEAF e+), and Renault Zoe R90 in the Energy System Integration Lab at the Technical University of Denmark. The measurements were done using a Yokogawa WT500 power analyzer. The voltage THD varied between 1.4% and 1.6% regardless of the EV type and charging rate. However, the current THD increased with a reduction of the charging current. At 6A, all the EVs demonstrated violation of harmonic standards i.e. IEEE 519 2014 and IEC 61000-3-2. Multiple charging of EVs resulted in increased THD in current, however, THD still demonstrated an inverse relationship with charging current for both single-phase and three-phase charging [34].

In their study of the Impact Analysis of Public Electric Vehicle Charging Stations on Transformers and Distribution Networks, [35] they showed that the presence of EV charging stations can lead to voltage drops, losses in kWh sales, and transformer inefficiencies, all of which affect the power factor of the system. Using public charging stations connected on the distribution network, harmonics generated by the voltage were measured using fluke 437; the results showed that the harmonics of the voltage are in the highest position, namely harmonic 3 with a value of 1.086% and harmonic 5 with a value of 1.664% and THDv with a value of 2.212% where the THDv standard still meets the standard [35].

3.2 Voltage fluctuations

Voltage fluctuations refer to the variability in the voltage levels in a power network. Voltage fluctuations as defined by IEEE are systematic variations of the voltage waveform envelope, or a series of random voltage changes, the magnitude of which falls between the voltage limits set.

The fluctuations in the voltage are normally caused by the changes in the high-power loads, i.e., with high current variations connected to the power system. Therefore, fast-changing loads cause voltage fluctuations in the system. The variation of voltage magnitudes can be visually observed in the change of light intensity in the light circuits i.e., lamps, which is referred to as light flicker. Therefore, light flicker is the response of the lighting system to such load variations as observed by the human eye and it is the most important effect of voltage fluctuation. The International Electrotechnical Commission (IEC) defines light flicker as the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Fast charging stations draw high current hence high-power demand from the power system to charge the EVs in a short time. The changes in the power drawn from the power system cause voltage fluctuation which results in light flicker which irritates the human eye [18]. Therefore, the voltage fluctuations caused by fast charging stations increase as the rated power of the station increases which makes light flicker more pronounced and more irritating. Using Monte Carlo method to probabilistically estimate the energy profiles, [18] assess the impact of four FCS rated 60 kW, 150 kW, 240 kW, and 350 kW on the voltage quality using the IEEE 4-node test feeder. It is observed that the voltage dip and voltage fluctuations on the bus for which the FCS is connected as well as light flicker increase with the increase in the rated power of the charging station. Using the IEEE 141 standard which is based on the General Electric (GE) flicker curve, it was noted that 60kW FCS did not violate the standard flicker threshold while 150 kW, 240 kW, and 350 kW FCSs all violate the borderline of irritation or flicker however the effect increases with increase in the rated power.

The impact of EVCSs on the voltage deviation was also studied by [31]. The charging circuit was simulated, and the results were analyzed while benchmarking the Chinese national standard for power quality. According to the study, the voltage fluctuation happens to the node or bus that is directly and electrically connected to the charging station while other buses in the network may not be affected by the charging station. The deviation of the voltage highly depends on the penetration rate of the charging stations on the system node/bus with both changing proportionately.

3.3 Voltage sag

In the study [36] based on the LV network using CIGRE benchmark grid, voltage drops were not observed in the 10-bus system until peak vehicle charging hours with more than 80 EVs connected to the network. When 80 or more EVs were connected to the network, the peak voltage drop was about 20% which violates the 5% acceptable limits in the voltage drop. In the same study considering a 20-bus mesh network, with over 80 EVs penetration, the loading of the cables was about 95%. However, the voltage drop was maintained within the acceptable limits.

Authors in [37] analyze the impact of different EV charging levels on the distribution network on the voltage profile of network buses. The authors emphasized the impact of fast charging technology (level 3) as well as combined level 3 and level 2 on the voltage profile of network buses. The maximum power for level 3 and level 2 is 100kW and 35kW respectively. According to the results obtained from the IEEE 33-bus system consisting of 33 buses, 32 branches, 7 solar generation units, 32 loads, and 32 EV charging points, the increase in the real power demand by the charging stations resulted in a reduction in the voltage magnitude on the respective buses with voltage magnitude less than 0.95 per unit for 18 hours for fast charging is utilized and 7 hours for the combined scenario. Authors [37] conclude that EV high-level charging (all levels except 1) can cause voltage violations.

