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SMART ELECTRIC VEHICLE CHARGING STATIONS TO IMPROVE EFFICIENCY AND RELIABILITY OF THE DISTRIBUTION NETWORK: A COMPREHENSIVE REVIEW

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Annotation. The rapid growth of electric vehicle adoption creates both promising opportunities and serious challenges for contemporary power distribution networks. Uncoordinated EV charging can impose substantial stress on the grid, resulting in voltage deviations, transformer congestion, and increased peak demand. This paper provides a comprehensive review of recent studies addressing smart EV charging strategies, uncertainty modeling approaches, benchmark test systems, and pricing mechanisms for improving distribution network performance. The IEEE 33-bus distribution test system is employed as a benchmark to examine the effects of EV penetration under different charging conditions. In addition, the study reviews smart charging strategies, Monte Carlo - based approaches for modeling charging uncertainty, and the integration of distributed energy resources, including solar photovoltaic systems and battery energy storage. Furthermore, several electricity pricing mechanisms - such as Time-of-Use, Real-Time Pricing, Critical Peak Pricing, and Peak Time Rebate - are analyzed in terms of their effectiveness for demand-side management and peak load mitigation. The reviewed literature indicates that the coordinated application of smart charging, DER integration, and dynamic pricing can significantly alleviate grid stress. This work offers a comprehensive perspective for the design of intelligent EV charging infrastructures that support grid stability, energy efficiency, and environmental sustainability.

Keywords: Electric Vehicles (EVs), Real-Time Pricing (RTP), Distribution Network Reliability, Smart Grid, Time-of-Use Pricing, Monte Carlo Simulation, IEEE 33-Bus Distribution System, Electric Vehicle Charging St

TAQSIMOT TARMOQLARINING SAMARADORLIGI VA ISHONCHLILIGINI OSHIRISH UCHUN AQLLI ELEKTR TRANSPORT VOSITALARINI ZARYADLASH STANSIYALARI: KOMPLEKS TAHLIL

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Annotatsiya. Elektr transport vositalarining (EV) tez sur’atlarda keng tarqalishi zamonaviy elektr taqsimlash tarmoqlari uchun ham katta imkoniyatlar, ham jiddiy muammolarni yuzaga keltirmoqda. Elektromobillarni muvofiqlashtirilmagan tarzda zaryadlash tarmoqqa sezilarli yuklama keltirib chiqarishi mumkin, bu esa kuchlanish ogʻishlari, transformatorlarning ortiqcha yuklanishi va maksimal talabning oshishiga olib keladi. Ushbu maqolada elektromobillarni aqlli zaryadlash strategiyalari, noaniqlikni modellashtirish usullari, etalon test tizimlari hamda taqsimlash tarmoqlari samaradorligini oshirishga qaratilgan narxlash mexanizmlari boʻyicha soʻnggi tadqiqotlarning keng qamrovli sharhi keltirilgan. Etalon model sifatida IEEE 33 tugunli taqsimlash tizimi turli zaryadlash sharoitlarida elektromobillar ulushining ta’sirini tahlil qilish uchun qoʻllanilgan. Bundan tashqari, tadqiqotda aqlli zaryadlash strategiyalari, zaryadlashdagi noaniqlikni modellashtirish uchun Monte-Karlo usuliga asoslangan yondashuvlar, shuningdek, quyosh fotoelektr tizimlari va energiya saqlash tizimlarini oʻz ichiga olgan taqsimlangan energiya resurslarining integratsiyasi koʻrib chiqiladi. Shuningdek, elektr energiyasini narxlashning turli mexanizmlari — masalan, vaqtga bogʻliq tariflar (Time-of-Use), real vaqt rejimidagi narxlash (Real-Time Pricing), kritik pik narxlash (Critical Peak Pricing) va pik vaqtda iste’molni kamaytirganlik uchun mukofotlash (Peak Time Rebate) — talabni boshqarish va maksimal yuklamani kamaytirish nuqtai nazaridan tahlil qilinadi. Adabiyotlar sharhi shuni koʻrsatadiki, aqlli zaryadlash, taqsimlangan energiya resurslarini integratsiya qilish va dinamik narxlashni muvofiqlashtirilgan holda qoʻllash tarmoq yuklamasini sezilarli darajada kamaytirishi mumkin. Ushbu ish elektr transport vositalari uchun aqlli zaryadlash infratuzilmasini loyihalashda tarmoq barqarorligi, energiya samaradorligi va ekologik barqarorlikni ta’minlovchi kompleks yondashuvni taklif etadi.

