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Review article

Grid integration of electric vehicles - Impact assessment and remedial measures

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HIGHLIGHTS

- Reviews EV charging technologies and grid integration for power grid integration.
- Analyses high EV charger penetration impacts on the power distribution grid.
- Reviews mitigation techniques for sustainable EV charging integration.
- Designs EV charging system with GFM inverter to enhance grid support.
- Highlights challenges and trends in large-scale EV charger integration.

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ABSTRACT

The transportation system is rapidly electrifying due to the socioeconomic and environmental benefits of electric vehicles (EVs). Moreover, global interest in clean energy sources and advancements in EV charging technologies have significantly accelerated EV adoption. However, as demand for EV charging proliferates, interaction with the distribution grid becomes increasingly complex and poses significant challenges for grid operators and stakeholders. The large-scale integration of EVs has produced new patterns of load demand, characterized by fluctuating power requirements and localized congestion. Intermittent nature and high-power demands of EV charging, which can strain distribution infrastructure, leading to impacts on power quality, voltage and frequency deviations, harmonic distortions, thermal overloading, and operational inefficiencies. This paper investigates various impacts of EV charging systems on the distribution grid and remedial measures to achieve optimal solutions to mitigate these negative impacts. The urgency for advanced insights and strategic measures in managing the evolving dynamics of EV charging on the power grid are underscores in this paper. The implementation of smart charging systems employs advanced algorithms and communication technologies to enable demand response (DR) and load management strategies which are effectively addressing the adverse impacts of EVs. Additionally, an EV charging system with grid forming (GFM) inverter-based controller is designed and implemented in the MATLAB/Simcape environment, which can enhance grid support during steady-state and transient conditions. Finally, challenging issues and prospects are discussed in detail to anticipate and identify potential challenges, ensuring a smooth EV transition to future transportation and energy sectors.

1. Introduction

Transportation electrification has garnered significant interest worldwide as a viable alternative to meeting growing energy demand, environmental concerns, and socioeconomic requirements. The emergence of electric vehicles (EVs) has accelerated by several factors

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including fossil fuel depletion, accumulating environmental pollution, growing urbanization and interest in clean technologies [1–3]. Recently, demand for electric vehicles (EVs) has surged due to their impressive capability to reduce carbon dioxide (CO_2) emissions. In addition to this environmental benefit, EVs offer greater reliability, efficiency, and cost-effectiveness compared to traditional internal combustion engine (ICE) vehicles [4–6]. In terms of CO_2 emissions, ICE vehicle approximately discharges 160 gCO_2/km, whereas, an EV emits 45 gCO_2/km because of CO_2 emissions from the generation of electricity [7]. Besides, new technologies including advanced power electronic components, wide band gap semiconductors, and smart charging strategies make EVs more competitive on energy savings, performance and efficiency [8].

Fig. 1 illustrates the trend of the global electric car fleet from 2010 to 2023, showing that the total number of EVs on the road has reached nearly 40 million by 2023 [9]. EV sales have been increasing rapidly worldwide, with almost 14 million battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) sold in 2023 [10,11]. Electric car sales keep increasing and could reach approximately 17 million in 2024, that making up over one in five cars sold worldwide [12,13]. EV sales continue to be boosted by factors such as price reductions, battery technological advancements, government incentives, and manufacturing innovations shift toward exclusively selling EV models, [14]. Predictions indicate that the global EV stock will grow to nearly 350 million vehicles by 2030, with efforts to scale up lithium-ion battery capacity to 100 GWh by the same year [12]. Therefore, governments across the globe are increasingly adopting policies to encourage the adoption of EVs. While this move has numerous benefits, the high penetration of EVs raises new concerns and challenges about its ramifications on the grid [15].

The rapid growth in EV adoption brings forth complex challenges to the distribution grid operations, reliability, and safety. As EVs draw significant amount of power during charging, particularly during peak hours, the grid faces strains that could lead to local overloads, increase peak demand, power losses, voltage and current fluctuations, transformer and feeder overloads [16–19]. These power losses in the distribution network reduce the quality of supplied energy and lead to high costs of supplying energy to consumers. Moreover, high load demand of EV charging leads to power quality decreases, harmonics distortions, voltage, and frequency stability issues. Also, intermittent nature of EV loads can degrade power quality, causing voltage sags, swells, and unbalances [20]. Additionally, this surge in EV usage introduces several technical challenges such as reduction in power system inertia, system strength, reliability and security impacts [19,21]. EV chargers often inject harmonics into the grid, increasing total harmonic distortion (THD) and poses potential resonance issues. Furthermore, the integration of EVs, especially alongside renewable energy sources (RES), reduces system inertia, making the grid more susceptible to frequency variations. The uncontrolled and uncoordinated deployment of EV chargers poses various challenges, leading to unexpected peaks and overloads in the distribution network. This situation leads to increased power losses, voltage deviations, and the need for dispatching energy sources [22].

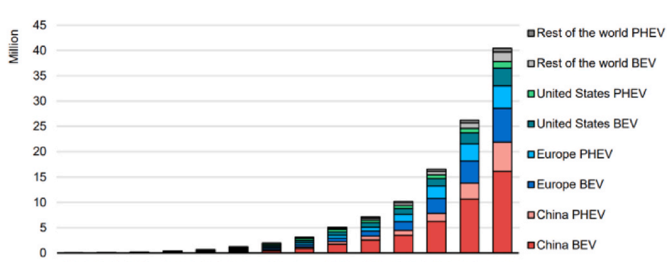


Fig. 1. Global electric car sales statistics, 2010–2023 [12].

The extent of EV impact depends on the degree and density of EV penetration on the distribution grid, charging time and power requirements, and the time of day they are charged. The high-power variations in different charging strategies including slow and fast charging are affected overall power system performance and increase complexity due to the intermittent nature of EV loads [23,24]. The behavior of EV owners, such as charging preferences and habits, can also influence grid impacts. Fast-charging systems and vehicle-to-grid (V2G) operations are reshaping overall power network dynamics by introducing sophisticated charging and discharging strategies for electric vehicles [25]. Fast chargers (50 kW–350 kW) draw a substantial amount of power to deliver quicker charging times compared to standard chargers, leading to higher peak loads on the grid [26–28]. Existing grid infrastructure may lack the capacity to handle these rapid changes and higher demands due to the clusters of EV charging stations in certain locations. Therefore, areas with a high concentration of EVs, may experience local grid congestion, which can strain transformers and distribution lines, potentially leading to equipment failures or reliability issues. V2G technology allows EVs to receive energy from and supply energy back to the electrical grid when required. However, the rapid changes in power output from EVs can disrupt the stability of the grid, affecting voltage and frequency control, which may result in power quality problems and grid disturbances [29].

Hence, remedial measures are necessary to reduce the impacts of electric vehicle (EV) charging systems on the power grid. Studies frequently focus on designing optimal charging systems that use advanced control methods. Some key improvements are smart charging algorithms, integration of DR capabilities, energy management systems, and RES and optimization techniques. Some of these advanced techniques may involve increasing power supply to meet the surging demand, developing charging points, ensure stability, reliability, and safety of the grid operations [19,27,28]. Moreover, coordinated charging distributes EV charging demand more evenly throughout the day, reducing the concentration of charging during peak hours and helps mitigate grid congestion and avoids simultaneous spikes in electricity demand [30]. V2G technology offers several benefits to mitigate the impacts of EVs on the grid including peak load management, facilitates grid balancing, ancillary services, grid resilience and RES integration [31,32]. Advanced metering infrastructure enables real-time grid monitoring and management, facilitating better load forecasting and DR [33]. Grid reinforcement and modernization, including upgrading transformers and distribution lines, can increase capacity and resilience, while installing harmonic filters can mitigate harmonic distortion effects caused by EV chargers [34,35].

Several studies have focused primarily on the impact of EV integration on the low voltage distribution system, highlighting challenges and issues it poses to the power grid. Various technical challenges faced by high level integration of EVs, and remedial solutions are discussed in Refs. [19,36]. The effects of residential EV charging on distribution systems and the strategies to mitigate these effects are discussed in Ref. [37], proposed a controlled charging algorithm to reduce the impact of voltage fluctuations and peak load demand. The study in Ref. [38] reviewed the challenges and contributions of EV integration to the smart grid, focusing on aspects such as energy management, grid balancing, grid-quality support, and socioeconomic impacts. The study in Ref. [39] examines the current state, recent developments, and challenges in EV infrastructure implementation and analyzes the societal impacts and prospects of EVs. The various charging solutions and optimization techniques have been studied in Refs. [40,41].

Although current research offers important insights on the effects of EV charging on the distribution grid, there are still several unexplored areas. Many previous studies have focused on specific aspects individually, such as power quality, voltage stability, grid stability or infrastructure requirements. But there is a necessity for more comprehensive analyses that consider multifaced impacts of EVs and short-term and long-term implications on the distribution grid. Moreover, broad analysis of EV impacts and mitigation strategies under different grid conditions have not been conducted [42]. Additionally, the integration of advanced charging strategies in grid infrastructure and EV adoption rates are often overlooked, necessitating more context-specific research. Addressing these gaps will help develop more effective strategies for managing the impacts of EVs on power distribution grids [34,43].

These technical aspects have been explored in this paper, which combines key findings from previous studies, providing a comprehensive overview of the impacts of EV charging on the distribution grid. Moreover, EV charging technologies, grid integration techniques, and the present status of different power requirements EV chargers are presented. This paper examines the effects of current charging technologies, their varied impacts, and both short-term and long-term implications and a perspective on the opportunities for providing grid services on a broader scale. Analyses of various strategies aimed to mitigate the negative impacts of EV charging are incorporated in this paper. Additionally, GFM inverter-based EV charging system is modelled to improve grid resilience and stability of the grid. Finally, this paper explores challenges and future trends aimed at understanding and addressing unresolved issues concerning the impacts of EV charging and the implementation of remedial measures. The key objectives of this article are given as follows.

- A review of the latest advancements in EV charging technologies and grid integration methods are presented to identify how EV charging systems are integrated into the power grid.
- Comprehensive analysis of various impacts on the distribution grid is conducted to understand obstacles of grid integration of high level of EV chargers.
- A detailed discussion on remedial measures is presented with the aim of understanding mitigation techniques to the negative impacts and providing insights into the sustainable integration of EV charging systems.
- The EV charging system with GFM inverter-based controller is designed that has a new feature of grid support capability to strengthen the grid during steady state and transient conditions.
- Challenges and future trends in integrating higher levels of EV chargers are addressed to ensure the smooth transition to a more sustainable EV adoption.

The remainder of this article is structured as follows. In Section II, presents the overview of EV charging technologies to identify power requirements, different charging/discharging methods, standards and advancements in EV charging technologies. Key aspects of Grid integration of EV charging systems are reviewed in Section III. Section IV presents the comprehensive analysis of EV impacts on distribution grid. Section V describes the remedial measures for EV impacts. Section VI includes the limitations, future work, and contribution to the field. EV charging system with GFM inverter-based controller is presented in Section VII. Finally, Section VIII summarizes the analysis and concludes this article.

2. Overview of EV charging technologies

EV charging technologies have undergone substantial advancements, offering various options to meet diverse requirements regarding charging speed, infrastructure, power capacities, and user convenience. The diverse range of EV charging techniques developed to various use cases, from slow, overnight home charging to rapid, high-power charging for long-distance travel. Each technology comes with its technical specifications, infrastructure requirements, and operational contexts, contributing to the overall feasibility and convenience of EV usage [44]. With the ongoing advancements in charging technologies, they will become increasingly pivotal in facilitating the shift towards sustainable transportation systems. This highlights the importance of continuous research, development, and investment in the necessary supporting infrastructure. EV charging topologies and power electronic converter solutions are broadly reviewed in Refs. [5,45,46]. Fig. 2 shows the classification of EVs which can be divided as hybrid vehicles and all electric vehicles based on the source of power they primarily rely on. Among them, plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs): and extended range electric vehicles (EREVs) employed with standard chargers to recharge their batteries by connecting to an external power grid [47]. BEVs are often referred to as EVs, relying exclusively on electricity stored in rechargeable batteries for propulsion. The onboard charger of BEV converts the AC power from the charging source into DC power suitable for charging the battery pack. The availability of charging infrastructure is essential for facilitating the widespread acceptance of EVs and their seamless integration into the power grid. EV charging infrastructure includes residential chargers, public charging stations, workplace charging, and fast-charging networks. These charging stations are connected to the grid through electrical distribution infrastructure, which delivers power from generation sources to charging points. Furthermore, charging infrastructure can be combined with RES like solar and wind power to offer environmentally friendly and sustainable charging alternatives [48,49]. Smart charging solutions allow EVs to charge during periods of high renewable energy generation, optimizing the utilization of clean energy and decreasing greenhouse gas emissions. V2G-enabled charging stations incorporate bidirectional power converters and communication systems to facilitate V2G operation and support grid services. Charging stations adhere to standardized protocols and communication standards, such as SAE J1772, CHAdeMO, and CCS, to ensure compatibility with EVs from different manufacturers. These protocols facilitate communication between charging stations, EVs, and grid operators, enabling data exchange and control functionalities.

2.1. Charging technology

EV charging technologies encompass a range of methods and standards for delivering electricity to charge the battery of an EV. From traditional wired charging to innovative wireless solutions, EV charging technologies are evolving rapidly to meet the diverse needs of EV drivers, improve charging efficiency, and support the transition to sustainable transportation. EV charging technologies can be categorized as shown in Fig. 3. Onboard chargers are integrated into the vehicle with charging capability for Level 1 (120 Vac) and Level 2 (240 Vac) charging [50]. It converts alternating current (AC) from an external power source into the direct current (DC) required to charge the EV battery through a charging cable and connector. Onboard chargers typically range in power from 1.4 kW to 19.2 kW and Level 2 chargers offer faster charging compared to Level 1. Dedicated chargers, integrated chargers, and

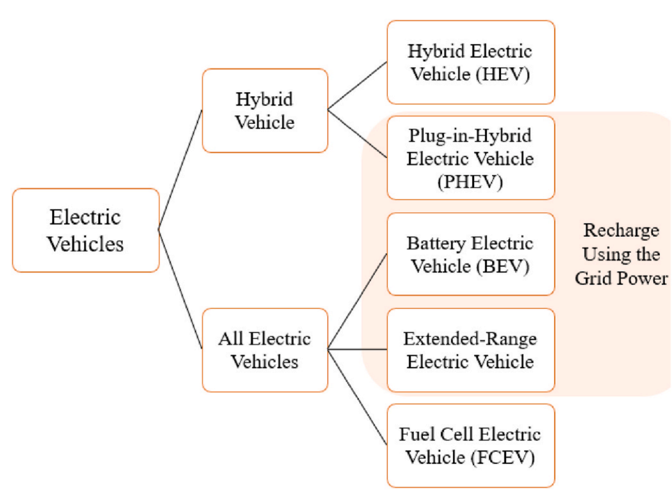


Fig. 2. Classification of electric vehicles.

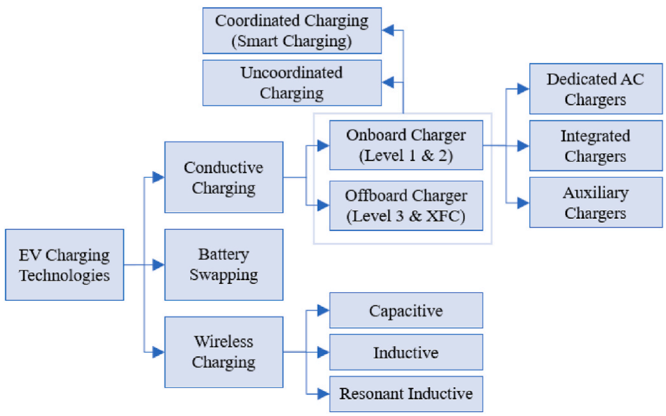


Fig. 3. Electric vehicle charging technologies.

auxiliary chargers are three primary types of onboard chargers. Offboard chargers are external charging units that provide direct current (DC) power directly to an EV battery, bypassing the onboard AC to DC conversion process. These chargers are designed for Level 3 (300–800 Vdc) and extreme-fast charging (XFC) (1000 Vdc) applications and are typically found in public charging stations and commercial environments [51]. DC fast chargers with 500 W power can charge a vehicle to 80 % capacity in around 30 min, making them suitable for long-distance travel. Advanced offboard chargers can be integrated with smart grid technologies to manage load distribution and optimize energy use.

Charging infrastructure for EV can be categorized into uncoordinated and coordinated charging. A comparison of uncoordinated and coordinated chargers is presented in Table 1. Uncoordinated charging refers to EVs charging without any central management or optimization. Each vehicle charges whenever it is plugged in, regardless of the current load on the power grid. Even though uncoordinated chargers have simple and flexible infrastructure, they can cause significant peaks in electricity demand during peak hours, grid instabilities and stress [52]. Coordinated charging requires employing advanced strategies and management systems to enhance the charging and discharging procedure of EVs. This approach ensures that EV charging is aligned with the grid's capacity, electricity demand, and the availability of renewable energy sources. Coordinated charging helps in reducing grid stress, lowering costs, and improving the overall efficiency of the power system [53–55].

2.2. Charging methods of EV batteries

EVs rely on sophisticated battery systems that require efficient and safe charging methods to ensure optimal performance and longevity. Several primary charging methods are used to manage the charging of EV batteries, each designed to address specific needs and characteristics of the battery. Various approaches for optimal placements of EV charging systems are widely examines in Ref. [17]. Main charge methods are constant current (CC), constant voltage (CV), constant power (CP) and constant current and constant voltage (CC-CV) charging [56]. Constant Current (CC) Charging supplies a consistent current, allowing the voltage to rise as the battery charges, which is ideal for quickly reaching a significant state of charge. CV Charging keeps the voltage steady while the current decreases as the battery charges, making it effective for the final stages of charging. CP Charging maintains a steady power level by dynamically adjusting voltage and current, optimizing both charging speed and efficiency. CC-CV charging is a common approach for charging rechargeable batteries [22]. This two-stage process combines the advantages of both CC and CV charging to optimize efficiency, safety, and battery health. Moreover, charging methods are trickle charging, float charging, pulse charging and taper

Table 1
Comparison of uncoordinated and coordinated chargers.