Scholars [30] simulated an EV charger in MATLAB/Simulink, and the voltage magnitude was studied. It is concluded, according to the presented voltage profile before and after connecting the chargers, that a lower voltage would result from connecting more than one EV charger on one phase. This is due to the overloading of the phase by connecting more chargers. Results obtained in [33] show that the RMS value of voltage reduced from 223.51 V to 221.64 V when a BMW i3 2020 was connected to the solar-based charging station supported by the grid. Due to the increased power demand because of EV charging, the study [28] shows a reduction in the voltage profile from the peak of about 325V to about 290V when EVs are connected to the low voltage side for charging.

In low-voltage distribution networks, when multiple EVs charge simultaneously, it can lead to significant voltage drops in the grid. Scholars [38] observed voltage drops of up to 10% at peak demand times, which can take the voltage level below the standard acceptable IEEE limits. This impact varies based on the location and capacity of the EV charging stations and the existing load on the grid.

The voltage magnitude at the buses investigated by the authors [39], considering a 24-kWh lithium battery for the EV charged by a 30 kW DC fast charger. At a 66.68% penetration level, violations of the voltage at some buses were observed with a minimum voltage of 0.90 per unit on phases A and C when an EV was plugged in. Therefore, if not addressed, EV penetration into the distribution network violates the voltage magnitude standards on the buses.

3.4 Power factor

The power factor is the ratio of real power to apparent power in an electrical system [40, 41]. Electric vehicles (EV) charging stations significantly impact the power factor due to the introduction of harmonics into the power grid, affecting the power quality of the distribution network [42]. Within nonlinear circuits, the power factor comprises two additional components named displacement power factor (DPF) and distortion power factor (DIPF). During the initial charging phase, reactive power demand is low, but it increases during the transition to the CV mode as the battery approaches full charge.

With attention to analyzing the harmonics, power factor, and phase imbalance, the authors [33] implemented the charging of a BMW i3 2020 using a solar-based EV charging station. The SEL-735 power quality meter was used to take measurements during the measurement. Considering the displacement power factor and distortion power factor, the true power factor reduced from 0.9977 to 0.9876 as the EV charging rate decreased, as shown in Figure 7 [33]. The power factor during constant charging is generally high (>0.99), but during the final charging stage, it can drop to as low as 0.28, indicating a substantial increase in reactive power [43].

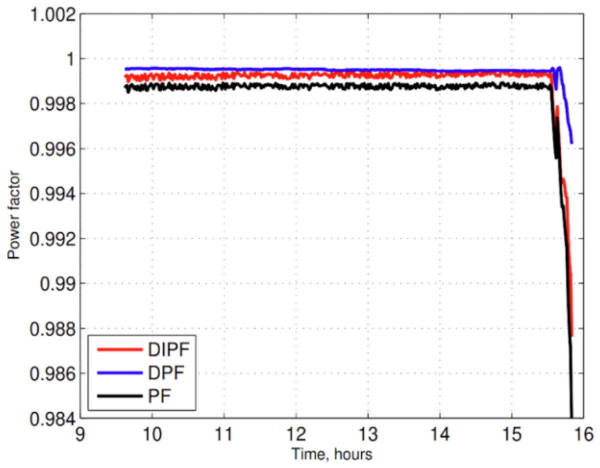

Figure 7. Variation of power factor with time during EV charging [36]

3.5 K-factor (transformer loading)

The authors [32, 44] also discuss transformer loss as an impact of EVCSs on the power distribution transformers due to the non-linearity of the power electronics connected to the transformer that constitutes the EV chargers. The study reveals that a 200kVA transformer had to be derated to 196.63, 191.64, and 186.11kVA when 1 EV, 3 EVs, and 5 EVs are respectively connected to the transformer output. This shows that power loss is high with a greater number of EVCSs due to harmonics.