Kalit so’zlar: elektromobillar (EV), real vaqt rejimidagi narxlash (RTP), taqsimlash tarmoqlari ishonchliligi, aqlli elektr tarmogʻi (Smart Grid), vaqtga bogʻliq tariflar (Time-of-Use), Monte-Karlo usuli asosida modellashtirish, IEEE 33 tugunli taqsimlash tizimi, elektromobillarni zaryadlash stansiyalari (EVCS), barqaror energetika tizimlari.

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1. Introduction

In recent years, the global automotive industry has undergone a significant transformation driven by the rapid development and adoption of Electric Vehicles. Growing concerns about climate change, depletion of fossil fuels, and the urgent need to reduce greenhouse gas emissions have accelerated the transition from traditional internal combustion engine vehicles to electric mobility. According to the International Energy Agency, the global electric car stock surpassed 40 million units in 2024, representing a growth of more than 50% compared to 2022. Leading countries such as China, the United States, and members of the European Union have implemented strong policies, subsidies, and infrastructure investments to support EV deployment. At the same time, improvements in battery technology, power electronics, and renewable energy integration have made electric vehicles more efficient, affordable, and practical for consumers worldwide. The integration of EVs into the power grid brings several advantages. Firstly, EVs help reduce dependence on fossil fuels and promote the use of clean and renewable energy sources, contributing to a more sustainable energy ecosystem. Secondly, EVs can serve as mobile energy storage units, enabling advanced grid support functions such as demand response, load balancing, and peak shaving through smart charging and Vehicle-to-Grid (V2G) technologies. Furthermore, the electrification of transportation contributes to improved air quality and reduced noise pollution, particularly in urban areas. However, despite these benefits, the large-scale integration of EV charging systems also presents several challenges. Uncontrolled charging during peak hours can lead to voltage fluctuations, increased power losses, and transformer overloading, thereby affecting the reliability and stability of the distribution network. Additionally, the uneven distribution of charging demand may cause local grid congestion and require expensive infrastructure upgrades. From the consumer perspective, long charging times and the limited availability of fast charging stations remain major concerns that slow down EV adoption, especially in developing regions. To address these issues, researchers and engineers are focusing on the design and implementation of smart charging systems. Such systems utilize advanced technologies, including Artificial Intelligence, Internet of Things, and data analytics, to optimize charging schedules, predict demand, and coordinate energy flow between EVs and the grid. AI-based smart charging can dynamically adjust charging rates based on electricity prices, grid load, and renewable energy availability, thereby improving both efficiency and reliability of the power distribution network. These intelligent systems not only minimize negative impacts on the grid but also enhance user convenience, reduce operational costs, and contribute to the development of sustainable smart cities. In this research, the main focus is on Designing a Smart Charging System for Electric Vehicles to Improve Efficiency and Reliability of the Distribution Network. The proposed approach aims to integrate EVs intelligently with the grid through optimized charging management, ensuring efficient energy utilization and stable system operation. Electric vehicles are becoming more and more popular as a result of growing modernization, which is also improving air quality, energy security, and economic opportunity. The grid, voltage, and current will be significantly impacted by an increase in the number of charging stations. Even while electric cars are a significant way to cut emissions, switching to alternative fuels and lowering reliance on fossil fuels also lowers greenhouse gas emissions [1]. Vehicle electrification is a result of growing energy usage, environmental concerns, and transportation sector advancements. However, it is impossible to foresee how negatively electric vehicles will affect the grid. Higher peak load demand, reduced reserve margins, voltage instability, and reliability problems at the charging stations are all consequences of high charging loads at fast-charging stations. It must also include the penalty that the utility paid for the electricity system's decreased performance, which cannot be disregarded. This study aims to examine the environmental effects of higher EV charging station loads brought on by frequent electric vehicle charging and discharging as well as charging infrastructure [2]. Recent studies emphasize that uncoordinated electric vehicle charging can significantly increase peak demand, cause voltage deviations, and overload distribution transformers, thereby threatening the reliability of distribution networks. To address these challenges, smart charging systems have emerged as a key solution, enabling coordinated charging control based on grid conditions, electricity prices, and user behavior [3]. Recent empirical studies indicate that electric vehicle charging loads exhibit strong temporal uncertainty and significant fluctuations throughout the day, which impose additional pressure on grid operation and load dispatching. In particular, charging demand tends to concentrate during midday and nighttime periods, making accurate load forecasting essential for maintaining distribution network reliability [4-9]. Table 1 shows the comparative analysis of recent review papers on EV Charging during 2020–2025 with proposed paper.