	Uncoordinated Chargers	Coordinated Chargers
Characteristics	• User-driven scheduling	• Use centralized management system to optimize charging rates and time based on real-time data from the grid
	• No grid communication with the power grid or other chargers	• Communication channels enable data exchange between EVs, other chargers and the grid
	• Simple infrastructure	• Demand response capability and ensure load balancing
	• Potential for high peak demand	• Smart grid integration
Advantages	• Simple and easy to implement with minimal technical requirements	• Reduce grid stress by shifting EV charging to off-peak time
	• Flexible and easy to use without restrictions	• Reduce overall energy cost by off-peak charging and integrating RES
	• Low initial cost	• Improves overall grid stability and reliability • Offer customer incentives • Reduces the need for costly grid upgrades • Enhances the integration of RES
Disadvantages	• Increase grid stress during peak times	• Complex and sophisticated control systems
	• Increase overall energy consumption and electricity costs	• Require grid upgrades due to increased EV loads
	• Potential for localized overloading	• High initial investment due to the requirement of smart components, RES integration and load management systems
	• Less efficient use of grid power	• Reduce flexibility
	• Requires grid upgrades to handle increased EV loads	• Requires data privacy and security measures to protect information
	• Difficulties in managing load balance and grid stability	

charging. Trickle charging is used to recharge a battery slowly and continuously at a low rate, typically at a rate of around 1 %–2 % of the battery's capacity per hour [55]. Therefore, trickle charging typically has a minimal impact on the power grid due to its low charging rate and steady power consumption.

The common charging profile of CC-CV mode in the Li-ion battery is shown in Fig. 4. The charging profile consists of three primary sections: pre-charge mode or trickle charge, CC mode and CV mode. The current is

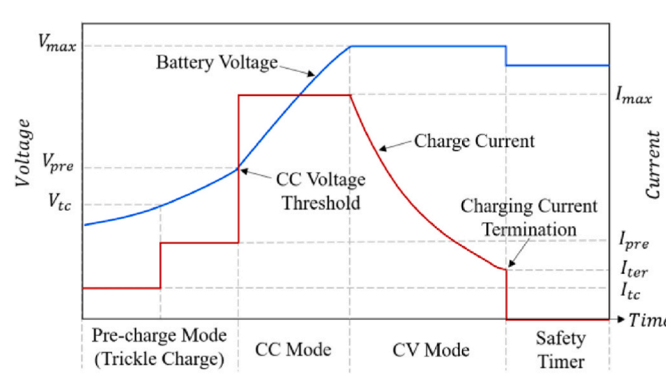


Fig. 4. Charging profile of CC-CV mode of EV battery pack.

incrementally raised until it reaches the pre-charge voltage (V_{pre}) during the pre-charge mode. The CC voltage threshold ensures proper power injection to the battery to avoid battery damage. The charger supplies a higher value of constant current to achieve an 80 % state of charge (SoC) during the CC mode. The battery charger switches to CV mode at the maximum set voltage (V_{max}). However, the battery voltage remains low due to internal impedance after reaching V_{max}. As a result, the charging current reduces as the internal voltage of the battery increases. Once the charge current reaches the predetermined termination value (I_{pre}), charging persists for a fixed duration before stopping. Charging is concluded with minimal impact on battery voltage, attributed to internal impedance.

However, charging EVs using various methods has different impacts on the power grid. Understanding these impacts is crucial for managing grid stability, ensuring efficient energy use, and preventing overloads. The high current demand at the beginning of the charging cycle in CC charging can cause significant load spikes if many vehicles start charging simultaneously, potentially leading to peak load issues [57]. As the battery voltage reaches its peak in CV charging, the current decreases and creates a variable load on the grid, which can be harder to predict and manage. Moreover, continuous adjustment of voltage and current can make real-time grid management more complex in CP charging mode [16]. High initial current demand of CC-CV charging mode can lead to peak load issues if many EVs start charging simultaneously and require real-time adjustments to grid supply due to variable current. Therefore, to mitigate the grid impact of EV charging, especially with methods like CC-CV and CP charging, several strategies can be employed. Employing smart grid technologies and infrastructure upgrades can help mitigate the challenges associated with widespread EV charging [58,59].

3. Grid integration of electric vehicles charging systems

The grid integration of EV charging systems is a critical aspect of modern energy management and grid infrastructure development. An optimal EV charging infrastructure typically comprises electrical infrastructure, control systems, communication networks, and standardized charging ports and connections. EV chargers can be broadly classified into AC chargers and DC chargers as shown in Fig. 5. Both types of chargers serve distinct roles in the EV ecosystem, offering different charging speeds based on the charging levels and technologies via power grid integration [6]. The unidirectional and bidirectional chargers play a distinct role in how EVs interact with the power grid, influencing factors like energy flow, grid stability, and overall efficiency. Unidirectional chargers allow electricity to flow in one direction from the grid-to-vehicle (G2V). They are relatively straightforward, focusing solely on transferring electricity from the G2V. Hence, unidirectional chargers are also suitable for areas with limited grid capacity with the primary goal of charging the vehicle rather than interacting with the grid.

Bidirectional chargers enable two-way energy flow, allowing electricity to move from the grid to the vehicle battery and vice versa. Additionally, bidirectional chargers with V2G operations can aid in balancing supply and demand, strengthen grid stability, and improve the utilization of RES [35]. The primary elements of a bidirectional charger include an inverter/converter, a bidirectional charger unit for managing electricity flow, and a communication interface for facilitating real-time data exchange and control among the EV, charging infrastructure, and grid operator. Moreover, control algorithms, data analytics and user interfaces are integrated to optimize G2V and V2G cycles based on the grid conditions and provide EV owners with real-time information and control over their charging and discharging activities.

EV chargers are integrated into the grid via isolated and non-isolated charging systems. The study in Ref. [46] discusses isolated and non-isolated charging systems and fast charging technologies comprehensively. Non-isolated chargers are directly connected between the grid and the EV battery system without any galvanic isolation. Therefore, they are generally more efficient because they eliminate the energy losses associated with the transformer found in isolated chargers. However, careful design is essential to manage safety risks in non-isolated chargers and protective measures such as insulation monitoring, fault detection, and robust control systems are crucial to ensure safe operation. Isolated chargers use a transformer to provide galvanic isolation between the grid side and the vehicle side, which helps to protect both the vehicle and the grid from electrical faults. Isolated chargers are more effective at reducing electromagnetic interference (EMI), which can potentially disrupt other electronic systems in both the vehicle and its surrounding environment [60].

4. Impacts of EVs charging systems on the distribution grid

The widespread adoption of EV charging systems poses challenges for grid operators, utilities, and policymakers. As the adoption of EVs accelerates, their charging requirements introduce new dynamics to the electrical grid, affecting load profiles, peak demand, and grid stability. Fig. 6 illustrates the impacts of EV charging systems on the power grid. The distribution and density of the EV load vary across common load curves and can fluctuate due to the variable nature of EV chargers, potentially leading to sharp increases in power demand. This surge in demand and intermittent nature of EV loads can strain local distribution networks, leading to grid congestion, voltage, and frequency fluctuations, necessitating upgrades to distribution infrastructure and control mechanisms. EV loads exhibit characteristics that differ from traditional loads, making it challenging to accurately estimate their power and

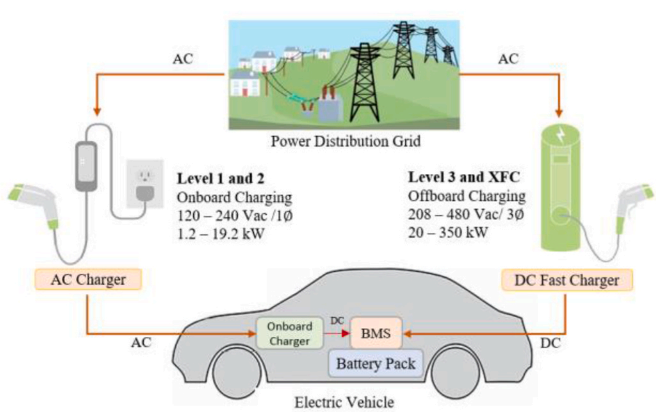


Fig. 5. Grid integration of EV charging system.

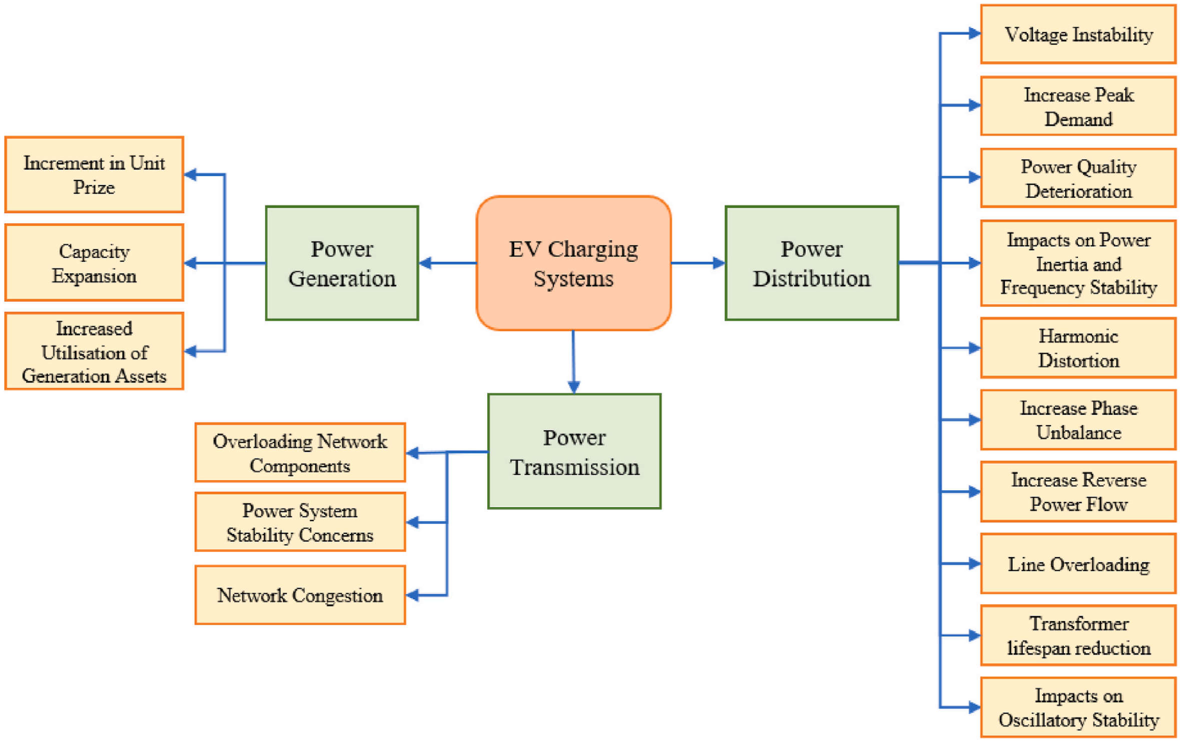


Fig. 6. Impacts of EV charging systems on the distribution grid.

energy demands. Many research studies demonstrate the negative impacts of EVs on the power grid on different perspectives such as power demand, voltage and frequency profiles, and system strength and reliability [19,36,61,62]. Additionally, while the integration of EVs with RES offers numerous benefits, it also presents some potential negative impacts and challenges that need to be addressed [52]. The intermittent of EV chargers and RES can present challenges to stability and reliability of the power grid, requiring sophisticated management, backup systems and significant investments are needed to develop and maintain the compatible infrastructure [63]. Therefore, understanding these impacts is crucial for ensuring grid stability, reliability, and efficiency.

4.1. Impacts on voltage stability

Voltage stability is fundamental to the safe, reliable, and efficient operation of the distribution grid in both steady-state and transient conditions [64]. Voltage instability due to the increasing penetration of EV charges is a multifaceted issue arising from high and variable EV load demand, localized overloading, voltage drops, unbalances and harmonic distortions. Sudden disruptions, fault occurrences, single or multiple contingencies, line overloading, stochastic nature of EV charging demand, rapid load variations, and interactions with DERs of high level of EV loads may result in power system voltage instability [65]. Voltage regulation issues primarily stem from uncoordinated charging events that cause excessive voltage deviations along distribution feeders, leading to undervoltage conditions, increased power losses, and excessive tap operations in voltage regulators and on-load tap changes. During peak demand periods, uncontrolled charging leads to a significant voltage drop, particularly in weak grids with high impedance lines, as increased power draw raises the feeder loading beyond its nominal capacity [48]. Conversely, V2G operations and high renewable energy penetration, such as solar PV, can introduce overvoltage issues due to reverse power flow, further complicating voltage stability [66]. The severity of these voltage deviations depends on factors such as grid strength, feeder impedance, and the spatial-temporal distribution of EV loads.

Therefore, grid voltage may exceed standard limits at the long feed terminals. Furthermore, EVs interface with LV distribution grids either as charging loads or as distributed generation (DG) sources when discharging. Uncontrolled and uncoordinated EV charging and discharging may elevate voltage imbalances in LV distribution grids, posing challenges to power quality, sustain grid stability and reliability [67,68]. Fig. 7 shows the relationship between the active power and voltage of a bus. Each bus has a critical voltage ($V_{critical}$) determined by the line resistance and reactance, which corresponds to the maximum active power (P_{max}) that can be drawn from the bus. Any additional load increase at the bus beyond this point will result in voltage failure [69]. The voltage sensitivity factor (VSF) is defined as the ratio of the change in voltage to the change in active power, which represents how sensitive the voltage at a bus is to variations in the active power load [70]. The VSF can be expressed as shown in (1).

$$VSF = \left|\frac{dV}{dP}\right| \forall P < P_{max} \tag{1}$$

Where, dV and dP the change in voltage and power transfer respectively. A high VSF indicates that even small changes in active power can cause a significant drop in voltage, and vice versa. To ensure system stability, bus voltages must be maintained within an acceptable limit, typically within 6 % of their nominal voltage [62,71].

Most EVs are expected to be recharged using single-phase private chargers, which could significantly disrupt the balance of the three phases. Because connecting several single-phase chargers to the different phases should be controlled separately as they have different charging times and profiles. Distributed generation (DG) systems, including EV charging systems, RES, and distribution network operators, are typically installed within LV distribution grids, closer to end-users, rather than the transmission grid. The unplanned installation and operation of EV charging stations at each node or bus contribute to a notable rise in network imbalance and uneven distribution of EV loads across the three phases. This imbalance can disrupt the stability of LV distribution systems [72,73]. Hence, the heightened capacity of DG systems can induce three-phase voltage imbalances within LV

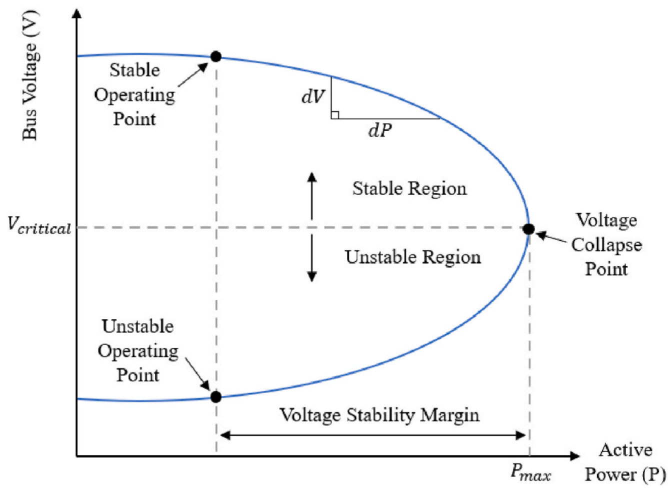


Fig. 7. Relationship between the active power and voltage (P-V Curve) of a load bus in the power system.

distribution grids when these systems are dispersed randomly among nodes [74,75]. Distribution network operators have shown minimum concern regarding system unbalancing due to the challenge of monitoring real-time EV loads [68].

As a result, prevailing voltage imbalances decrease the capacity of the distribution grid by elevating neutral current, increasing voltage drops, and reducing the utilization of network assets [76,77]. Some significant impacts of voltage instability and unbalance in a distribution grid include:

- Network congestion rises, hosting capacity of the network decreases, and power supply capability weakens during peak load periods.
- Node voltage reduction, increased harmonics generation, and interference with power-line communication.
- Unbalanced inductive loads can lead to unwanted pulsations, causing noise, vibration, and malfunction of protective components.
- Neutral lines need to be sized larger than usual to accommodate the overrated current flows resulting from system imbalance.
- Leads to higher distribution and transformer losses due to overheating, resulting in decreased overall efficiency and increased operation and maintenance costs.

During periods of low overall demand (e.g., late night or early morning), even a moderate amount of EV charging can cause overvoltage conditions if the grid is lightly loaded. There are several imbalance indicators that are used for analyzing in a voltage stability of the distribution network which can be explained as voltage unbalance factor (VUF), load balancing index (LBI), phase unbalance index (PUI) and neutral current [70]. The VUF quantifies the degree of voltage imbalance in a three-phase system. The VUF increases with an increased EV load and RES if they are uncoordinated between phases in a distribution grid [78,79]. The VUF can be calculated using the equation provided in (2).

$$VUF\,\% = \frac{\sqrt{\frac{(V_{max}-V_{min})^2}{V_{avg}^2}}}{\sqrt{3}} \times 100\,\% \tag{2}$$

where, V_{max} and V_{min} are maximum and minimum phase voltages, V_{avg} is average phase voltage. According to the standards the limit of the network VUF should be 2 % as well as controls the VUF to 1.3 % at the load point [80]. Moreover, symmetrical load power calculation is used to maintain rated voltage limits (±10 %) and EV chargers are developing to maintain the voltage stability by coordination each resources [81]. Increased penetration of EVs and uneven distribution of chargers across the three phases could result in VUF surpassing acceptable thresholds. Therefore, EV charging stations are required voltage control mechanism to predict line voltage variation range, maximum load level of lines to maintain voltage stability and mitigate voltage transient variations and system disruptions between EV and the power distribution grid [82]. The study in Ref. [71] is investigated the uncontrolled EV charging impacts on voltage deviation for BEV and PHEV. The analysis concludes that PHEV has a lesser impact on voltage drop due to their lower battery capacity, as well as Level 2 chargers exhibit higher voltage drop compared to Level 1 chargers.