The study by Ashish et al used a MATLAB Simulink model to analyze the impact of Electric Vehicle Charging Stations (EVCS) on power quality in a distribution network. The model includes a 132kV utility grid connected through step-down transformers (132/33kV, 33/11kV, and 11/0.4kV) to simulate EV charging. Both public and private EVCS were modeled, with the primary components being rectifiers and DC-DC converters. The study focuses on key metrics like power demand, harmonics, voltage profile, and transformer performance. Harmonic distortion was assessed by comparing total harmonic distortion (THD) for voltage and current, especially under different EV charger loads [28]. The harmonic current caused heating losses in the core of the transformer which not only reduces the kVA rating of the transformer but also the overall power loss. For instance, a 200kVA rated transformer output 119.80 kVA, 186.75 kVA, and 181.45 kVA when 1, 3, and 5 EVs were connected, respectively [28].

3.6 Phase imbalance

Voltage unbalance arises primarily due to the use of single-phase EVCs, which are commonly installed in residential areas. Studies show that the addition of EVCs, especially in high penetration scenarios, leads to a considerable increase in voltage unbalance. In a field study involving almost 100 households, with 36 EVCs and 43 photovoltaic inverters (PVI), voltage unbalance increased by approximately 0.1% during EVC charging but remained within the acceptable limits set by IEC 61000-2-2 (less than 2%) [29]. However, when both EVCs and PVIs were operating simultaneously, the unbalance levels were significantly higher, particularly at the end of feeders, indicating the need for better phase distribution to mitigate this issue [45].

During the operation of the PV and EV charging of 42.2 kWh and 120 A-h EV, at level II charging, the loading of one phase increased the voltage unbalance from 0.33 to 0.65%. This is below the allowed 2% by IEEE standard, however, only one vehicle was connected for charging [33].

4. POWER QUALITY VIOLATIONS DUE TO HIGH PENETRATION LEVEL OF EVs

The effect of EV charging on the power quality depends on factors such as the penetration level, the state of charge of the battery, the level of charging stations, the time of connection of the charges to the network, and the location of the charging station on the grid distribution network [46]. In this section, the impact of the penetration level of the EV chargers on the power quality of the grid distribution network is analyzed.

The penetration level of EVs has a significant effect on the different aspects of power quality. For instance, as the penetration level of EVs increases, the amount of THD increases in all the phases of the grid for a three-phase network; therefore, the penetration level must be limited. Authors [46] investigated the variation of voltage magnitude and THD with the penetration level (number of charging stations) in an IEEE–33 bus distribution network. The minimum voltage magnitudes recorded for 5, 12, and 25 level 3 chargers were 0.89, 0.86, and 0.81 per unit, respectively. With the same penetration levels, 5, 12, and 25 level 3 charging stations, maximum THD of 2.93%, 7.35%, and 16.7% were recorded, implying that THD increases with the increase in the penetration level. This reveals that 25 level 3 chargers violate the IEEE 519 – 2014 standard. The transformer loading and service disruption were also analyzed against the penetration level of EVs for an IEEE European low-voltage test feeder by [47]. The authors considered a Nissan Leaf electric car with a battery capacity of 24 kWh and a 3.3 kW rated charger. The distribution transformer fuse exceeds its rating limit when subjected to 100% penetration rate therefore, the transformer fuse blew during uncontrolled charging of the EVs. However, for all other penetration levels, the power demand of the transformer was found to be within the fuse rating [47].

Utilizing a modified IEEE 33-bus system with 33 buses, 32 branches, 32 loads, 7 solar generation plans, and 32 EV charging points, researchers in [37] analysed the power quality implications of high-level charging rates of 50% penetration rate of EVs within the distribution network. The voltage at bus 18 reduces to below 0.95 per unit during two scenarios. The first scenario is when all the EVs connected to the distribution system are first chargers, and the second scenario is when the EV charger at 18 was a first charger while the rest were level 2 chargers. Scholars [48] employed a probabilistic approach to analyze the impact of electric vehicle penetration on low-voltage residential distribution networks. Transformer loading was particularly studied. It was concluded that the penetration level varies proportionately with the transformer loading, considering two probability distribution functions i.e., Weibull and lognormal distributions. The transformer loading exceeded 50% during the 100% penetration level. The load flow simulation does not converge as the penetration level increases, and voltage falls to below 0.96 per unit for terminals starting from the midpoint of the network.

The voltage magnitude was also studied during controlled and uncontrolled level one charging of electric vehicles [49]. The scholars considered 19 models that were utilized and distributed randomly on the buses in the LV distribution network with a maximum charging power of 7.6 kW. During uncontrolled charging, there were extreme voltage violations where voltages below 0.95 per unit were recorded for a 100% penetration level.

Authors [50] assessed the impact of the electrical charging on the power quality of the residential power grids. A distribution network consisting of 240 primary buses serving 1,120 customers was considered, with EV penetration levels of 20%, 40%, 60%, 80%, and 100%. For a 10-kW charger, the maximum loading increased sharply from 97.5% with no electric vehicle (EV) connected to 400% at full penetration. increased the loading percentage for a 6.19 kV; however, the maximum loading at 13.8 kV was 121.7% and 48% for that of a 34.5 kV system. EV charger rated 5 kW, and 15 kW resulted in 23 violations at 100%, and 38 violations at 60% adoption, respectively.

5. DISCUSSION

The impact of EV charging stations on power quality spans from harmonics to voltage deviations and transformer loading; however, the effect becomes more significant with the increase in the penetration levels of EVs.

Connecting many EVs during charging of the vehicles introduces harmonics in the power system, voltage sags/dips, transformer overloading, voltage fluctuations, phase unbalance, power factor reduction, frequency variations, and increased power demand. It is observed that with high penetration of EVs, the total harmonic distortion increases to exceed the acceptable limits as prescribed by like IEC 61000-3-12 and IEEE 519-1992. The harmonics affect electrical components connected in the power system like transformers, which is termed as transformer loading. Appropriate k-rated transformers must be installed to handle the effect of harmonics. These transformers are made with the capability to handle the harmonics introduced by non-linear loads like the EVCSs. To reduce the injection of harmonics, Distribution Static Compensators (DSTATCOMs) are often implemented, which help manage reactive power and filter out harmonic distortions in the grid. In addition, active filters are utilized along with EVCSs to filter out harmonic distortions to safeguard the grid.

Due to the increased power demand, i.e., both real and reactive power, voltage sags and voltage fluctuations could exceed the acceptable limits due to high penetration of EVs. The high-power chargers lead to more line violations and transformer loading as the adoption of EVs increases globally. Phase imbalance is primarily due to the numerous residential charging stations connected to single-phase supplies. The introduction of harmonics increases the distortion factor, which reduces the true power factor of the power delivered. The true power factor can drop as low as 0.28 during the final stages of the EV charging.

Integration of power systems with distributed renewable energy sources such as solar energy and wind energy can help reduce the impact of the EVCSs on the power quality. These generation plants balance real and reactive power into the grid to help alleviate issues created by EVCSs. This improves voltage stability and the overall grid reliability on the LV distribution networks. The use of energy storage systems and hybrid systems, such as combining solar and biomass, can reduce reliance on the grid during peak hours and lower harmonic distortion.

Additionally, vehicle-to-grid, distributed energy resources, and energy storage technologies can be crucial in managing the penetration of EVs into the power grid, ensuring that the grid remains stable and efficient with high levels of EV penetration. Deployment of smart charging strategies, the use of advanced control strategies, artificial intelligence for grid optimization, and vehicle-to-grid technologies are such technologies that facilitate optimal power flow, real-time monitoring, and control of the grid conditions to enable stability and resilience of the grid with EV penetration.

6. CONCLUSION

Manufacturing and adoption of electric vehicles have accelerated over recent years in many countries to reduce greenhouse gas emissions. Electric vehicles (EVs) offer notable advantages such as reduced environmental pollution and a cost-effective mode of transportation, making them increasingly appeal to consumers. This is true since EVs operate on electrical energy stored in batteries for propulsion, contrary to internal combustion engines in traditional vehicles. EVCSs are vital to charging EVs to provide energy to EV batteries.

However, most EVs are charged using residential connections due to the lack of adequate charging stations, preventing the power sector from capitalizing on this market. Despite their benefits, EV penetration introduces vulnerabilities to the power system due to the power electronics that exhibit non-linear characteristics, which degrade power quality. This paper analyzes power quality issues, including harmonics, voltage fluctuations, and transformer power losses. Additionally, the study discusses mitigation techniques involving renewable energy resources. While EVs contribute to grid stability during underload conditions and reduce greenhouse gas emissions, it is crucial to properly manage power quality issues for sustainable growth in the power sector.

ACKNOWLEDGMENT

This paper was developed in the laboratories of Centre of Electrical Energy Systems, CEES, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM). For this project, registration proposal Q.J130000.3009.04M67.