Many research studies have explored the effects of EV charging on voltage instability, variation, and phase imbalances, suggesting different control strategies to mitigate these native effects [24,83]. In Ref. [84], examined the effect of uneven distribution of EVs across the three phases on voltage unbalance and study uncovered that the VUF reached its threshold at a 25 % EV penetration level. The study [79], the study investigated the effect of single-phase EV charging and discharging on voltage imbalances within the low-voltage distribution network. The results indicated that the VUF exceeded capacity limits in both charging and discharging modes due to the increased EV loads. Nevertheless, elevated levels of EV penetration can lead to significant voltage drops, potentially surpassing acceptable limits, particularly at the terminal of lengthy feeders [80].

To mitigate voltage regulation issues, Smart inverters with Volt-VAR and Volt-Watt control can provide localized reactive power support, reducing voltage fluctuations. Additionally, model predictive control (MPC) based smart charging strategies can dynamically regulate EV charging profiles based on real-time grid conditions, reducing peak demand-induced voltage fluctuations [26]. The integration of DERs, including solar PV and battery energy storage systems (BESS), can further support local voltage regulation by supplying active and reactive power during peak demand periods. Moreover, decentralized and peer-to-peer energy trading between EVs and DERs can balance local power demand and supply, reducing voltage variations [34]. Hybrid EV charging stations with integrated BESSs can buffer charging power, alleviating the impact on the grid by storing excess energy during low demand periods and supplying it during peak loads. Infrastructure reinforcements, such as upgrading distribution transformers, deploying static VAR compensators, and utilizing dynamic voltage restorers, can enhance voltage stability and mitigate deviations [70]. Furthermore, decentralized voltage control algorithms and adaptive droop-based strategies can provide real-time voltage regulation in microgrid configurations, ensuring a more resilient and stable power network. Active network management systems using real-time data from smart meters and phasor measurement units can enable adaptive voltage control, improving overall grid resilience. Through the implementation of these advanced control techniques, EV charging can be effectively managed to maintain voltage stability and ensure efficient grid operation, particularly in high-penetration scenarios [62].

4.1.1. Increase in phase unbalance

The phase unbalance issues arise from the uneven distribution of single-phase EV chargers across the three-phase power system commonly used in distribution networks. Moreover, charging patterns of EVs, especially during peak hours, can concentrate load on specific phases, leading to phase unbalance. Phase unbalance within a three-phase power system occurs when the voltages or currents in the three phases are unequal in magnitude or are displaced by more than 120° [68]. Therefore, connecting multiple single-phase chargers to different phases needs to be carefully managed, as they have varying charging times and profiles. The charging speeds of EVs may differ based on factors like battery capacity, charger capabilities, and the charging preferences of EV owners [85]. If there is a wide variation in charging rates among EVs connected to the same phase, it can contribute to phase imbalance. The phase unbalance due to higher EV integration can have several adverse effects on the power distribution grid such as voltage fluctuations, reduce equipment life, increased losses, reduce efficiency and exacerbate power quality issues [44]. Voltage unbalance can cause overvoltage or undervoltage conditions in certain phases, affecting the operation of connected equipment and potentially leading to equipment damage or malfunction. Additionally, unbalanced loading can lead to the presence of negative sequence currents, which can cause additional heating and vibration in induction motors and increase resistive losses in distribution lines and transformers [73]. Several solutions can be implemented to address phase unbalance in the grid including implement load-balancing techniques, smart charging strategies, install phase monitoring and voltage regulation devices and deploy DERs to offset unbalanced loads and reduce reliance on centralized generation.

4.1.2. Challenges on low voltage ride through (LVRT) and fault ride through (FRT) capability

Low voltage ride through (LVRT) and fault ride through (FRT) are critical capabilities for modern power systems, particularly as they integrate increasing amounts of IBR like solar panels, wind turbines and EVs. These capabilities ensure that power generators and other critical components can withstand and remain operational during voltage sags, faults, and other disturbances [86]. LVRT is the ability of power generation equipment to continue operating during short-term voltage dips. In the absence of EVs and RES equipped with LVRT capabilities, faults occurring at the transmission level could result in widespread voltage depression across regions and increased power loss on the generation side. These voltage dips can cause additional thermal and mechanical stress on electrical components and careful coordination is essential to avoid unnecessary tripping of generation units during faults [35]. The energy storage systems are utilized to mitigate intermittent nature of wind farms and solar PV as they have ability to support transients in DC bus as they can improve LVRT capabilities. The grid support ability during extreme voltage transients depends on technical and dynamic characteristics and grid connected loads. The voltage support capabilities of inverters rely on reactive power injection and the ability to distinguish between faulty and proper phases during FRT events characterized by unbalanced voltage sags [87].

FRT is the ability of power generation equipment to remain connected and operational during and after fault conditions. which is essential for maintaining grid stability and resilience. The factors influencing FRT include the shape and severity of the fault, the depth of the voltage dip, the location of the fault, the strength of the grid, the time taken to clear the fault, the state of active and reactive power prior to the fault, and the characteristics of the load. The grid codes are developed to stabilize the grid and consumer power quality, mainly include active power control and reactive power control [88–90]. As distributed generation becomes more prevalent, ensuring that all distributed resources have adequate FRT capabilities is a growing challenge. Moreover, maintaining system stability during and after fault conditions can be challenging, particularly in systems with high penetration of EVs, which can behave differently from traditional synchronous generators during faults. Generally, peak current limiter used after the reference current calculation to address FRT problems and various studies proposed three/four wire inverters [91,92]. Moreover, in Ref. [90] suggested an LCL filter circuits in between inverter and grid can enhance LVRT strategy and allowing current limitation under faulty requirements in the grid. Effective FRT requires robust communication and control systems to manage the response of various grid components during fault conditions. Developing advanced inverters with enhanced LVRT and FRT capabilities to ensure better performance during voltage sags and faults. Implementing GFM inverters that can provide stable voltage and frequency support even during disturbances.

4.1.3. Impacts of high dv/dt and di/dt due to fast switching of power devices

The power electronic devices with high switching speed have provided opportunity in achieve highly efficient, high density and high switching frequency performance with less copper losses and ripple output and switching losses [93]. However, these high switching frequencies increase the impacts of supported devices, which may produce overvoltage reflected transient on grid terminals, lowering the reliability and lifetime of electric components. The transient switching period or rate of voltage change over time (dv/dt) is used to indicate the rate of change in voltage control source affected by switching impact. The resultant high rate of voltage rise (dv/dt) critically effect for voltage failures and power insulation systems deterioration, degrade the efficiency and reliability [94,95]. Therefore, the transmission cable between the grid and the inverter causes to high voltage overshoot due to reflected signal phenomenon [96]. High dv/dt can lead to significant losses in capacitors due to equivalent series resistance and equivalent series inductance and reduce efficiency and lifespan of the inductors. Moreover, High dv/dt and di/dt can induce significant stress on the switching devices themselves, affecting their operation and longevity.

The voltage reflections could be occurred when the narrow PWM signals passing through the cable between grid and inverter due to pulse rise time of the inverter and the cable urge impedance [97]. Therefore, high reflections in voltage may be possible to overload grid terminals. An excessively sharp dv/dt rate may possibly produce false switching states or damage to power devices. The high dv/dt inverter outputs and surge impedance mismatch between grid and the inverter cable are causes overloading of the power network [98]. Furthermore, high dv/dt and di/dt can cause significant electromagnetic interference, affecting nearby electronic devices and communication systems due to the generation of high-frequency electromagnetic fields. High dv/dt and di/dt due to fast switching in EV charging systems can have a broad range of impacts, from EMI and insulation stress to component degradation and acoustic noise. The most conventional methods used to address these high dv/dt drawbacks are inverter output filters, inverter output reactors and transmission line termination filters. The gate drivers can be designed to handle high dv/dt and incorporating protective circuits to prevent false triggering.

4.2. Increase reverse power flow

EVs usually charge during off-peak periods when electricity demand is minimal and renewable energy production is at its peak. Consequently, excess energy may be sent back to the grid, causing reverse power flow in these situations. Power flow analysis is utilized to determine the operational status of a system under normal conditions and power flow calculation is integral to various aspects of system operation, including voltage and reactive power optimization [99]. state of the grid estimation, supply restoration and optimal configuration [100]. Therefore, power flow calculations can be used to identify instances of reverse power flow and critical nodes, and transmission lines are pinpointed where reverse power flow may have the most significant impact on system operation and stability. Reverse power flow occurs when the output of a distributed electric power plant exceeds the local demand, causing electricity to flow in the opposite direction from its usual path, often toward neighboring power networks [101,102]. When high level of EV integrated to the distribution, the local generation capacity may surpass the local demand, causing power to flow back towards the substation [103].

Therefore, many electric utilities must find efficient ways to maintain the stability of the distribution system as the current flows in the opposite direction. Reverse power flow is influenced by the real and reactive loads of the network relative to the generator outputs and any losses in the network. This shift in grid behaviour poses new challenges for utilities in determining how to plan, design, and operate distribution systems that were not originally intended for local generation applications [104]. Reverse power flow can take place for two primary reasons. Firstly, it occurs when the output of one or more distributed power stations surpasses the local load demand, when the local demand decreases to the point where the system experiences overgeneration, resulting in reverse power flow and potential voltage spikes [105]. Secondly, reverse power flow can be caused by abnormal behaviour in the protection system due to the injection of power from DG [100,106]. When massive EV loads causes high power levels and local load consumption is low, it can result in reverse power flow from LV to MV grids, potentially causing overvoltage conditions and stressing transformers [107]. The intermittency of EV loads and RESs can exacerbate this phenomenon, influencing the power system with voltage spikes. As a result, the sensitivity and different protection parameters are substantially influenced, leading to additional implications for power quality [102].

In worst case scenarios marked by high solar PV generation and low consumption at EV charging stations, power flow reverses in the feeder, breaching upper voltage limits. The high penetration of EV charging systems in the traditional unidirectional distribution system necessitates a shift to a bidirectional system, prompting a revision of regulations to accommodate this change. According to Ref. [108], shows that the reverse power flow primarily contributes to voltage rise in distribution feeders due to the high penetration of V2G operation and solar PV systems. It suggests that rapidly controlling the active power output of those systems can effectively mitigate the voltage rise issue in microgrids. Additionally, the most common technical impact of reverse power flow arises from the activation of network protection devices, which are typically designed to halt 'upstream' current flow exclusively. Also, voltage regulators may experience destabilization in their control systems because they are not designed to manage both forward and reverse power flow. There are no standardized solutions for preventing reverse power flow in MV grids. However, methods to regulate voltage in distribution grids typically involve two approaches: control algorithms and the deployment of intelligent devices [107].

4.3. Impacts on power quality and harmonic distortion

The introduction of EV chargers has led to a significant transformation in power consumption patterns. This shift is characterized by the addition of unsynchronized loads at multiple entry points and voltage levels across the distribution grid. EV chargers can demand hundreds of kilowatts of power, and the substantial energy needs of data centers, along with their associated equipment like heating, and air conditioning, contribute to unwanted voltage distortions, harmonics, and transient blackouts [109]. Abnormal behaviours on a power system arising in the form of voltage or current defines as power quality issues, mainly coming from energy production, and non-linear components [110]. The power electronic devices incorporate in the EV charging systems including controlled rectifiers, adjustable speed drives, inverters, converters, considered as major nonlinear loads in EV charger which could create a many power quality disruptions for the grid and the equipment [80]. Non-linear elements absorb non-sinusoidal current, leading to the emission of harmonic currents and these harmonic currents, in turn, generate harmonic voltages [111]. The harmonic voltages are depending on the network impedance at each frequency, exhibiting specific harmonic magnitude and phase values as well as their frequencies are multiples of the fundamental frequency. Harmonics in the voltage are mainly produced by current harmonics and create deviations in the voltage due to grid impedance affecting voltage drops across grid impedances, distorting voltage waveform.

The majority of power quality issues stem from deviations in voltage. Consequently, standards in the field of power quality primarily emphasize keeping the supply voltage within defined limits. Furthermore, many industrial applications not only introduce numerous unwanted harmonics into the grid but also contribute to voltage swells, dips, flickers, transient brownouts, transients and, exacerbating power quality issues. Power quality problems may lead premature failure of devices (capacitors, motors, cables, and transformers), reduce energy efficiency with increased heating and losses, trigger tripping of devices and can lead to charges from interconnected utility [24]. Different types of power quality parameters and requirements are shown in Table 2. Power electronic inverters used in grid-connected EV charging systems and RESs utilize phase-locked loop (PLL) technology to synchronize with the grid. However, this method is susceptible to power quality disturbances like unbalance and inter-harmonics. The main effect of harmonics on the power grid can be short-term effects (interfering with the equipment operation) or thermal effects such as heating and degradation components. Also, inter-harmonics occurring below the fundamental frequency have the potential to disrupt the electronic devices operation and result in additional grid power losses.

The power quality problems can be divided under different classifications as represented in standards. The transient and steady-state types of power quality problems [112]. The steady-state power quality challenges encompass load harmonic currents, long-duration voltage variations, unbalanced voltages, waveform distortions, notches, poor power factor, unbalanced load currents, DC offset, and excessive neutral current [58,113]. Oscillatory transients over voltages are frequently caused by high switching frequencies [114]. The most prevalent power quality issue is voltage sags, which can be produced by the utility or customer loads. The power quality impacts depending on the quantity of voltage, current, and frequency [115]. For the voltage related power quality impacts are over and under voltage, voltage distortions, unbalanced, noise, flicker, sag, notches, swell. Based on the current harmonics, unbalanced currents, excessive neutral current, distort the utility supply voltage and damage equipment are main considerations [116,117]. In general, charging system structure affects power quality impacts. The PFC and PWM control techniques used in onboard chargers are the generated less harmonics [117]. Moreover, DC charging station construct with 12-pulse diode rectifier produce low order harmonics [118]. Most of the studies employed PWM rectifiers, active power filters, and power PFC stages to mitigate power quality impacts of the EV charging stations [119–121].

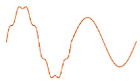
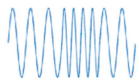
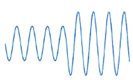
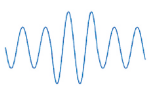
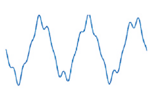
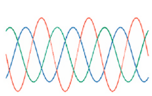
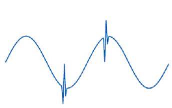
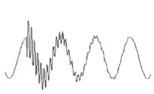
Compared to fundamental frequency, the increase in high frequency elements of voltage and current is described as harmonics mainly coming from energy production, and non-linear components [110]. The power electronic devices like controlled rectifiers, adjustable speed drives, inverters, converters, considered as major nonlinear loads which could create a many disruptions for the grid and the equipment [80]. Non-linear elements absorb non-sinusoidal current, emitting harmonic currents, which in turn generate harmonic voltages. The characteristics of these harmonic voltages are contingent upon the network impedance at each frequency, with distinct harmonic magnitude and phase values. Harmonics in the voltage are mainly produced by current harmonics and create deviations in the voltage due to grid impedance affecting voltage drops across grid impedances, distorting voltage waveform [111]. The positive sequence reactive power is critical to control fundamental voltage, electromechanical stability, power losses [122]. A crucial aspect and challenge in establishing power quality requirements for distributed energy resources meets in their reliance on frequency response and the relative capacity at the point of common coupling (PCC).

High EV loads in the power system will make LV feeder loading prediction more difficult, and the power quality issues become increasingly evident. These issues become more pronounced, manifesting as unbalanced currents, poor power factor, excessive neutral current, and harmonic currents [112,123]. Harmonics are comprised of sinusoidal voltages or currents with frequencies that are multiples of the fundamental frequency of operation in the supply system. According to the Fourier theorem, all non-sinusoidal periodic functions, where the h is harmonic order usually preferred as hth and periodic function y(t) of harmonic expansion can be evaluated using (3).

$$y(t) = Y_0 + \sum_{h=1}^{h=\infty} Y_h \sqrt{2}\sin(h\omega t - \varphi_h) \tag{3}$$

Where: Y_0 is DC component value, Y_h is harmonic of order h (rms

Table 2
Various power quality impacts [124–127].

Power Quality Impacts	Waveform	Causes	Effects	Solutions
Harmonic distortion		• Steady-state variation due to increase EV loads during peak demand • Non-linear loads of EV chargers • Distortion of the normal waveform	• Power quality degradation • Increased losses resonant issues • Overheating and equipment stress • and reduce life span and efficiency • Increase power losses, signal distortion and communication errors • Reduce efficiency and longevity of EV battery chargers	• Integrate active/passive harmonic filters, power factor correction devices • Design transformers to handle higher harmonic loads
Frequency Deviations		• Simultaneous charging of large number of EVs • Sudden disconnections of large EV loads and intermittent power generation (V2G and RES) • Uncoordinated charging patterns • Lack of smart charging infrastructures	• Voltage fluctuations, impacting stability and power quality • Increase mechanical stress on generators and leading to potential failures • Pose synchronization issues and affect overall grid stability • Grid protection systems malfunction	• Implement g frequency regulation services • Utilize real-time monitoring and control systems • Upgrade grid infrastructure • Employing V2G technology and smart chargers
Under voltage/ Overvoltage	 (Voltage at the load drops below or rises above nominal voltage limits for longer than a minute)	• Simultaneous charging and steady-state variation of EV loads • Decrease or increase line voltage for extended period of time • System overload, faults, and overcompensation • Load variation and sudden voltage drops of EV charges	• Lead to load imbalance and instability in the grid • Damage sensitive electronics shorten lives of grid components • Insulation breakdown in transformers and cables • Decrease charging process of EVs, poses a risk to onboard charging equipment, BMS and battery health	• Implement smart chargers to adjust charging rates based on grid voltage conditions • Enable V2G operation to discharge energy during high demand or overvoltage • Deploying advanced voltage regulation devices, ESS, and DERs • Incorporate real time monitoring systems and automated control devices
Voltage sag/ swells	 (Voltage drops below or exceeds nominal voltage for a short duration)	• High instantaneous EV demand • Fast charging stations • RMS disturbances and short term low and high voltage variations • Inadequate grid infrastructure to manage additional Ev loads • Adoption of additional EV load to long distribution lines with higher impedance. • Uncoordinated Charging Patterns	• Cause localized overvoltage due to the reverse power flow • Local generation exceeds power consumption • Failures and shut down grid components • System halts and data losses • Equipment damages and reduces life • Lead to longer charging times and pose malfunction in charging process	
Voltage flickers		• Multiple EVs begin charging at the same time • High power consumption of fast chargers • Uncontrolled rapid and unpredictable changes in EV load • Insufficient grid capacity and steady-state variation	• Malfunction, restart or unexpected shutdown of sensitive equipment • Increase frequent maintenance and shorter operational lifespans of grid components • Challenge for grid operators and lead to overall instability in the grid	• Implement smart chargers to adjust charging rates and times. • Coordinate EV charging times to avoid simultaneous high demand • Integrate static VAR systems, energy storage systems to buffer load changes
Unbalance		• Uneven distribution of EV charging loads (single phase EV loads) • Diverse charging behaviors and charging patterns and rates • Inadequate design or installation of charging infrastructure • Intermittent generation of Ev and RES	• Increase losses, voltage instability • Equipment damage and inefficiency • Reduce power quality and affecting the performance of electrical equipment • Cause to grid instability and frequency variations • Lead system malfunctions and grid operational challenges	• Implement load-balancing techniques, phase monitoring devices and smart charging systems • Upgrade transformers, and strengthen distribution lines to withstand increased stress from unbalanced loads
Transient	 Impulsive transient  Oscillatory transient	• Sudden changes in current drawing due to the witching events of various charging sessions • Unidirectional power variation of distribution system • Magnify high impedance sections of the distribution grid by EV charging • Charging equipment (rectifiers, converters) introduces harmonic currents and voltage distortions • Resonant effects of EV chargers and the distribution network • Improper grounding or lack of proper grounding in EV charging infrastructure	• Introduce harmonic distortions in the grid reduce equipment reliability and subject distribution transformers to sudden changes in load • Damage internal circuits and regulators • Equipment malfunction and damage • High level disturbances may shut down or damage equipment • Introduce voltage flickers, destabilizing the grid and impacting connected loads. • Result in frequency variations, affecting the grid synchronization and grid instability • Increase the risk of premature failure of circuit breakers • Line/cable switching • switching of power factor correction capacitors, or transformer ferro resonance	• Deploy advanced monitoring systems to detect transient events in real-time • Upgrade distribution infrastructure with transformers, switchgears, transient filters, damping devices, surge arresters • Implement smart charging algorithms • Implement dynamic response capabilities to adapt charging behavior based transient events

which should not surpass specified limits as outlined in Ref. [113]. TRD can be calculated using the (7) below.

value), ω is angular frequency, φ_h is harmonic component displacement at t = 0. Total harmonic distortion (THD) is a measure of the non-sinusoidal properties of a waveform and can indicate the level of distortion in voltage and current waveforms [80]. The total current and voltage harmonic distortion (THD_i& THD_v) can be calculated as below. For signal Y, the THD is described as: Where, Y_1 is fundamental component.

$$\%THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} {Y_h}^2}}{Y_1} \times 100\% \tag{4}$$

$$\%THD_i = \frac{\sqrt{\sum_{h=2}^{h_{max}} {I_h}^2}}{I_1} \times 100\% \tag{5}$$

$$\%THD_v = \frac{\sqrt{\sum_{h=2}^{h_{max}} {V_h}^2}}{V_1} \times 100\% \tag{6}$$

Where, I_h, V_h = the current and voltage hth harmonic component (rms value). I_1, V_1 = main frequency current and voltage component (rms value) respectively. Current distortion is constrained by harmonic current distortion and total rated-current distortion (TRD) at the reference point of applicability,

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{\text{rated}}} \times 100\% \tag{7}$$

Where, I_{rated} is rated current capacity of DER and I_{rms} is rms value of DER current. High THD levels can have several impacts including increased equipment overheating due to the presence of harmonic currents, reduce overall grid efficiency, malfunction or mis operation of sensitive electronic devices and lead to voltage distortion, causing fluctuations in voltage levels [35]. To mitigate these detrimental effects, proactive measures such as the installation of harmonic filters, voltage regulation equipment, and meticulous system design are imperative to uphold the integrity and functionality of electrical systems amidst elevated THD levels.

To mitigate these power quality challenges, several strategies can be implemented. Harmonic filtering techniques, including LCL filters in EV chargers and active power filters at substations, can significantly reduce high-order harmonics and ensure compliance with IEEE 519 and IEC 61000 power quality standards [53]. The adoption of multi-level inverters, such as three-level neutral point clamped inverters controlled with MPC, provides a better sinusoidal waveform, reducing THD and improving overall power quality. Phase balancing strategies, such as dynamic phase-switching algorithms and the adoption of three-phase charging infrastructure, help mitigate unbalanced loading effects. Smart charging algorithms, including MPC-based real-time control, can smooth power fluctuations by dynamically adjusting charging rates based on grid conditions, reducing voltage flicker [66]. Energy storage integration, particularly hybrid EV charging stations with BESS, can act as buffers, absorbing charging power variations and minimizing transients. Soft switching techniques in power converters can reduce EMI emissions and improve power quality. Additionally, grid reinforcement measures, such as upgrading feeder lines and deploying Static VAR compensators and Static synchronous compensators, can enhance voltage stability and reactive power control [24]. Advanced monitoring using phasor measurement units and real-time power quality assessment through Smart Grid Infrastructure can help identify and mitigate disturbances proactively. By integrating these advanced control strategies, filtering techniques, and infrastructure reinforcements, power quality issues associated with high EV penetration can be effectively managed, ensuring a stable and efficient power grid [117].

4.4. Impacts on frequency stability and power systems inertia

Frequency stability and power system inertia are crucial for maintaining reliable and stable power distribution grids. Frequency stability ensures that the grid operates at its designated frequency (e.g., 50 Hz or 60 Hz), balancing power supply and demand to prevent issues like equipment malfunction or grid instability. Inertia is provided primarily by the rotating masses of synchronous generators (SGs), acting as a buffer against sudden frequency changes by absorbing or releasing kinetic energy without the need for active control. Inertia slows the rate of frequency change, giving time for secondary control mechanisms to respond and restore balance [128]. This is crucial for preventing rapid frequency deviations that could lead to instability or even a blackout and help to smooth out the rate of change of frequency (RoCoF), providing time for slower control systems to react and restore balance. With lower inertia, the power system becomes more susceptible to instability. Disturbances that would have been easily absorbed by a high-inertia system can cause significant frequency excursions, potentially leading to blackouts or other stability issues [60].

The integration of high level of EV charging systems and RES introduces new challenges to frequency stability. Inverter-based resources (IBR) are commonly linked to the grid through power electronic inverters, which inherently lack inertia. As the penetration of IBR increases, the traditional inertia provided by synchronous generators decreases, leading to a lower overall system inertia [129]. The reduction in inertia makes the grid more susceptible to rapid frequency changes and requires faster and more precise control mechanisms to maintain stability. The RoCoF is heavily influenced by the power grid conditions before a contingency event. Limiting RoCoF can extend the time it takes for the frequency to deviate from its normal operating range. To reduce RoCoF before a contingency event, different strategies can be implemented to increase system inertia including reducing load consumption, decreasing generation output, or limiting interconnector power flow [130]. A high level of RoCoF required a faster correction of the imbalance between supply and demand and the correction timeframes must be faster than the rise or lower services which is termed fast frequency response [131].

The higher integration of EV charging has required significant changes in dynamic characteristics of exiting power systems particularly non-synchronous power electronic based resources, which do not contribute system inertia. As the high penetration of RESs on the power grid drastically decreases inertia with increased RoCoF of the power system, particularly during low load conditions [132,133]. Decreasing system inertia could increase system frequency fluctuations, which leads to system performances deterioration and instability. The RoCoF after a contingency increase as system inertia declines. The power system dynamic challengers of frequency instability and power grid security are:

- Low or non-inertial responses in RES resulting in frequency instability.
- System frequency deviates from fundamental frequency in the event of a malfunction and a sudden load change.

In the event of a malfunction or sudden load change, which causes the load-shedding controller to trigger the frequency relay, the RoCoF and frequency nadir required to be higher. The critical inertia conditions could be reduced by controlling size of the critical contingency, over and underload frequency settings, load resources response characteristics and providing responsive reserve service by using sensitivity inertia parameters.

The system inertia defines the initial frequency decline rate after an unexpected imbalance in power supply and demand. After a contingency event, such as the loss of a generator or a sudden increase in load, the RoCoF typically increases due to a decrease in the inertia of the power network. Under steady-state operation, electromagnetic torque (T_e) which is equivalent to the operating mechanical torque of generator

(T_m) while losses neglected [134]. In the event of a disturbance, an imbalance can arise between the two opposing torques of T_m and T_e. When the rotor net torque is not zero, it can lead to either deceleration ($T_m < T_e$) or acceleration ($T_m > T_e$). This can be calculated using the swing equation as shown below (8).

$$T_a = T_m - T_e \tag{8}$$

Where, T_m is driving mechanical torque (Nm) and T_e is electromagnetic torque (Nm). According to Newton's rotating masses equation, the rate of change of rotational speed is completely linked to the rotor torque balance when neglecting damping torques and friction as shown below (9):

$$T_a = T_m - T_e = J\frac{d^2\delta_m}{dt^2} \tag{9}$$

Where, P_m - Mechanical power (W), P_e = Electrical power (W), δ_m = Rotating position (rad). The power is equal to angular velocity time torque, above equation in terms of power can be calculated, which is shown as (10).

$$P_m - P_e = \omega_m T_m - \omega_m T_e = J\omega_m\frac{d^2\delta_m}{dt^2} \tag{10}$$

Where, P_m = Mechanical power, P_e = Electrical Power, ω_m = Angular velocity (rad/s). Traditional power systems are connected to SGs, which can utilize stored energy in their rapidly spinning heavy rotors. The kinetic energy of these rotating masses can be described using (11).

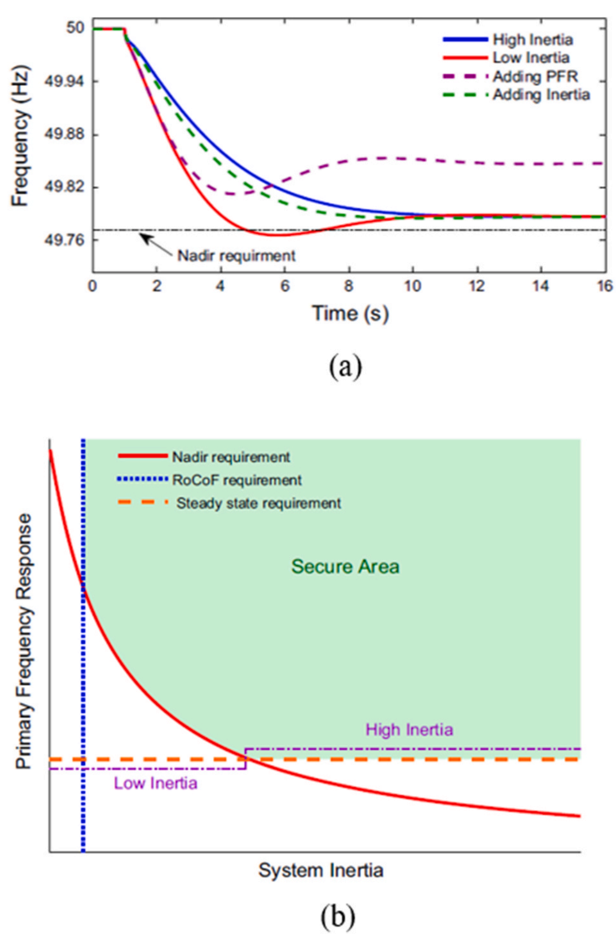


Fig. 8. Effects of inertia variations on system frequency performance and requirements (a) Effect of lower and higher inertia, (b) Frequency response requirement [135,136].

$$E_{KE} = \frac{1}{2}J\omega_m^2 = \frac{1}{2}M\omega_m \tag{11}$$

Where, M = $J\omega_m$ is inertia constant, represents the angular momentum of the rotor, E_{KE} is kinetic energy of the rotor (MJ), J is moment of inertia of the rotor ($kg\,m^2$). The system inertia constant or per unit inertia constant (H) can be calculated as shown in (12).

$$H = \frac{\text{Kinetic Energy (MJ)}}{Machine\ Rating\ (MVA)} = \frac{E_{KE}}{S} = \frac{J\omega_r^2}{2S} \tag{12}$$

Where, H is inertia constant (pu) and S is base power (MVA). A higher inertia constant implies more stored kinetic energy, which translates to slower frequency deviations during disturbances and tends to have better damping of oscillations and are more resilient to disturbances. The correlation between RoCoF and inertia constant can be represented by the following (13).

$$\frac{d\omega_m}{dt} = \frac{(P_m - P_e)\,\omega_m}{2HS} \tag{13}$$

The development of virtual inertia control techniques for virtual synchronous generators (VSG) is based on (11). Enhancing the rotational inertia level of the system can help alleviate power imbalances in the RoCoF by employing frequency deviation-based control and fast reserves with RoCoF-based control.

Fig. 8(a) shows the effects of low and high inertia response of the power grid. A system with high inertia will exhibit slower frequency changes in response to disturbances compared to a system with low inertia. The nadir refers to the lowest point reached by the frequency during a disturbance, which is the acceptable nadir limits for frequency deviations. These limits ensure the stability and reliability of the power system and the threshold below which the frequency should not drop. Power frequency response (PFR) refers to the ability of power plants and grid-connected resources to provide rapid adjustments to generation or consumption in response to frequency deviations. With PFR, the frequency response following a disturbance is faster, resulting in a shallower nadir and quicker recovery to the nominal frequency [60]. Fig. 8 (b) depicting frequency response requirements, steady-state requirement line, indicating the desired frequency deviation from the nominal frequency during normal operating conditions. The secure area on the graph represents the region where the system remains stable under various operating conditions.

EV charging, especially fast charging, increases the demand for the electrical grid, leading to a reduction in the overall system inertia. As system inertia decreases due to EV charging, the rate of change of frequency (RoCoF) increases. This means that frequency deviations occur more rapidly in response to changes in power generation or consumption. Rapid RoCoF can lead to instability and grid disruptions if not properly managed. Moreover, grid operators rely on various frequency regulation mechanisms to maintain grid stability. However, the integration of EV charging introduces additional challenges for frequency regulation. The fluctuating power demand from EVs requires more frequent and responsive adjustments to generation and grid control devices to counteract frequency deviations.

The study in Ref. [137] explores the potential of EVs to offer frequency regulation support through both G2V and V2G modes. This investigation tackles issues such as EV aggregation, assessing net load uncertainty, and modeling post-fault frequency dynamics within a stochastic security-constrained scheduling framework. Investigation of how the inertia supplied by grid-tied converters in EVs affects frequency regulation performance is conducted in Ref. [138] with the aim of explores scenarios where SGs are substituted with fast-response variable synchronous machines (VSMs) to assess the impact on frequency control capabilities. The study [135] provides a review of solutions and technologies aimed at compensating for reductions in system inertia including synchronous inertia and emulated inertia utilizing fast-acting reserve. To address the impacts of EV charging on power system inertia and frequency stability, grid-integrated solutions are essential. This may include the deployment of advanced grid control technologies, such as smart charging algorithms, DR programs, and grid-connected energy storage systems [139]. These solutions help mitigate the effects of EV charging on grid dynamics and ensure the reliable operation of the electrical grid.

4.5. Increase peak demand and load profile

The introduction of EV chargers influences the overall electricity demand and the shape of the demand curve, impacting electric power generation and transmission infrastructure [140]. The increasing demand for power, particularly due to the charging of electric vehicles (EVs), leads to higher flowing currents within the power distribution network. This surge in current not only places additional stress on the system but also compromises its smooth operation [141]. The heightened currents contribute to increased power losses across various components of the network, including generators, transformers, and transmission cables. For utilities, this presents a significant concern, as it impacts the overall efficiency and reliability of the grid [70]. The escalation of peak demand in power systems can have a range of impacts, extending beyond immediate operational challenges. Higher peak demand necessitates the operation of existing infrastructure at or near its maximum capacity, leading to accelerated deterioration. This strain can result in increased maintenance requirements, shorter equipment lifespans, and the need for costly upgrades or expansions to accommodate the heightened demand [142].

Several studies have explored the impact of EV charging on the increase in peak demand, load profile and losses in devices [6,143]. Studies in Refs. [34,144] examined the effects of uncontrolled EV charging on distribution systems showed uncontrolled charging led to significant rises in energy losses and necessitated investment costs due to increased peak demand. Rapid charging of residential EVs leads to a substantial rise in household electricity consumption, potentially surpassing the maximum power capacity of the distribution system. This situation is exacerbated during periods of high electricity demand, such as peak hours or extreme weather events [145]. High-power charging of EVs can significantly elevate electricity loads at the regional level and introduce new peak demand periods. Charging stations offering up to 350 kW each are commonly installed in clusters, collectively representing substantial connections exceeding 1 MW in size [146]. The case study in Ref. [145] demonstrates the behavior of residential EV charging on the power grid, along with mitigation techniques aimed at reducing the increase in peak demand.

When considering the entire system, the effect on peak demand from EVs is anticipated to be less significant compared to local impacts. This is due to diverse charging behaviors among EV owners, such as charging at work or home overnight, using fast-charging stations, or charging fleet vehicles during the day [140]. When these varied load profiles are aggregated, an overall increase in peak demand could be around 15 % if charging times are unmanaged [147]. Fluctuations in load profile, especially during peak periods, can lead to voltage instability within the distribution network. This instability may manifest as voltage sags or spikes, adversely affecting the performance and lifespan of connected electrical equipment, such as motors, appliances, and sensitive electronic devices. Overloaded equipment and stressed infrastructure are more susceptible to failures and outages, posing reliability concerns for both utilities and consumers [52,62]. Increased peak demand heightens the risk of service interruptions, which can disrupt operations, inconvenience customers, and potentially result in economic losses. Higher peak demand intensifies the need for DR initiatives aimed at reducing or shifting electricity consumption during peak periods. However, achieving meaningful DR participation may be challenging, requiring effective communication, incentives, and behavioral changes among consumers.

EV charging loads typically exhibit low load factors (f_{Load}), particularly for unmanaged high-power public DC fast charging. A low load factor implies inefficient utilization of electric power, a characteristic that can be determined from the load profile of the specific load or system can be shown as (14).

$$f_{Load} = \frac{Average\ Load}{Maximum\ load\ in\ given\ time\ period} \tag{14}$$

A low load factor in EV charging indicates occasional spikes in demand, leading to idle capacity and higher costs. Load balancing or peak shaving aims to address this by optimizing usage. The demand factor represents the relationship between the maximum peak demand and the maximum capacity available as shown in (15).

$$f_{Demand} = \frac{Maximum\ load\ in\ given\ time\ period}{Maximum\ possible\ load} \tag{15}$$

A low demand factor may indicate the need for additional charging infrastructure to accommodate growing EV adoption, while a high demand factor suggests efficient utilization of existing infrastructure.