REFERENCES

[1] L. Jeffry, M. Y. Ong, S. Nomanbhay, M. Mofijur, M. Mubashir, and P. L. Show, "Greenhouse gases utilization: A review," *Fuel,* vol. 301, p. 121017, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.fuel.2021.121017.

[2] P. Katila, C. J. P. Colfer, W. de Jong, G. Galloway, P. Pacheco, and G. Winkel, *Sustainable Development Goals*. Cambridge University Press, 2019.

[3] K. S and N. R, "Green House Gases: Challenges, Effect, and Climate Change," in *Biomass and Bioenergy Solutions for Climate Change Mitigation and Sustainability*, A. K. Rathoure and S. M. Khade Eds. Hershey, PA, USA: IGI Global, 2023, pp. 65-74.

[4] A. L. C. Ferrer and A. M. T. Thomé, "Carbon Emissions in Transportation: A Synthesis Framework," *Sustainability,* vol. 15, no. 11, p. 8475, 2023.

[5] H. Du, Z. Chen, B. Peng, F. Southworth, S. Ma, and Y. Wang, "What drives CO2 emissions from the transport sector? A linkage analysis," *Energy,* vol. 175, pp. 195-204, 2019/05/15/ 2019, doi: https://doi.org/10.1016/j.energy.2019.03.052.

[6] R. Alhindawi, Y. Abu Nahleh, A. Kumar, and N. Shiwakoti, "Projection of greenhouse gas emissions for the road transport sector based on multivariate regression and the double exponential smoothing model," *Sustainability,* vol. 12, no. 21, p. 9152, 2020.

[7] J. Dujmović, T. Krljan, N. Lopac, and S. Žuškin, "Emphasis on occupancy rates in carbon emission comparison for maritime and road passenger transportation modes," *Journal of Marine Science and Engineering,* vol. 10, no. 4, p. 459, 2022.

[8] H. N. D. Senyapar, U. Cetinkaya, S. Ayik, Z. A. Altinok, and R. Bayindir, "Importance of Charging Infrastructure for the Public Adoption of Electric Vehicles - Recommendations for Turkey," in *2023 11th International Conference on Smart Grid (icSmartGrid)*, 4-7 June 2023 2023, pp. 1-5, doi: 10.1109/icSmartGrid58556.2023.10170969.

[9] M. Muratori *et al.*, "The rise of electric vehicles—2020 status and future expectations," *Progress in Energy,* vol. 3, no. 2, p. 022002, 2021.

[10] E. Agyemang, E. F. Amankwaa, and J. Essandoh-Yeddu, "Exploring the Barriers to Consumer Adoption and Applications of Electric Vehicles: Ghana's Experience," in *2022 IEEE/IET International Utility Conference and Exposition (IUCE)*, 3-4 Nov. 2022 2022, pp. 1-5, doi: 10.1109/IUCE55902.2022.10079349.

[11] M. R. Ahmed and A. K. Karmaker, "Challenges for Electric Vehicle Adoption in Bangladesh," in *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 7-9 Feb. 2019 2019, pp. 1-6, doi: 10.1109/ECACE.2019.8679288.

[12] P. G. Pereirinha, "Electric vehicles," in *Encyclopedia of Electrical and Electronic Power Engineering*, J. García Ed. Oxford: Elsevier, 2023, pp. 350-387.

[13] S. Muslimin, Z. Nawawi, B. Y. Suprapto, and T. Dewi, "Comparison of Batteries Used in Electrical Vehicles," in *5th FIRST T1 T2 2021 International Conference (FIRST-T1-T2 2021)*, 2022: Atlantis Press, pp. 421-425.

[14] S. Chon, M. Bhardwaj, and H. Nene, "Maximizing power for Level 3 EV charging stations," *Texas Instrument Article,* pp. 1-33, 2018.

[15] A. Bahrami, "EV Charging Definitions, Modes, Levels, Communication Protocols and Applied Standards," *Changes,* vol. 1, pp. 10-01, 2020.

[16] N. Matanov and A. Zahov, "Developments and challenges for electric vehicle charging infrastructure," in *2020 12th Electrical Engineering Faculty Conference (BulEF)*, 2020: IEEE, pp. 1-5.

[17] M. Yasko, A. Balint, J. Driesen, and W. Martinez, "Future workplace EV charging architectures: DC and AC charging choices," in *2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, 2023: IEEE, pp. 1-7.