4.6. Impacts on power System strength

Power system strength refers to the ability of an electrical power system to withstand and recover from disturbances, maintain stable operation, and deliver reliable electricity to consumers. It encompasses various factors such as voltage and frequency stability, grid resilience, capacity to handle load fluctuations, and ability to maintain power quality standards. However, the integration of IBR such as EV charging systems, RES, and energy storage Systems (ESS) into the power grid can indeed impact the overall strength. High EV loads can lead to voltage and frequency fluctuations and weaken the system strength in the power system, especially during peak charging periods [148,149]. This can result in voltage sags or surges, which may affect the operation of sensitive electrical equipment and disrupt power quality. Moreover, rapid changes in load, such as those caused by simultaneous EV charging, can lead to frequency deviations, potentially impacting the synchronization of generators and overall system stability.

High EV loads can exacerbate grid congestion, particularly in distribution networks with limited capacity and result in voltage violations, thermal overloads, and increased line losses, reducing the reliability and efficiency of the power system. The concentrated charging of EVs in specific areas can overload distribution transformers, leading to equipment failure, increased maintenance costs, and potential outages [150]. High EV loads may require additional investment in voltage regulation equipment, such as voltage regulators and capacitor banks, to maintain voltage within acceptable limits and ensure reliable operation of the power system. IBRs may disconnect or reduce output during faults, leading to voltage collapse or other system disturbances and increased vulnerability to faults, potentially leading to cascading failures and system-wide outages. The robustness of the power grid against disturbances and contingencies may be compromised with a higher penetration of IBRs, which is particularly true in systems with limited inertia and fast-reacting components [22].

Analyzing power system strength involves assessing various aspects of the electrical grid's ability to maintain stability, reliability, and resilience in the face of disturbances or changes in operating conditions. Power system strength can be analyzed using voltage stability, transient stability, frequency response load flow analysis and dynamic simulation. Various methodologies have been implemented in previous papers to analyze impacts of EV loads on power systems strength [124,127,151]. Probabilistic load flow analysis used to assess the impact of EV loads on distribution systems, considering factors like charging behaviors, power constraints, and randomness in solar PV generation in Ref. [152]. The experimental assessments method is conducted in Ref. [153] to validate models of power system response to EV loads, particularly focusing on changes in power levels and harmonic current distortion. Comparative assessments analyze the effects of EV operation against performance indicators, evaluating influences such as the charging process's impact on distribution network problems, load demand, losses, and voltage drop [154]. Understanding and addressing these impacts are essential for ensuring the reliability, resilience, and efficient operation of the distribution grid in the context of increasing EV adoption. Efforts towards grid modernization, advanced control algorithms, and smart charging solutions are crucial for mitigating these challenges and facilitating the seamless integration of EVs into the distribution grid.

4.7. Power losses and impacts of distribution components

The high demand for energy from EVs needs a significant amount of electricity to be distributed to the distribution networks from the generating stations. The introduction of new EV loads causes distribution network equipment, such as transformers and cables, to become overloaded. This increased stress on these components reduces their lifespan and necessitates grid infrastructure upgrades [155]. EV charging demands high power, causing increased current through distribution lines. Thus, as the current increases, the losses in the distribution lines increase quadratically. Because power losses are proportional to the square of the current (I^2R losses). Moreover, EV charging, especially during peak hours, significantly amplifies peak loads. This can lead to overloading of distribution transformers and other components, exacerbating power losses and potentially causing overheating and failures [37,73].

In [144], examined the effects of unregulated EV charging on large distribution systems across various penetration levels. The results emphasis, uncontrolled charging led to a significant increase in energy losses and implementing delayed or controlled charging strategies reduced both losses and investment costs. In Ref. [62], the rise in power losses within the IEEE 33-bus distribution system resulting from EV fast charging stations was assessed through different scenarios, which involved modifying the charging station bus and its power consumption. The results indicated that placing charging stations at vulnerable buses (i.e., those distant from the primary transformer) notably elevated system power losses.

High loading conditions due to EV charging increase both copper losses and core losses in transformers, leading to decreased efficiency and potential overheating, which can shorten transformer lifespan [6]. Moreover, increased current flow can cause significant thermal stress, leading to overheating conductors, transformers, and switchgear. Prolonged exposure to high temperatures degrades insulation materials, increasing the risk of faults and reducing the lifespan of these components [156]. Frequent and rapid load fluctuations due to EV charging induce mechanical stress on distribution components, such as switches and relays, leading to accelerated wear and tear and higher maintenance requirements [153].

Thermal overloading due to high EV loads can significantly affect grid components and over time, elevated temperatures degrade the insulation material around conductors. This can lead to insulation failure, short circuits, and potentially dangerous electrical faults. Thermal expansion due to overheating can cause overhead lines to sag, which may result in clearance violations and increase the risk of short circuits, especially during high-demand periods. Higher loading also increases core losses, contributing further to the thermal stress on transformers and the insulation of oil and materials within transformers degrade faster at higher temperatures. This reduces the transformer's dielectric strength and can lead to failures [37,60]. Therefore, Prolonged exposure to high temperatures accelerates the aging process of transformers, significantly reducing their operational lifespan and necessitating more frequent replacements [67,157].

Additionally, switchgear and circuit breakers experience increased thermal stress with higher current flows, which can lead to overheating and impair the performance of circuit breakers, affecting their ability to interrupt fault currents effectively. High current flows through busbars cause them to overheat, which can lead to thermal expansion and increased resistance, further escalating the heat generation [158]. These challenges can lead to insulation degradation, reduced lifespan of components, increased maintenance costs, and reduced system reliability. Addressing these impacts requires strategic upgrades, enhanced cooling, effective load management, and continuous monitoring [159,160].

4.8. Impacts on oscillatory stability

Oscillatory stability focuses on the response of the power system to small disturbances that do not significantly alter the system's operating point. Oscillatory stability in a power system typically refers to the ability of SG within the grid to remain in sync after a disturbance. This involves each synchronous machine's capacity to maintain or restore the balance between electromagnetic torque and mechanical torque [161]. A power system with good oscillatory stability will have well-damped oscillations, meaning the amplitude of oscillations will decrease over time and the system will return to a steady state. Poor damping can lead to sustained or growing oscillations, potentially causing system instability, or even leading to power outages. EVs loads, especially when charging rapidly, can exhibit dynamic behavior, contributing to oscillations in the power system. Moreover, the use of power electronic converters in EV chargers introduces non-linear characteristics and can affect the system's oscillatory modes. The addition of high EV loads increases the overall demand of the power system, leading to higher loading of transmission and distribution lines. Increased loading can stress generators, particularly those with lower reserve margins, potentially reducing their ability to provide adequate damping [162].

Additionally, uncoordinated EVs charges can lead to sudden spikes in demand, triggering oscillations and these high peak demand periods can stress the grid, reducing its ability to damp oscillations effectively. High EV loads, particularly with fast chargers, can inject harmonics into the system, which can interfere with control systems and exacerbate oscillations [163]. Also, uncertainties surrounding EV charger connection points, charging duration, and the timing of charging and discharging present challenges in accurately predicting the behaviors of this emerging load. Therefore, RES and EVs together can cause voltage fluctuations, influencing the damping of oscillations [164]. Oscillations in power systems can be categorized into various modes based on their characteristics and causes [163].

- Local Modes: These oscillations occur within specific localized areas of the power system and are typically associated with the dynamics of individual generators, transmission lines, or loads.
- Voltage Modes: characterized by fluctuations in voltage magnitude and phase angle across different nodes or buses in the power system due to the changes in load demand, reactive power exchange, and voltage control actions.
- Interarea Modes: involve oscillatory behaviour between different areas or regions of the power system, often characterized by the exchange of power and energy between interconnected subsystems.
- Control Modes: refer to oscillations that arise due to the action of control systems and devices within the power system.

The analysis in Ref. [162], concluded that the anticipated extensive integration of EVs into the power grid would affect the oscillatory stability of the grid. This impact is attributed to the inclusion of components such as inverters, filters, and control devices. The study in Ref. [165] focuses on accurately assessing EV load impacts on grid oscillatory stability. The detailed models of EV charging systems are developed with the aims to provide a comprehensive understanding of how EV penetration affects grid stability, facilitating the development of effective mitigation strategies. The integration of EV loads into the grid led to a reduction in the damping ratio of the oscillatory stability of the distribution grid. This decrease in damping ratio indicates a

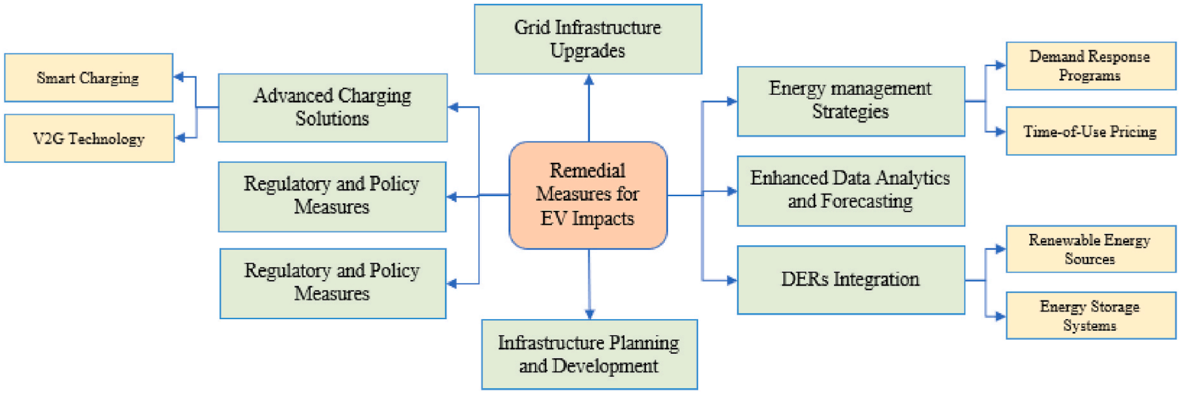


Fig. 9. Remedial measures for EV impacts.

deterioration in the oscillatory stability of the power grid because of high EV integration [119]. Effective mitigation strategies, such as coordinated charging, infrastructure upgrades, and advanced control systems, are essential to maintain stable and reliable power system operation in the face of growing EV adoption.

5. Remedial measures

The rapid increase in EV adoption necessitates the implementation of effective remedial measures to mitigate their impact on the distribution grid. As EVs contribute to higher load demand, load variability, voltage regulation issues, and potential transformer overloading as shown in Fig. 9. It is crucial to adopt strategies that ensure grid stability and reliability. Advanced solutions such as smart charging, V2G technology, and the integration of DER can significantly alleviate grid stress [19,166]. DR programs incentivize EV owners to shift their charging patterns, while advanced metering infrastructure provides real-time data for optimizing grid operations [167,168]. Moreover, enhancing infrastructure and strategically incorporating renewable energy sources into EV charging schedules additionally bolster grid resilience and sustainability [60]. These measures collectively help in managing the growing electricity demand from EVs, ensuring a balanced and efficient power distribution system [169].

5.1. Advanced charging solutions

Advanced charging solutions for EVs are designed to address the impacts of EV adoption on the power grid, ensuring that the grid remains stable, efficient, and capable of supporting the increasing demand and focus on managing the increased electricity demand resulting from EV charging while ensuring grid stability, reliability, and efficiency. These smart charging solutions primarily address challenges such as peak demand, voltage and frequency fluctuations, distribution system congestion and cost efficiency. Smart charging systems employed advanced algorithms and communication technologies to mitigate the adverse impacts of EVs on the power grid by optimizing charging schedules and aligning demand with grid capacity [28]. Advanced algorithms utilize load balancing techniques to shift charging to off-peak periods, reducing peak demand and alleviating stress on the distribution network. Utilizing smart charging algorithms to distribute EV charging load evenly throughout the day, avoiding simultaneous high-demand periods that could strain the grid [170,171]. Moreover, smart algorithms predict and manage localized impacts, such as voltage drops or transformer overloads, through controlled charging in areas with limited grid capacity. By integrating real-time data on grid conditions, electricity pricing, and renewable energy availability, smart charging systems align EV charging with periods of lower demand or higher renewable generation. They also predict and manage localized grid constraints, such as voltage sags or transformer overloads, ensuring reliable operation [166].

Smart charging systems employing communication technologies mitigate the adverse impacts of EVs on the power grid by enabling real-time data exchange between EVs, charging infrastructure, and grid operators. These systems use two-way communication protocols to dynamically adjust charging schedules based on grid conditions, electricity pricing, and renewable energy availability, reducing peak demand and preventing grid congestion. DR strategies enable dynamic adjustments to charging rates based on real-time grid conditions, renewable energy availability, and electricity pricing [162]. Integration with renewable energy sources ensures EVs charge during periods of high renewable generation, enhancing grid efficiency and sustainability [29,172]. Some methods employed in smart charging are time-based charging, grid integrated charging, V2G operation and predictive charging. Smart charging strategies play a vital role in optimizing EV charging operations, maximizing grid efficiency, and advancing the transition to a sustainable energy future [173]. Furthermore, real-time monitoring and control systems address localized issues, such as voltage sags or transformer overloads, while optimizing charging station utilization minimizes infrastructure strain. Collectively, these technologies enhance grid stability, improve renewable energy integration, and support the seamless adoption of EVs at scale [37].

Vehicle-to-grid technology allows electric vehicles to both draw power from the grid and supply stored energy back to it when needed. Moreover, V2G offers a flexible and dynamic approach to EV charging and grid interaction, enabling EVs to play a proactive role in supporting grid operations, integrating renewable energy, and enhancing grid resilience [174]. By harnessing the potential of V2G technology, EVs can mitigate their impact on the grid and contribute to a more efficient, reliable, and sustainable energy system. Through engaging in grid balancing tasks, the V2G capabilities of EVs assist in stabilizing the grid, handling variations in supply and demand, and enhancing the overall reliability and resilience of the grid. [175,176]. V2G technology allows grid operators to manage EV charging and discharging patterns to match supply and demand, reducing peak loads, and avoiding grid congestion. EVs have the capability to respond to DR signals from grid operators by adjusting their charging patterns. They can delay or reduce charging during periods of high demand or supply shortages, thereby assisting in alleviating stress on the grid [177].

5.2. Energy management strategies

Energy management strategies are essential to ensure the efficient, reliable, and sustainable operation of the power grid, especially with the increasing integration of EVs. These strategies encompass a range of technologies, policies, and practices designed to optimize energy production, distribution, and consumption [51]. Dynamic load management involves actively adjusting the electricity demand in response to real-time conditions on the grid, ensuring stability, efficiency, and reliability. Key components of dynamic load management are smart meters, advanced sensors and IoT devices to provide real-time data (such as voltage, current, and power quality) on energy usage, enabling precise monitoring, dynamic adjustments, and control of electrical loads [50]. Benefits of Dynamic load management helps reduce the peak load on the grid, preventing overloads and blackouts and reduces the need for expensive infrastructure upgrades. Furthermore, effective load management helps utilities reduce operational costs by minimizing the requirement for costly peaking power plants.

Implementing Time-of-Use (TOU) pricing is an efficient tactic for mitigating the effects of EVs on the power distribution grid. TOU pricing involves varying electricity rates based on the time of day, reflecting the fluctuating costs of generating and delivering electricity [178]. This strategy aims to mitigate the impacts of EVs on the power grid by smoothing out demand patterns and reducing strain on the grid infrastructure during peak periods. During peak hours, when demand is high, electricity rates are higher to reflect increased costs, while off-peak hours offer lower rates to incentivize charging. This encourages EV owners to charge during off-peak hours, helping to alleviate grid strain during peak demand periods [60,179]. By balancing electricity demand throughout the day, TOU pricing helps minimize the need for costly grid upgrades and promotes grid stability. EV owners benefit from potential cost savings by charging during off-peak hours, while the integration of clean energy sources is encouraged. Successful implementation requires smart charging infrastructure, consumer education, regulatory support, and incentives to promote participation [180]. DR and load management techniques, including DR programs and load shifting, incentivize EV owners to adjust their charging schedules based on grid conditions, spreading the impact of EV charging more evenly and alleviating peak demand.

5.3. Distributed energy resources integration

Advanced electric vehicle charging systems (EVCS) have revolutionized EV charging by seamlessly integrating multiple energy sources and various energy storage systems. DERs, such as solar PV systems, ESS, and smart inverters, can be installed at EV charging stations to generate and store renewable energy, which can be used during peak EV charging periods to reduce grid strain. Additionally, smart inverters with grid-support functionalities, such as reactive power control and voltage regulation, enable DERs to provide ancillary grid services, improving grid reliability and stability [181]. DER integration can provide numerous benefits, including enhanced grid stability, reduced peak demand, and improved utilization of renewable energy. DERs can help balance demand fluctuations generated by EV loads, ensuring stable grid operations. Furthermore, DERs can offer backup power during grid failures, thereby improving the reliability of the EV charging infrastructure [182,183].

DERs like energy storage systems can store surplus energy and release it during peak demand times. This action helps to smooth out the demand curve, lower energy expenses, and postpone investments in upgrading grid infrastructure. [87]. Incorporating renewable DERs such as solar and wind assists in diminishing dependence on fossil fuels, fostering sustainable energy consumption, reducing greenhouse gas emissions, and advancing sustainability efforts. Various methods of DER integration include on-site renewable energy generation, such as installing solar panels at EV charging stations to generate electricity during daylight hours, and utilizing wind energy to power EV chargers, especially in areas with high wind potential. Distributed energy management systems can offer real-time monitoring and control of DERs to optimize their performance to enhance ancillary services [168].

Technological innovation in battery technology, smart grid solutions, and renewable energy systems will enhance DER integration. Collaboration between utilities, EV manufacturers, and technology providers can drive the successful integration of DERs into the EV charging ecosystem. By implementing these methods and leveraging the benefits of DER integration, the impact of EV charging on the power grid can be significantly mitigated, leading to a more stable, efficient, and sustainable energy system. Numerous studies have explored the integration of DER with EV charging systems, highlighting their potential benefits [52,67]. The DER management system is presented in Ref. [184] to enable mass integration of EV charging systems on the power grid and a real-life case study is presented to identify opportunities for DER integration.

5.4. Grid infrastructure upgrades

Grid infrastructure upgrades refer to enhancements made to the electrical grid to accommodate the increasing demand for electricity, particularly concerning the charging requirements of electric vehicles (EVs). These upgrades are essential for ensuring the reliability, efficiency, and sustainability of the grid as more EVs are integrated into the transportation system. Key aspects of grid infrastructure upgrades related to EV charging include:

- Capacity Expansion - Increasing the capacity of substations, transformers, and distribution lines to handle higher loads resulting from widespread EV adoption.
- Distribution System Upgrades - Installing smart switches, sensors, and monitoring devices to improve grid reliability and responsiveness, enabling better management of EV charging demand.
- Grid Modernization - Deploying advanced metering infrastructure to provide real-time data on electricity usage, enabling accurate billing and demand management.
- Grid Resilience Enhancements - Strengthening grid infrastructure to reduce the risk of prolonged outages that could disrupt EV charging.
- Interconnection Upgrades - Improving interconnection facilities between transmission and distribution networks to facilitate the integration of large-scale EVs loads.

5.5. Vehicle-to-grid (V2G) technology

V2G technology plays a crucial role in enhancing grid stability and providing ancillary services by enabling bidirectional power flow between EVs and the grid. The primary contribution is frequency regulation, where EVs act as DERs to inject or absorb power in response to real-time frequency deviations, thereby maintaining grid stability [29,175]. Through grid-following and grid-forming inverters, V2G-enabled EVs can support voltage regulation by providing reactive power compensation, reducing voltage fluctuations, and improving power quality in distribution networks. Additionally, V2G contributes to peak shaving and load balancing by discharging stored energy during peak demand periods and recharging during off-peak hours, thus reducing stress on transformers and distribution feeders [32]. This capability is particularly beneficial for mitigating overloading issues in areas with high EV penetration. Furthermore, V2G enhances renewable energy integration by acting as a dynamic storage system that absorbs excess solar or wind energy when generation exceeds demand and supplies power when renewable generation is low, thereby smoothing fluctuations in the grid [35].

The key ancillary service provided by V2G is black start support, where aggregated EV fleets can supply power to restart the grid after a blackout, reducing reliance on conventional generators. Furthermore, V2G-enabled active filtering mitigates harmonics and improves power factor correction by dynamically adjusting inverter switching patterns, ensuring compliance with IEEE 519 harmonic standards [49,55]. The effectiveness of V2G integration depends on high-speed communication protocols, robust predictive control strategies, and market mechanisms (real-time pricing, frequency response markets) to enable real-time coordination. Moreover, power factor correction and harmonic compensation can be achieved through advanced control strategies, such as

MPC, improving overall grid efficiency [185,186]. However, successful V2G implementation requires robust communication infrastructure, smart charging algorithms, standardized grid interconnection protocols, and appropriate market incentives to encourage widespread participation. By leveraging V2G technology, utilities can enhance grid resilience, optimize energy utilization, and facilitate a smoother transition toward a sustainable, decentralized energy system [157].

Enhanced data analytics and forecasting leverage advanced technologies and methodologies to improve the accuracy and efficiency of predicting future trends and demands. Optimized charging stations can be deployed by analyzing traffic patterns, population density, and existing charging infrastructure and data analytics can help in strategically placing EV chargers to ensure accessibility and minimize grid stress [148]. Advanced forecasting models can predict EV charging demand based on factors such as time of day, season, and geographic location. This helps utilities manage and balance loads more effectively, reducing the risk of overloads and blackouts. Moreover, data analytics can optimize routes for electric fleets by considering factors like traffic conditions and charging station availability [19]. This reduces unnecessary energy consumption and ensures more efficient use of the existing infrastructure. Predictive analytics enable utilities to implement DR programs, where EV charging is shifted to off-peak times. This reduces peak demand and helps in maintaining grid stability. Moreover, utilizing data-driven insights can aid in integrating renewable energy sources with EV charging systems. This enables EVs to be charged with renewable energy, reducing their carbon footprint and promoting sustainability.

5.6. Modeling and managing uncertainty in EV charging systems

Modeling uncertainty in an EV charging system for grid support involves incorporating variability and unpredictability into the system's operation, considering factors such as fluctuations in charging demand, renewable energy availability, and user behavior [187,188]. The ability to model these uncertainties is crucial for optimizing the charging process and ensuring grid stability, especially with the increasing penetration of EVs and RES. Several factors contribute to uncertainty in EV charging systems for grid support, including user behaviour, charging infrastructure, grid condition and demand, renewable energy integration and V2G interactions. The timing, frequency, and amount of energy consumed by EVs can be highly unpredictable, as users may charge their vehicles at different times, durations, and power levels. Additionally, the state of charge (SoC) at the beginning of the charging session varies depending on user driving patterns and previous charging behavior. Variability in the charging infrastructure, such as the number of available charging stations, their power ratings, and the load distribution across multiple chargers, introduces uncertainty in the overall charging load. During peak hours, the grid may already be under stress, affecting the feasibility of charging large numbers of EVs without compromising stability [189,190].

Several methods can be used to model and account for uncertainty in EV charging systems for grid support. Stochastic models use probability distributions to represent the randomness in charging demand, renewable generation, and grid conditions. By modeling the EV charging load and renewable energy availability as probabilistic events, these models help simulate a range of potential outcomes and assess how uncertain factors affect grid stability [38]. Monte Carlo simulations generate multiple scenarios by randomly sampling from the probability distributions of uncertain variables. This technique allows for comprehensive risk analysis, evaluating the performance of the EV charging system under various conditions, such as high or low renewable generation, unexpected grid failures, or fluctuations in user behavior. Robust Optimization technique seeks to optimize EV charging schedules under the worst-case scenario [191]. By considering the full range of uncertainties, robust optimization aims to develop strategies that ensure grid stability even under the most extreme conditions, balancing EV charging demand, renewable energy supply, and grid load fluctuations.

The uncertainty modeling techniques for electric grids with vehicle-to-grid integration are review in Ref. [192], by highlighting Monte Carlo and probabilistic scenario analysis as the most widely used approaches and discussing trends, applications, and future research directions. The study in Ref. [193] compares parametric and non-parametric methods for probabilistic load flow analysis in distribution systems, highlighting that non-parametric approaches effectively estimate uncertainties in EV charging systems while reducing computational time. In Ref. [194] proposes a data-driven distributionally robust optimization (DRO) approach to balance EVs in autonomous mobility-on-demand (AMoD) systems, minimizing worst-case costs under demand and supply uncertainties while improving mobility and charging fairness. The study in Ref. [195] designs a Stackelberg game-based framework for V2G frequency regulation, incorporating a decision-dependent distributionally robust approach to manage endogenous uncertainty in EV charging demand, demonstrating improved economic efficiency and grid stability.

MPC is an advanced control technique that predicts future states of the system based on a mathematical model and optimizes control actions (e.g., charging schedules) over a prediction horizon [196]. The demand response scheduling model for residential communities using an energy management system aggregator, integrating MPC and Q-learning to optimize power demand, distributed energy resources, and market trading while reducing operational and storage degradation costs in Ref. [197]. In the context of EV charging, MPC can incorporate uncertainty by using predicted values for renewable generation, grid load, and charging demand, adjusting charging schedules in real-time to minimize grid congestion and improve stability [190]. Fuzzy logic systems handle imprecision and vagueness, making them useful when dealing with uncertain or incomplete information. In EV charging systems, fuzzy logic can model uncertainties in user behaviour, charging preferences, and unpredictable grid conditions, allowing for flexible, adaptive charging schedules that optimize grid support without precise data. In Ref. [198] proposes a novel sliding-mode load frequency control, demonstrating its robustness against uncertainties and load disturbances through Lyapunov stability analysis and numerical comparisons with other control methods [189].

By accurately modelling and incorporating uncertainty, grid operators can better predict the behaviour of EV charging systems, which is critical for services such as frequency regulation, voltage support, and peak shaving. For instance, stochastic models help optimize when and how much power to draw from EVs for grid support, ensuring that the grid remains stable even with fluctuations in renewable generation or unpredictable charging demands [166]. Additionally, uncertainties in user behaviour can be mitigated by incentivizing off-peak charging through demand response programs and smart charging infrastructure, helping to balance the load on the grid.

6. EV charging system to enhance grid resiliency and stability

The integration of EV charging systems equipped with GFM inverters represents a transformative approach to enhancing grid resiliency and stability during steady-state and transient conditions [134]. GFM inverters provide the unique capability to establish and regulate grid voltage and frequency, enabling EV charging systems to contribute actively to grid stability, especially during transient events or periods of high renewable energy generation. By emulating the inertia of traditional synchronous generators, GFM inverters offer virtual inertia, improving the grid's ability to respond to frequency disturbances and maintaining a stable supply. Additionally, GFM inverters allow for seamless integration of distributed energy resources, such as solar power and wind, which are often variable, helping to smooth fluctuations and enhance grid flexibility [199,200]. Through features like voltage and frequency regulation, fault ride-through, and black start capabilities, EV charging systems with GFM inverters can bolster grid reliability, manage

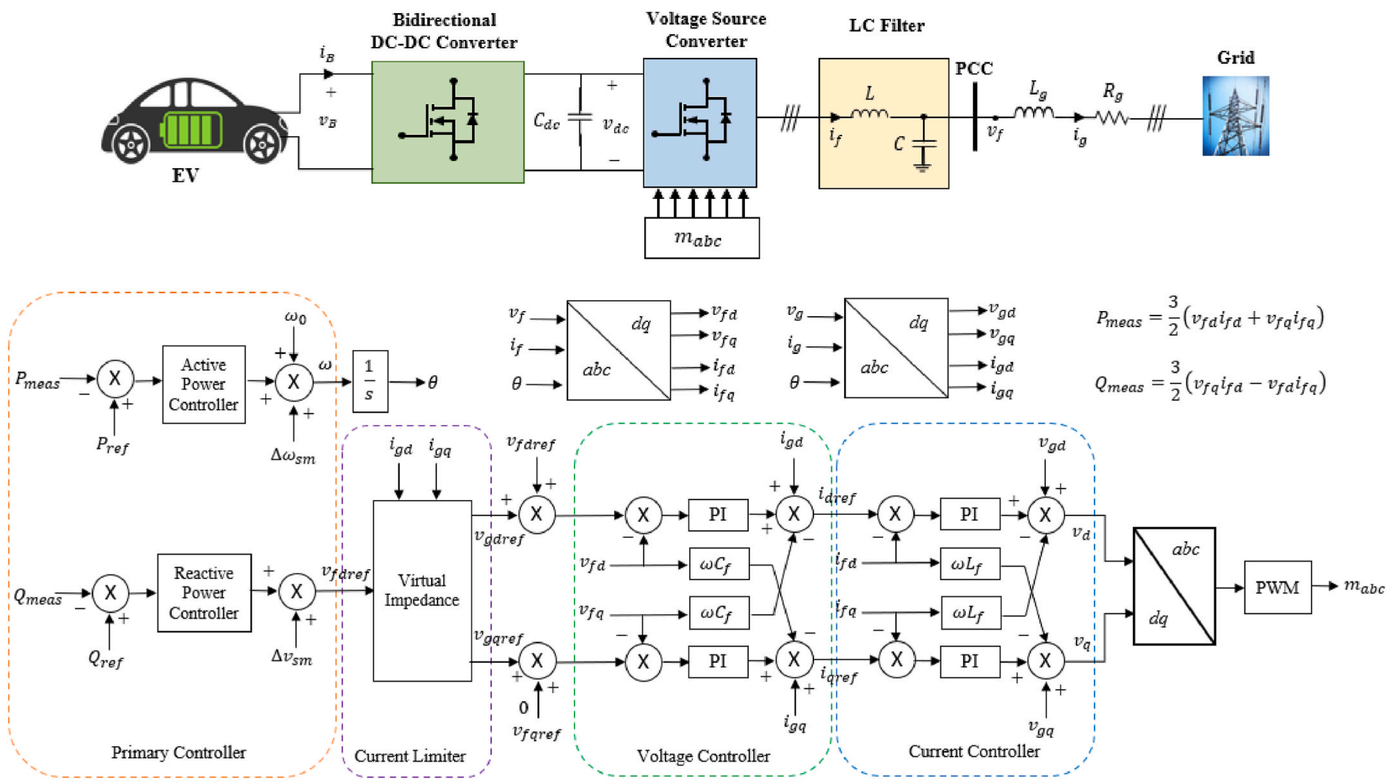


Fig. 10. System structure of EV charging system and inner controller of GFM inverter.

local load variations, and provide valuable ancillary services. Furthermore, GFM inverters enable dynamic power sharing in multi-inverter setups, ensuring balanced active and reactive power distribution. Additionally, they respond effectively to transient events such as voltage sags and frequency deviations, minimizing disruptions [196]. Their ability to stabilize low-inertia grids and seamlessly integrate distributed energy resources makes them critical for ensuring reliability and robustness in modern power systems [201]. This section provides how GFM inverter-based EV charging systems can support grid resilience and contribute to the stability of modern power networks during steady-state and transient conditions.

6.1. System structure

The system structure of a grid-connected GFM inverter-based EV charging system with controllers is shown in Fig. 10. The presented EV charging system comprises of an EV battery, bidirectional DC-DC converter, GFM converter, LCL filter, local load, transformer, and power grid. Two controllers are implemented in this system to manage EV battery charging and discharging and VSC control. The battery charge and discharge modes are controlled by the charger controller and the GFM controller is responsible for regulating the output voltage and current, to synchronize the system with the grid. Power variations within the system trigger the charger controller to activate charge or discharge modes. The DC link is used to connect EV battery to inverter via a bidirectional DC-DC converter, which facilitates charging and discharging by controlling buck and boost modes. The bidirectional DC-DC converter allows power to flow bidirectionally between the battery and the DC bus, enabling energy to be stored or extracted as needed. The charger controller can switch between buck/boost modes to either charge or discharge the battery and battery discharging mode (V2G) mode is considered in this simulation.

The system configuration and control diagram of the EV charging system, which includes a VSM controlled GFM inverter, are depicted in Fig. 10. The system consists of an EV battery, bidirectional DC-DC converter, three-level voltage source converter (VSC) with LC filter, power grid and respective controllers. This charging system enables effective energy exchange between the EV battery and the power grid, ensuring excellent power quality and system stability. The bidirectional DC-DC converter is utilized to link the EV battery to the DC-link, regulating the DC voltage from the EV battery to the necessary power level for the VSC. The VSM controller of inverter offers better dynamic response by emulating the inertia and damping of synchronous machines when compared to the droop controller, which is critical for maintaining frequency stability in the face of rapid changes in load or generation. The model incorporates a 500 kVA, 415 V, 50 Hz, three-phase GFM converter connected to a 415 V/11 kV transformer with 11 kV grid. A local load is connected to the output of the VSC at the low voltage level. The three-level VSC with an LC filter ensures seamless

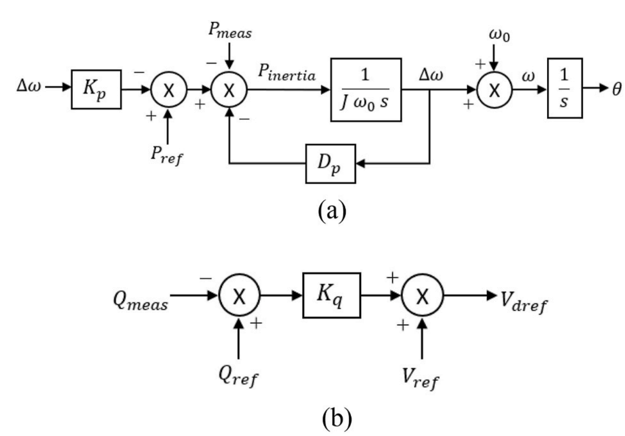


Fig. 11. Simplified control diagram of swing-equation based virtual synchronous machine controllers (a) Active power controller, (b) Reactive power controller.

voltage conversion and minimizes harmonics, thereby improving the overall performance and reliability of the power system. The GFM converter model offers stable and efficient regulations during the grid voltage, frequency, phase, local load, islanding mode, and three-phase short circuit fault.

6.2. Virtual synchronous machine-based control of GFM inverter

The employed VSM control method has cascaded connection of a swing-equation based active power controller, reactive power controller, virtual impedance control loop, voltage, and current control loops. The VSC employs a VSM control method, which mimics the inertia and damping characteristics of a synchronous machine. This approach enhances the stability and resilience of the power grid by providing synthetic inertia and improving the system's response to frequency deviations and transient disturbances. The active power controller is shown in Fig. 11(a) where the controller damping power is computed by using measured frequency of the grid. Due to its reliance on grid frequency measurements, damping power provides superior performance during grid frequency disturbances [129,202]. The $P-\omega$ and the $Q-V$ droop control can be presented as shown in (16) and (17) respectively.

$$\omega = \omega_0 - K_p \left(P_{meas} - P_{ref} \right) \tag{16}$$

$$v = v_0 - K_q \left(Q_{meas} - Q_{ref} \right) \tag{17}$$

where ω and ω_0 are the output angular frequency and rated angular frequency of VSG. v and v_0 are the terminal voltage and reference voltage. K_p and K_q are the coefficient of P-ω droop and $Q-V$ droop control. P_{meas} and P_{ref} are measured and reference value of active power. Q_{meas} and Q_{ref} are measured and reference value of reactive power respectively.