[18] S. M. Alshareef and W. G. Morsi, "Impact of fast charging stations on the voltage flicker in the electric power distribution systems," in *2017 IEEE Electrical Power and Energy Conference (EPEC)*, 2017: IEEE, pp. 1-6.

[19] P. Energy Sector Management Assistance, "Electric Mobility and Power Systems: Impacts and Mitigation Strategies in Developing Countries," World Bank Group, 2023-06-01 2023, issue Report: 181847. [Online]. Available: https://policycommons.net/artifacts/3936822/electric-mobility-and-power-systems/

[20] Y.-O. Udoakah, H. B. Sonder, and L. Cipcigan, "Low voltage distribution network simulation and analysis for electric vehicle and renewable energy integration," in *2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2021: IEEE, pp. 1-5.

[21] X. Liu, T. Zhao, P. Wang, and C. B. Soh, "Quality of Service Oriented Impact Analysis on Power Systems Considering EV Dynamics," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, 2018: IEEE, pp. 1-5.

[22] G. Pisano *et al.*, "Impact of electrical vehicle private charging stations on the quality of the low voltage network supply," *IEEE Open Access Journal of Power and Energy,* 2023.

[23] T. Pothinun and S. Premrudeepreechacharn, "Power quality impact of charging station on MV distribution networks: A case study in PEA electrical power system," in *2018 53rd International Universities Power Engineering Conference (UPEC)*, 2018: IEEE, pp. 1-6.

[24] B. Basta and W. G. Morsi, "Probabilistic assessment of the impact of integrating large-scale high-power fast charging stations on the power quality in the distribution systems," in *2020 IEEE Electric Power and Energy Conference (EPEC)*, 2020: IEEE, pp. 1-6.

[25] S. Letha, T. Busatto, and M. Bollen, "'Interaction between charging infrastructure and the electricity grid," *Luleå Univ. Technol., Luleå, Sweden, Tech. Rep,* 2021.

[26] Eaton, "Installation and Service Manual Dual AC Level 2 Electric Vehicle Supply Equipment (EVSE)," 2013. [Online]. Available: https://www.evchargesolutions.com/v/downloads/EATON-U-107-112.pdf

[27] E. a. ABB. "EVgo and ABB to Deploy Nation's First High-Power Electric Vehicle Fast Charging Station." EVgo and ABB. https://www.evgo.com/press-release/evgo-abb-deploy-nations-first-high-power-electric-vehicle-fast-charging-station/ (accessed.

[28] A. K. Karmaker, S. Roy, and M. R. Ahmed, "Analysis of the Impact of Electric Vehicle Charging Station on Power Quality Issues," in *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, 7-9 Feb. 2019 2019, pp. 1-6, doi: 10.1109/ECACE.2019.8679164.

[29] C. Balasundar, C. Sundarabalan, J. Sharma, N. Srinath, and J. M. Guerrero, "Design of power quality enhanced sustainable bidirectional electric vehicle charging station in distribution grid," *Sustainable Cities and Society,* vol. 74, p. 103242, 2021.

[30] S. Pankaj, M. R. Khalid, M. S. Alam, M. J. Asghar, and S. Hameed, "Electric vehicle charging stations and their impact on the power quality of utility grid," in *2022 International Conference on Decision Aid Sciences and Applications (DASA)*, 2022: IEEE, pp. 816-821.

[31] Q. Gu, Y. Zhu, H. Zeng, D. Zeng, and Y. Guo, "Research on the influence of electric vehicle charging station on power quality of distribution network," in *2021 IEEE International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT)*, 2021: IEEE, pp. 286-293.

[32] P. Sivaraman, J. S. S. Raj, and P. A. Kumar, "Power quality impact of electric vehicle charging station on utility grid," in *2021 IEEE Madras Section Conference (MASCON)*, 2021: IEEE, pp. 1-4.

[33] B. Martínez and N. Garcia, "Power Quality Analysis at a Renewable Energy-Based Charging Station," in *2023 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, 2023, vol. 7: IEEE, pp. 1-6.

[34] M. Senol *et al.*, "Measurement-based harmonic analysis of electric vehicle smart charging," in *2024 IEEE Transportation Electrification Conference & Expo*, 2024: IEEE.