The active power controller of a VSM mimics the primary frequency regulation, damping, and inertia characteristics of a SG. Meanwhile, the reactive power controller, responsible for determining the amplitude of the modulating signal, replicates the voltage regulation function of a SG. The control of a VSM is implemented based on equation (10), with the swing equation representing the rotor side dynamics of a synchronous machine as shown in (18).

$$J\,\omega_0 \frac{d\omega}{dt} = P_m - P_e - D_p\omega \tag{18}$$

Where ω_0, ω , D_p, J, P_m, and P_e are nominal speed of the rotor, virtual angular speed of the rotor, damping constant, the moment of inertia, mechanical power, and electrical power, respectively [203]. Hence, the transfer function of the VSM controller (K_{vsm}) can be expressed as shown in (19).

$$K_{vsm} = \frac{\Delta\omega}{\Delta P} = \frac{1}{D_p + K_\omega + J\omega_0 s}$$

$$K_{vsm} = \frac{\Delta\omega}{\Delta P} = \frac{1}{(D_p + K_\omega)} * \frac{1}{\left(\frac{J\omega_0}{D_p + K_\omega}\, s + 1 \right)} \tag{19}$$

The moment of inertia (J) value is selected based on the required virtual inertia provision. This design ensures that the VSG can supply and absorb active power in EV charging and discharging systems [204]. The damping coefficient (D_p) and frequency droop coefficient (K_ω) are decided based on the desired steady-state P-ω droop requirement. The parameter D_p of the VSM is designed based on (20).

$$D_p = \frac{1}{m_p}, m_p = \frac{2\pi\,(f_{max} - f_{min})}{2 * P_{max}} \tag{20}$$

Where, f_{max} and f_{min} are the maximum and minimum frequency deviations allowed in the operation of island mode. Additionally, P_{max} represents the maximum active power that can be supplied by the VSM. The distributed generator can adjust its target power in reaction to frequency variations to alleviate frequency fluctuations. Conversely, the damping unit aims to minimize oscillations by regulating the distributed generator's behavior.

The VSMs can contribute to regulating the IBR plant's terminal voltage by adjusting their voltage and reactive power controls. Fig. 11 (b) shows the simplified control diagram of $Q-V$ droop regulation, which follows the control structure of a traditional synchronous generator. VSM operation is established based on the reference reactive power, which is adjusted by altering the voltage drop, droop characteristics, and line impedance to an appropriate value. The value of K_q determines the $Q-V$ gain characteristic. The VSC operation is configured according to the designated reactive power reference, which is accomplished by modifying VSM voltage drop, droop characteristics, and line impedance to reach a suitable level [205]. The parameter K_q dictates the Q-V gain characteristic, influencing the relationship between reactive power and voltage variations in the system. The reactive power adjustment is carried out gradually to mitigate its impact on the system under given circumstances [206]. The Q-V droop coefficient K_q is determined according to equation (21).

$$K_q = \frac{(V_{max} - V_{min})}{2 * Q_{max}} \tag{21}$$

where V_{max} and V_{min} are the allowed maximum and minimum voltage deviations, respectively. Q_{max} represents the maximum reactive power capacity provided by the VSM. Additionally, a Proportional and Integral (PI) controller is incorporated into the control loop. This controller regulates the output voltage in response to a reference value, emulating the behavior of a synchronous generator. VSMs can provide terminal voltage support to IBR plants in weak grids and inject or absorb reactive power to/from the grid, helping maintain stable terminal voltage [201]. This capability helps prevent the excessive extraction of reactive power from the IBR plant to regulate voltage in networks with low resilience. Consequently, the IBR plant gains additional capacity for controlling active power, enhancing its operational flexibility.

The virtual impedance method is employed as a current limiting controller of GFM inverter which is incorporated before the voltage controller as shown in Fig. 10. The current limiter establishes significant virtual impedance between the grid and the inverter in response to overcurrent events [207]. This manipulation shapes the impedance generated by the converter, effectively neutralizing the influence of the line resistance-to-reactance ratio on the primary controller. The VI is exclusively active during a faulty occurrence and is deactivated during normal operational conditions. The virtual impedance outputs of dq axis (v_{md}, v_{mq}) are subtracted from the terminal voltage of dq axis (v_{fdref}, v_{fqref}). Therefore, input reference voltages of inner voltage controller are effectively regulated with respect to the voltage variations at the inverter terminal and so curtailing the current. The cascaded inner voltage and current loops are integrated into the GFM inverter.

The proposed grid-connected GFM inverter-based EV charging system offers efficient load demand management and variability handling compared to traditional methods to reduce stress of the power network. The control system dynamically adjusts charging and discharging based on real-time grid conditions, reducing peak demand and alleviating network stress. The bidirectional DC-DC converter enables V2G functionality, providing grid support during high demand or low generation. The GFM inverter with a VSM controller emulates inertia, enhancing frequency stability and load response, unlike conventional droop-controlled systems. It also ensures superior voltage and frequency regulation, controls sudden load fluctuations effectively, and integrates RES for optimized EV charging. Moreover, local load variations are managed efficiently, improving overall grid stability by the controllers. This system is more flexible, resilient, and efficient in managing load demand and variability. Overall, the proposed system offers greater flexibility, resilience, and efficiency in managing load demand and variability, making it a significant improvement.

6.3. Simulation results and discussion

6.3.1. Case 1 – changing local load power

In this test case, the system experiences an instantaneous change in the active and reactive power of the local load. The power variations of the local loads can affect the operation and stability of the grid. Changes in active power demand affect line losses in the transmission and distribution network. An increase in reactive power demand (leading to a lagging power factor) can cause a decrease in voltage levels, and vice versa. This test scenario shows efficient response time of GFM converter, tracking ability, and power regulation capabilities of the EV charging system. Simulation results of local load power change are shown in Fig. 12. The active power of local load is increased up to 0.9 pu at t = 2 s and reactive power is increased from 0.1 to 0.3 at t = 4 s in case 1. Fig. 13 (a) shows active and reactive power outputs of the system. Active power increases at t = 2 s and decreases at t = 4 s to compensate for instantaneous active power changes of the local load. The system increases reactive power from 0.2 pu to 0.3 at t = 4 s due to required reactive power increases in the local load. The system frequency is decreased suddenly at t = 2 s due to the P_{Load} increases and slightly varied at t = 4 s as shown in Fig. 13 (b). Therefore, GFM inverter adjusts system outputs to balance the sudden changes in load and maintain system frequency within acceptable limits. Voltage and current outputs are shown in Fig. 13(c) and (d) respectively. The instantaneous load changes result in temporary deviations in voltage and current levels and the GFM inverter ensures the reliable operation of the power system under changing load conditions. A sudden increase in active power demand at t = 2 s and t = 4 s leads to a drop in voltage levels at the point of consumption as shown in Fig. 13(c). The EV charging system supplies the additional power quickly enough by increasing current as shown in Fig. 13(d).

6.3.2. Case 2 - temporary three-phase fault condition

To assess the ability of the EV charging system to endure temporary three-phase faults without experiencing significant performance degradation or failure, demonstrated in this case. During a temporary three-phase fault condition in a power system, there is a sudden and transient interruption in the flow of electricity due to a fault occurring simultaneously in all three phases. Fig. 14(a) and (b) represent the fault trigger signal and fault current respectively. Temporary three-phase fault is applied to the system for 200 msec from t = 2 s to t = 2.002sec and active power reference is dropped to 0 pu during t = 5 s to t = 5.5 s to verify fault ride through capabilities of GFM inverter. Fault current changes suddenly at t = 2 s and it decreases at t = 5sec. The fault may cause a rapid interruption in the flow of power through the affected lines and can lead to a momentary loss of electrical supply to the connected loads. However, the GFM inverter can control the active and reactive power of the system effectively as shown in Fig. 15(a). The frequency is restored at t = 2.002 s after the fault is cleared and then frequency increases up to maximum 50.07 Hz when active power

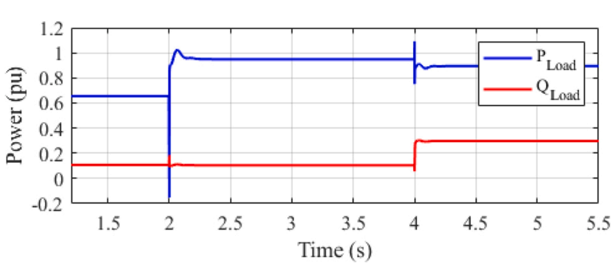


Fig. 12. Case 1 - Active and reactive power of the local load (pu).

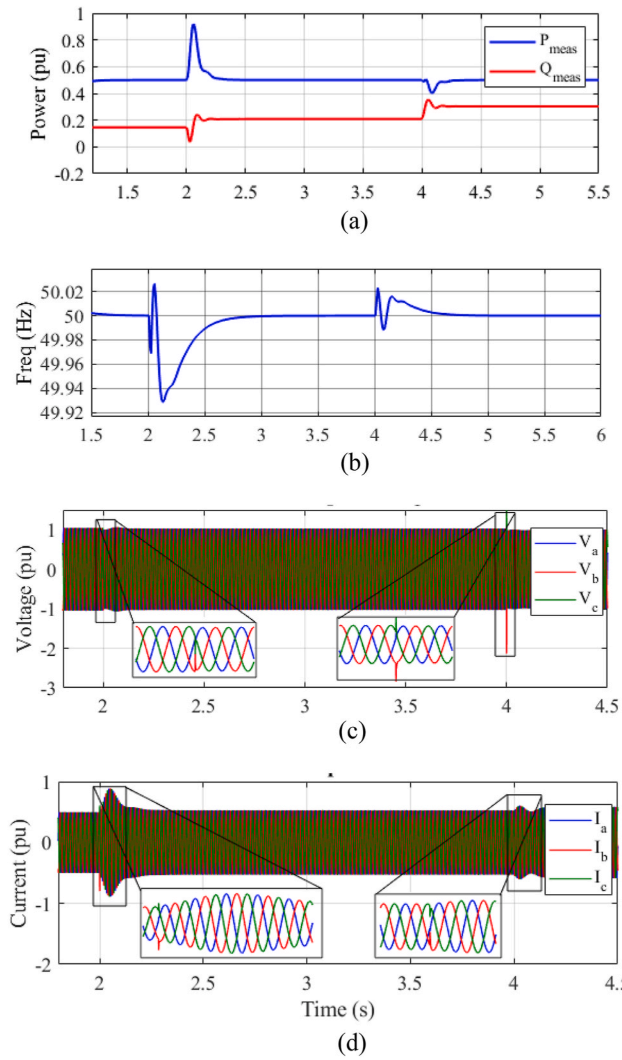


Fig. 13. Case 1 – Results of local load power changing (a) Active power and reactive power outputs (pu), (b) Frequency (Hz), (c) Three-phase voltage (pu), (d) Three-phase current (pu).

reference is zero. The grid voltage is well maintained within the allowed limit during temporary short circuit fault condition and large active power dropped scenario. The fault results in voltage and current transients in the system and three phase voltage levels distorted due to the short circuit, while current levels generate spike to very high values as the fault current flows through the system. However, inverter mitigates transient stability issues due to the sudden changes in voltage and current levels during and immediately after the fault as shown in Fig. 15(c) and (d). The short circuit fault creates a sudden impedance path, leading to a significant increase in current flow as shown in Fig. 15(d) at t = 2 s. This can cause a voltage dip, especially if the fault impedance is low and the fault is close to the source. The system recovers to its equilibrium point within 500 ms once the fault is cleared.

6.3.3. Case 3 – changing grid voltage and phase angle

Case 2 demonstrates that the system can maintain stability and performance without disruptions during changes in grid voltage and phase angle. The internal grid voltage and phase angle are shown in Fig. 16(a) and (b) respectively. The internal grid voltage is reduced from 1 pu to 0.2 pu for 200 ms at t = 2 s and grid phase angle is increased by 10° after t = 4 s in case 3. Fig. 17(a) shows the active and reactive power outputs of the system. The power of the system is slightly varied when

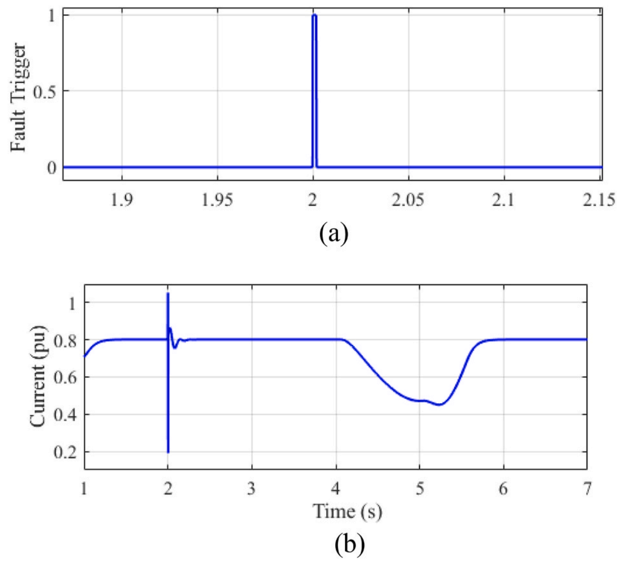


Fig. 14. Case 2 – Results of temporary three-phase fault condition (a) Fault trigger signal, (b) Fault current (pu).

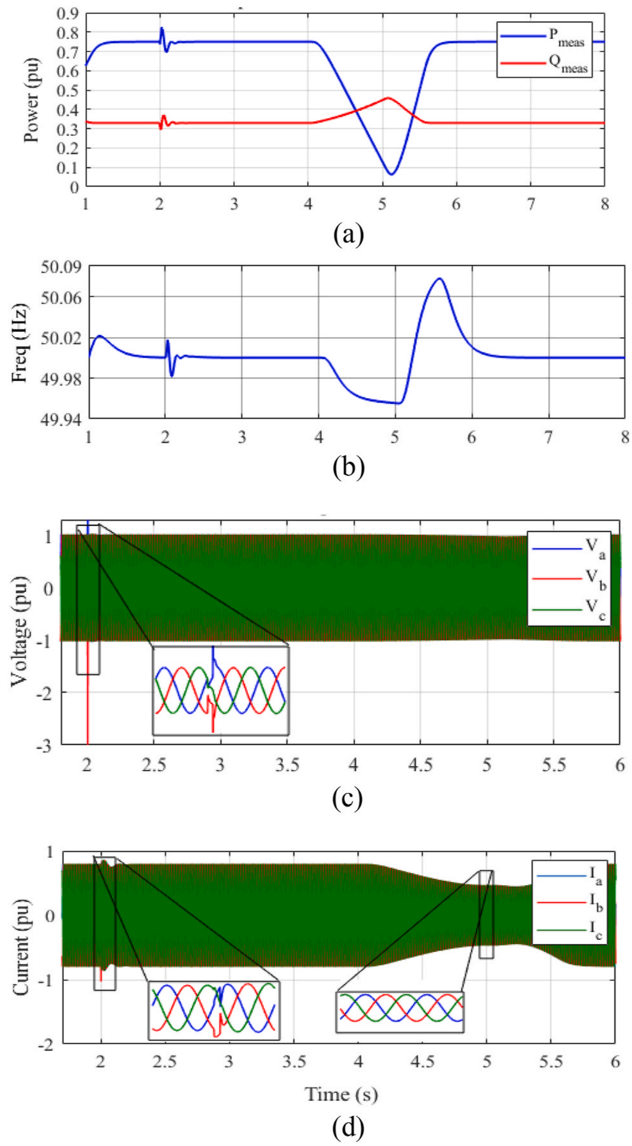


Fig. 15. Case 2- Results of temporary three-phase fault condition (a) Active power and reactive power outputs (pu), (b) Frequency (Hz), (c) Three-phase voltage (pu), (d) Three-phase current (pu).

internal grid voltage drops and shows fast responses. The active power suddenly decreases at t = 4 s up to 0.15 pu. Because active power is directly related to the voltage magnitude and the cosine of the phase angle difference between voltage and current. The reactive power increased from 0.15 pu to 0.4 pu at t = 4 s when phase angle increased as an instantaneous change in the phase angle between voltage and current can also affect reactive power flow. A change in the phase angle can alter the direction of reactive power flow or change its magnitude. Fig. 17(b) represents the frequency of the system in Case 3. The system frequency is slightly varied at t = 2 s and rapidly varied at t = 4 s when phase angle changes. Therefore, grid frequency responds dynamically to instantaneous changes in grid voltage and phase angle and GFM inverter is playing major role in stabilizing grid frequency and ensuring the reliable operation of the power grid. Three-phase voltage and current outputs are shown in Fig. 17(c) and (d) respectively. The system controls instantaneous changes in grid voltage and phase angle and provides transient stability instantly.

7. Challenging issus and future prospects

Examining both the challenging issues and prospects of EV charging systems and the impacts of high EV penetration on the power distribution grid is critical for understanding the implications of widespread electric vehicle adoption. Fig. 18 shows major challenges and prospects of EV charging systems. The major challenge in the increasing electrified transport system arises the electricity demand which is necessary to integrate the alternative resources of energy such as RES and DES [208].

7.1. Challenging issues

Load management and peak shaving become challenging in an increased EV charging system due to several factors. EV charging patterns can vary significantly based on factors like driver behaviour, charging infrastructure availability, and charging incentives. This variability makes it harder to predict and manage peak demand periods effectively [149]. Rapid charging of EVs without proper load management strategies, this strain can result in equipment failures and reliability issues. The insufficient to support the growing number of EVs can exacerbate peak demand issues, as drivers may resort to charging during specific times when the infrastructure is available [181]. Coordinating EV charging with renewable energy generation can be challenging, especially during periods of low generation or high demand. Because the intermittent nature of RES introduces additional complexity to load management [36].

The challenges related to infrastructure requirements for EV charging systems can be multifaceted. As the number of EVs on the road increases, there's a corresponding need to scale up the charging infrastructure to meet demand. The pace of infrastructure deployment must match or exceed the rate of EV adoption to prevent bottlenecks and ensure convenient access to charging for EV owners. Upgrading grid infrastructure to support increased electricity demand requires significant investment and coordination between utilities, regulators, and other stakeholders. Identifying suitable locations for charging stations and obtaining permits for their installation can be challenging due to regulations, land use restrictions, and competing interests [137]. Offering a variety of charging speeds and connector types to accommodate different EV models and driver needs can complicate infrastructure planning and implementation. Moreover, Aligning the deployment of EV charging infrastructure with the growth of renewable energy sources can present technical and logistical challenges.

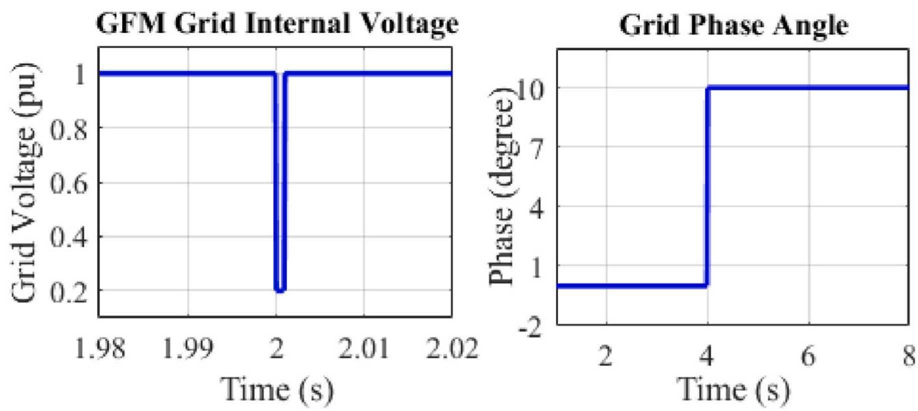


Fig. 16. Case 3 - changing grid voltage and phase angle.

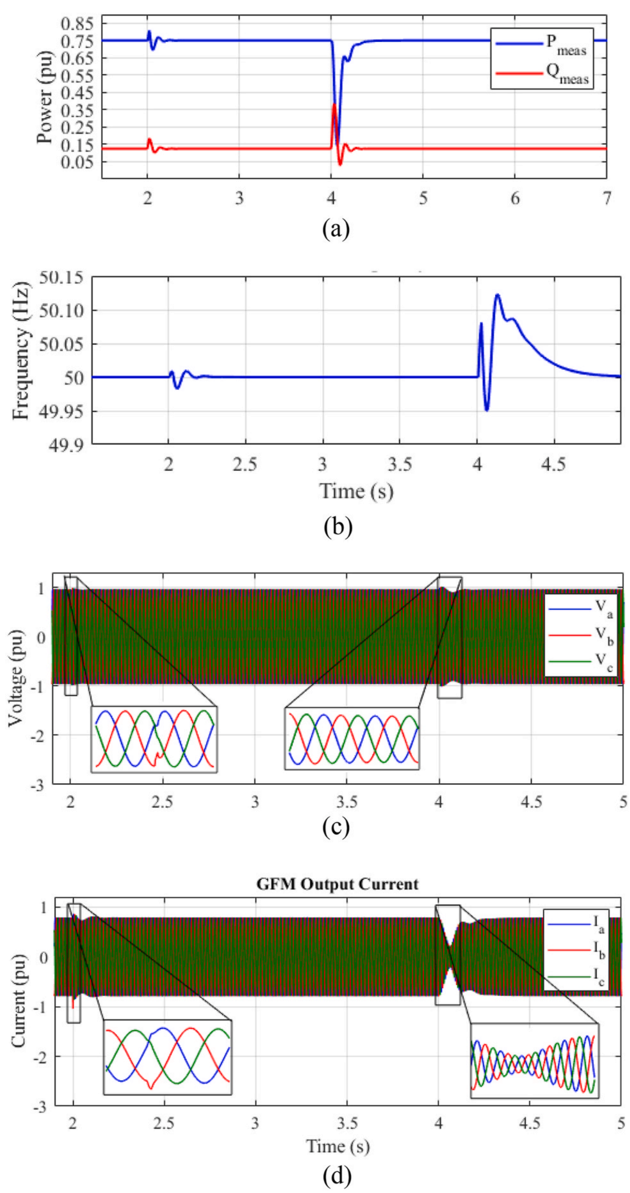


Fig. 17. Case 3 – Results of changing grid voltage and phase angle of the system (a) Active power and reactive power outputs (pu), (b)Frequency (Hz), (c)Three-phase voltage (pu), (d) Three-phase current (pu).

The implementation of smart charging and DR programs for EVs presents several technical, economic, regulatory, and behavioral challenges that must be addressed to ensure their effectiveness. From a technical perspective, existing distribution networks may struggle with the additional load from coordinated charging and V2G operations, leading to voltage instability, increased power losses, and transformer overloading [209]. Communication and interoperability issues arise due to the lack of standardized protocols across different EV models, charging stations, and grid operators, while cybersecurity risks pose threats to data privacy and system integrity [210]. Additionally, accurate load forecasting and real-time control remain complex due to uncertain user behavior, dynamic grid conditions, and seasonal variations, requiring advanced predictive control strategies such as MPC, which increases computational complexity [211,212].

Economically, the high initial investment required for smart meters, bi-directional chargers, and energy management systems can be a barrier to widespread adoption. Moreover, uncertain financial incentives, fluctuating electricity market structures, and the absence of clear revenue-sharing mechanisms create challenges for utilities, aggregators, and consumers in monetizing smart charging and DR participation [195, 213]. Regulatory hurdles further complicated implementation, as inconsistent policies governing V2G participation, tariff structures, and grid services compensation across regions create uncertainty for stakeholders. Additionally, legal and contractual issues must be addressed to establish clear agreements between grid operators, aggregators, and EV

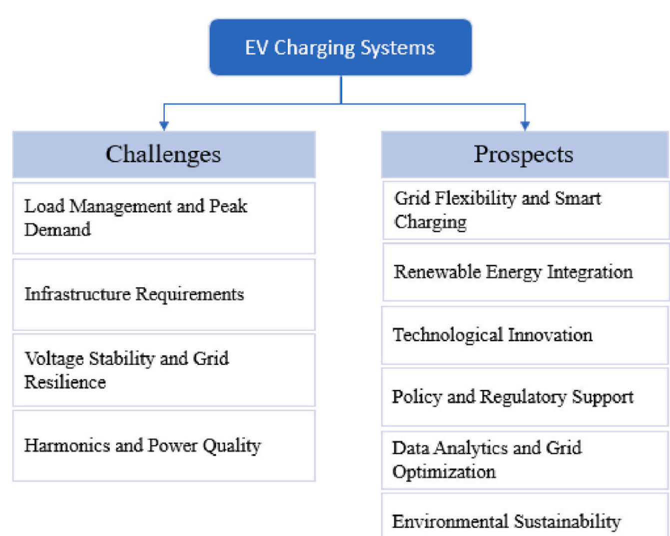


Fig. 18. Challenges and prospects of EV charging systems.

owners. Consumer behavior also plays a critical role, as low awareness of smart charging benefits, concerns about range anxiety, and fears of battery degradation deter participation in DR programs. Users may be reluctant to allow grid operators to control their charging schedules unless clear incentives, compensation for battery wear, and user-friendly interfaces are provided to enhance engagement [183]. Despite these challenges, addressing them through the development of standardized communication protocols, robust cybersecurity measures, advanced forecasting algorithms, market incentives, and public awareness campaigns will be crucial in enabling the successful deployment of smart charging and DR programs, ultimately enhancing grid stability and optimizing energy utilization [213].

In addition to that, voltage stability and grid resilience can indeed face challenges with the increasing adoption of EV charging systems. Concentrated EV charging in specific locations can overload distribution transformers and feeder lines, particularly during peak charging times. This increased load can lead to overheating, voltage drops, and potential equipment failures if not adequately managed [33]. Maintaining voltage within acceptable limits becomes more challenging as the demand for electricity from EV charging increases. Voltage regulation devices such as voltage regulators and capacitor banks may need to be upgraded or installed strategically to stabilize voltage levels and ensure reliable power delivery [22]. Grid congestion can occur when the capacity of distribution infrastructure is insufficient to support the demand for EV charging, especially in densely populated areas or locations with limited grid access. EV charging systems can affect grid resilience by altering load patterns and increasing demand in specific areas [183]. Grid operators must anticipate and mitigate potential disruptions caused by EV charging, such as voltage instability, equipment failures, and cybersecurity risks, to ensure the continued reliability and resilience of the electric grid. Harmonic distortion generated by EV chargers can interfere with communication systems, and control signals used for grid monitoring and management. This interference can disrupt communication and data transmission, affecting the reliability and efficiency of grid operations.

The integration of DERs and RES with EV charging schedules has significant implications for both the central grid and local demand. For the central grid, this integration enhances grid flexibility, allowing for better management of power supply and demand fluctuations [180]. RESs such as solar and wind introduce variable generation profiles, which can be mitigated through demand-side management strategies that align EV charging with periods of high renewable generation. By shifting charging to coincide with times when renewable generation is abundant, such as midday for solar or windy periods for wind generation, it helps reduce curtailment of excess renewable energy and improves the overall efficiency of the grid [5]. Additionally, load leveling and peak shaving become feasible, as EVs can be charged during off-peak periods or when excess renewable energy is available, reducing the need for traditional fossil-fuel-based peaking plants and alleviating stress on the grid during peak demand times [214].

Locally, EVs serve as mobile storage systems, contributing to localized energy management. With intelligent smart charging systems and V2G technology, EVs can provide backup power and act as distributed storage assets for local communities, especially during grid outages or periods of high demand. This local interaction with DERs allows for more efficient use of local RES, as EVs can charge directly from rooftop solar systems or small-scale wind turbines, reducing the reliance on the central grid [189]. BESS integrated with EV charging stations can further enhance this, enabling energy storage during periods of surplus and discharging during periods of high demand, thus balancing local energy needs without relying on the central grid. The broader implications also extend to grid stability and resilience. By integrating EV charging with smart grid technologies, the system can dynamically respond to fluctuations in renewable generation, changing load conditions, and grid imbalances. This integration can reduce voltage fluctuations, harmonic distortion, and the need for extensive grid reinforcements, particularly in areas with high penetration of both EVs and renewables [132].

Moreover, real-time optimization of charging schedules can help prevent overloading of transformers and distribution feeders, enabling the grid to accommodate higher levels of RES and DERs without compromising stability [125,127]. On a macro scale, the integration of EVs, DERs, and RES enhances decarbonization efforts, by making it easier to incorporate more intermittent renewable generation while reducing dependence on conventional fossil-fuel-based power generation. In the long term, this can lead to a decentralized and resilient energy system, where EVs act as flexible resources that support both local and central grid operations, contributing to the overall efficiency and sustainability of the energy transition [212]. However, achieving these benefits requires overcoming challenges such as the need for robust communication infrastructure, real-time grid balancing algorithms, standardized control frameworks, and policy incentives to encourage the widespread adoption of these integrated systems [208].

To address these challenges, innovative solutions such as smart charging algorithms, DR programs, vehicle-to-grid (V2G) technologies, and advanced grid monitoring systems are being developed and deployed. These solutions aim to optimize charging schedules, alleviate peak demand, and enhance the overall stability and efficiency of the electric grid amidst the growing adoption of EVs. Moreover, collaboration among stakeholders, including government agencies, utilities, automakers, charging infrastructure providers, and community organizations are required to overcome these challenges [33,127,215].

7.2. Future prospects

Grid flexibility and smart charging hold significant promise for addressing the challenges associated with the increasing adoption of EVs and their integration into the electricity grid. Demand responds programs, V2G technology, smart charging algorithms, grid-integrated charging infrastructure DER integration and artificial intelligence and machine learning technologies offer promising avenues for enhancing the resilience, efficiency, and sustainability of the electricity grid in the face of increasing electrification and the proliferation of EVs [216,217]. Moreover, renewable energy integration into the electricity grid, particularly in the context of increasing EV adoption, holds several promising prospects. Techniques such as predictive analytics, machine learning, and AI can forecast renewable generation and electricity demand more accurately, enabling better coordination between renewable energy supply and EV charging demand. Large-scale battery storage systems can store excess renewable energy generated during periods of low demand and release it during peak demand times and satisfy EV charging demands loads when it necessary [45].

Technological innovation will play a pivotal role in shaping the future of energy systems, particularly in the context of integrating renewable energy and accommodating the growing demand from EVs. Specifically, Innovations in battery technology, smart grid strategies, vehicle-to-everything (V2X), advanced power electronics (Wide Bandgap Semiconductors and smart inverters) promise higher energy densities, faster charging times, longer lifespans, and improved safety compared to current lithium-ion batteries [181]. Policy and regulatory support are crucial for facilitating the adoption of EVs. Some key areas and prospects for policy and regulatory support are incentives for EV adoption, standards and regulations, sustainable transportation policies and regulatory support for EV adoption and smart charging [179]. By implementing and enhancing these policy and regulatory measures, governments can create a supportive environment for the transition to a sustainable energy system, promoting the widespread adoption of EVs while ensuring grid stability and economic growth in the future [61].

Moreover, Data analytics and machine learning algorithms optimize EV charging schedules based on grid conditions, improving efficiency, and reducing costs. Advanced grid planning tools identify optimal locations for charging infrastructure deployment, minimizing grid impacts, and maximizing benefits. Continued research, innovation, and collaboration among industry stakeholders will be essential to realize the full potential of these technologies and accelerate the transition to a more flexible and resilient energy system [61,173]. By leveraging these strategies and technologies, the integration of renewable energy with the electricity grid can be significantly enhanced, supporting the transition to a sustainable and resilient energy system that accommodates the growing demand from EVs.

Several infrastructure upgrades are required, focusing on advanced grid technologies, energy storage, and power electronics to effectively handle increased loads and improve grid resilience in the face of rising EV adoption and increased loads. Grid modernization is at the core of these upgrades, where the deployment of smart grid systems, including advanced metering infrastructure, smart sensors, and communication networks allows for real-time data collection and control [140,215]. With these technologies, utilities can implement demand-side management, load balancing, and real-time optimization strategies to prevent grid congestion and improve stability. Advanced distribution management systems further enhance grid flexibility by integrating distributed generation, automating fault detection, and enabling self-healing networks [37]. These systems facilitate the dynamic reconfiguration of the grid, minimizing disruptions and improving reliability under high penetration of DERs [218]. Another crucial upgrade is the enhancement of transmission and distribution lines. Existing infrastructure often lacks the capacity to support the added loads from EV charging and DERs. Therefore, upgrading transformers to higher-rated capacities and reinforcing feeder lines is essential to prevent overloading. In areas with significant RES integration, High-Voltage Direct Current (HVDC) transmission lines are a key solution to efficiently transfer power over long distances with lower losses compared to traditional AC transmission [219].

The integration of advanced power electronics is essential for supporting both EV charging infrastructure and DERs. High-efficiency inverters are necessary to ensure seamless power conversion between DC sources (like solar or EVs) and the AC grid [171,183]. These inverters must be capable of grid-forming and grid-following operations, enabling active power injection and reactive power compensation. This improves voltage regulation and mitigates harmonic distortion, essential for maintaining grid stability with increased penetration of renewable energy [137]. Additionally, the installation of flexible AC transmission systems, such as Static var compensators and Static Synchronous Compensators, can provide real-time reactive power support, enhancing voltage stability and enabling efficient integration of renewable generation [217]. Moreover, the establishment of microgrids and community energy systems will further bolster grid resilience. Microgrids can operate autonomously or in coordination with the central grid, providing energy security for critical infrastructure and enabling islanding during grid outages. These microgrids integrate local DERs, such as solar, wind, and storage, to serve local demand and maintain grid stability. Furthermore, community energy systems aggregate distributed energy assets, such as residential solar systems, EVs, and small-scale batteries, to provide collective resilience and reduce dependency on the central grid [215].

The implementation of these infrastructure upgrades must be supported by advanced control algorithms, high-speed communication protocols, and coordinated grid management systems. Real-time grid balancing algorithms, and optimal power flow, will be required to dynamically adjust the operation of DERs, EVs, and storage systems in response to changing grid conditions. Additionally, cybersecurity measures must be incorporated to protect the grid infrastructure from potential vulnerabilities associated with increasing digitalization and the integration of Internet of Things (IoT) devices [37,128]. Therefore, the successful integration of EVs, DERs, and RES into the grid necessitates significant upgrades in grid infrastructure, energy storage, power electronics, and control systems [220]. These upgrades, including the deployment of smart grid technologies, advanced inverters, energy storage systems, and EV charging infrastructure, will improve grid reliability, facilitate the efficient integration of renewable energy, and enhance overall system resilience. Effective implementation requires a collaborative approach among utilities, regulators, and technology providers, as well as continued investment in both infrastructure and research to meet the growing demands of modern, decentralized energy systems [165].

The authors project a transformative evolution in EV charging systems, recognizing both opportunities and challenges. They predict substantial growth in EV deployment, driven by advances in battery technology, increased consumer adoption, and stringent emissions regulations. This influx of EVs is expected to impose significant demands on the electrical grid, potentially exacerbating issues related to grid stability and load management. To counteract these impacts, the authors recommend several technical interventions. They advocate for the implementation of advanced smart charging infrastructure that utilizes real-time data and dynamic pricing to optimize charging patterns and mitigate peak demand pressures. Additionally, they emphasize the need for grid modernization efforts, including the deployment of high-capacity transformers, energy storage systems, and enhanced grid management software to support increased loads and maintain grid reliability.

The authors also foresee the integration of V2G technology as a pivotal development in future grid-connected EV systems. V2G enables bidirectional energy flow, allowing EVs to discharge stored energy back into the grid during peak periods, thus providing ancillary services and enhancing grid stability. This approach, coupled with increased adoption of renewable energy sources and distributed energy resources (DERs), is expected to foster a more resilient, flexible, and sustainable energy infrastructure capable of accommodating the evolving demands of a high-EV penetration scenario.

8. Conclusion

The increasing adoption of EVs presents significant challenges and opportunities for the communities, businesses and distribution grid utilities. However, the transition to an electrified transportation sector must be managed carefully to ensure the stability and reliability of the distribution grid. As EV penetration rises, the impact on the grid becomes more pronounced, necessitating a comprehensive understanding of these impacts and the development of effective remedial measures. Key impacts include increased load demand, and load variability, which can lead to fluctuations in demand, making it challenging to maintain grid stability and reliability. High concentrations of EVs can cause voltage regulation issues, leading to power quality problems, and prolonged high demand can result in transformer overloading and failure. Additionally, uncoordinated charging can exacerbate peak demand issues, increasing operational costs and the need for additional generation capacity.

To address these challenges, several advanced solutions and remedial measures are essential. Implementing smart charging and DR programs encourages off-peak charging and balances load more effectively. V2G technology allows bidirectional energy flow, providing ancillary services and enhancing grid stability by discharging electricity back to the grid during peak periods. Integrating DER, such as local solar panels and battery storage, mitigates the impact on the central grid and supports local demand. Furthermore, integrating RES with EV charging schedules maximizes the use of clean energy. Moreover, deploying advanced metering infrastructure facilitates real-time monitoring and control systems to optimize grid operations and manage EV charging more effectively. Infrastructure upgrades are necessary to handle increased loads and improve overall grid resilience. This paper can assist the grid operators to take necessary steps for the management of large-scale EVs in distribution grids.

CRediT authorship contribution statement

Sithara S.G. Acharige: Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization. **Md Enamul Haque:** Writing – review & editing, Supervision. **Mohammad Taufiqul Arif:** Writing – review & editing. **Nasser Hosseinzadeh:** Writing – review & editing. **Kazi N. Hasan:** Writing – review & editing. **M.J. Hossain:** Writing – review & editing. **Kashem M. Muttaqi:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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