[35] H. Syafruddin, A. H. Rambe, and A. Prabowo, "Impact Analysis of Public Electric Vehicle Charging Stations on Transformers and Distribution Networks," *Journal of Mechanical, Civil and Industrial Engineering,* vol. 4, no. 4, pp. 08-19, 2023.

[36] S. Haider and P. Schegner, "Simulating the impacts of uncontrolled electric vehicle charging in low voltage grids," *Energies,* vol. 14, no. 8, p. 2330, 2021.

[37] A. F. Soofi, R. Bayani, and S. D. Manshadi, "Analyzing power quality implications of high level charging rates of electric vehicle within distribution networks," in *2021 IEEE Transportation Electrification Conference & Expo (ITEC)*, 2021: IEEE, pp. 684-689.

[38] S. Helm, I. Hauer, M. Wolter, C. Wenge, S. Balischewski, and P. Komarnicki, "Impact of unbalanced electric vehicle charging on low-voltage grids," in *2020 IEEE PES innovative smart grid technologies Europe (ISGT-Europe)*, 2020: IEEE, pp. 665-669.

[39] S. Mondal and M. De, "Distributed Energy Resource Deployment to mitigate adverse effects of High EV Penetration in unbalanced distribution system by Analytical sensitivity-based optimization," *Electric Power Components and Systems,* pp. 1-12, 2024.

[40] S. Gharat, D. Patilkhede, S. Patil, and A. Yadav, "Automatic Power Factor Correction Using Microcontroller," *International Journal of Engineering Technology Science and Research (IJETSR),* vol. 4, no. 4, 2017.

[41] S. Vendoti, D. R. Kishore, K. Arunasri, A. E. Harini, K. Vinayak, and P. J. S. N. Sai, "Bridgeless Landsman Converter with Hybrid Control Technique for Power Factor Correction in EV Application," in *2024 International Conference on Recent Innovation in Smart and Sustainable Technology (ICRISST)*, 15-16 March 2024 2024, pp. 1-6, doi: 10.1109/ICRISST59181.2024.10921933.

[42] T. Bogaraj, S. Karthikeyan, P. S. Jose, and A. Natarajan, "Impacts on power systems: integrating electric vehicles, charging stations," in *Advanced Technologies in Electric Vehicles*: Elsevier, 2024, pp. 299-320.

[43] A. Verma and B. Singh, "CAPSA based control for power quality correction in PV array integrated EVCS operating in standalone and grid connected modes," *IEEE Transactions on Industry Applications,* vol. 57, no. 2, pp. 1789-1800, 2020.

[44] B. Hudson, G. Razeghi, and S. Samuelsen, "Mitigating impacts associated with a high-penetration of plug-in electric vehicles on local residential smart grid infrastructure," *Journal of Power Sources,* vol. 593, p. 233961, 2024.

[45] F. Möller, J. Meyer, and M. Radauer, "Impact of a high penetration of electric vehicles and photovoltaic inverters on power quality in an ürban residential grid Part I-Unbalance," in *International Conference on Renewable Energies and Power Quality (IREPQ)*, 2016.

[46] M. Shadnam Zarbil and A. Vahedi, "Power Quality of Electric Vehicle Charging Stations and Optimal Placement in the Distribution Network," *Journal of Operation and Automation in Power Engineering,* vol. 11, no. 3, pp. 193-202, 2023.

[47] A. Visakh and M. P. Selvan, "Analysis and mitigation of the impact of electric vehicle charging on service disruption of distribution transformers," *Sustainable Energy, Grids and Networks,* vol. 35, p. 101096, 2023.

[48] N. Nalo, A. Bosović, and M. Musić, "Impact of Electric Vehicle Charging on Voltage Profiles and Unbalance on Low Voltage: (Case Study of a Real Rural Low-Voltage Distribution Network)," in *International Symposium on Innovative and Interdisciplinary Applications of Advanced Technologies*, 2019: Springer, pp. 52-73.

[49] D. Kothona, A. G. Anastasiadis, K. Chrysagis, G. C. Christoforidis, and A. S. Bouhouras, "EVs in Distribution Networks—Optimal Scheduling and Real-Time Management," *IEEE Access,* vol. 12, pp. 108313-108327, 2024, doi: 10.1109/ACCESS.2024.3438242.

[50] E. Raffoul and X. Li, "Assessing the Impact of Electric Vehicle Charging on Residential Distribution Grids," *arXiv preprint arXiv:2411.13710,* 2024.