Study	This Paper	Conductive Charging	Inductive Charging	DER Integration	Pricing Schemes	Monte Carlo Modeling	Smart Charging Strategies	Grid Impact Analysis	EV types
[9] (2020)	✓	✓	×	×	×	×	✓	✓	BEV, PHEV
[10] (2021)	✓	✓	×	×	×	×	✓	✓	BEV
[11] (2022)	✓	✓	✓	×	×	×	✓	×	BEV
[12] (2023)	✓	✓	×	✓	×	×	✓	✓	BEV
[13] (2024)	✓	✓	×	✓	✓ (only ToU)	×	✓	✓	BEV
[14] (2025)	✓	✓	✓	✓	✓ (ToU, RTP, CPP, PTR)	✓	✓	✓	BEV, PHEV
[15] 2025	✓	✓	×	×	✓	✓	✓	✓	BEV
[16] 2025	✓	×	✓	✓	✓	✓	✓	✓	BEV, PHEV

Table 1. Comparative Analysis of Recent Review Papers on EV Charging (2020–2025)

2. Architectures and Communication Technologies for Smart Charging

The rapid growth of electric vehicles requires modern energy systems to adopt new strategies for efficiency, reliability, and stability. One of the most important solutions in this field is smart charging, which optimizes the charging process based on grid conditions, energy availability, tariffs, and user requirements. Smart charging relies on two core components: system architecture and communication technologies. Recent literature highlights that the integration of artificial intelligence, Internet of Things, and edge computing enables real-time monitoring and adaptive control of energy-intensive systems, which is highly suitable for smart electric vehicle charging applications. The adoption of edge computing and advanced communication technologies, such as 5G, reduces latency and improves the responsiveness of smart charging systems, particularly in large-scale charging infrastructures. Together, they enable intelligent, flexible, and grid-friendly EV charging. Smart charging architecture defines how EVs, charging stations, grid operators, and control centers interact. One widely used model is the centralized architecture, in which all decision-making is performed in a central management system or cloud platform. This structure is suitable for large charging networks because it provides accurate monitoring, coordinated control, and efficient load balancing [9-12]. A more flexible approach is the decentralized architecture, where some decisions are made locally by the charging station or local controller. This reduces communication delays and improves the system's ability to react to sudden changes in grid load. The most advanced concept is the distributed architecture, where each EV or charging point operates with high autonomy and can make independent decisions using IoT and edge-computing technologies. This architecture offers scalability and faster local response. Another emerging direction is Vehicle-to-Grid architecture, which allows EVs not only to consume electricity but also to supply it back to the grid [13]. This enables peak-load reduction, renewable energy integration, and improved grid stability. Reliable communication is essential for smart charging systems to function effectively. The most widely adopted protocol is the Open Charge Point Protocol, which manages communication between the charging station and the backend platform. OCPP enables remote control, session monitoring, billing, firmware updates, and overall system interoperability. For direct EV-to-charging-station communication, the ISO 15118 standard is used. It supports secure identification, encrypted data exchange, and the well-known "Plug and Charge" feature, which automates authentication and payment. ISO 15118 also provides the communication framework necessary for implementing V2G services [14]. Wired communication methods include Power Line Communication, which transmits data over existing electrical cables, making it ideal for EV-EVSE interactions. Ethernet and fiber-optic connections are used in large-scale charging infrastructures to provide high reliability and bandwidth. Wireless communication technologies also play an important role. Wi-Fi, ZigBee, Bluetooth Low Energy, 4G/5G, and NB-IoT are frequently implemented for real-time monitoring, control, and data exchange. Among these, 5G is especially promising due to its low latency, massive device connectivity, and suitability for real-time V2G energy transactions [15]. Recent studies widely adopt Monte Carlo–based approaches to model the stochastic nature of electric vehicle charging behavior. By incorporating random variables such as arrival time, initial state of charge, and charging duration, these studies generate probabilistic charging scenarios and realistic aggregated EV load profiles. By incorporating probabilistic distributions of daily mileage, initial state of charge, and charging start time, Monte Carlo-based models are able to capture realistic charging behavior and load uncertainty under different operational scenarios. Recent literature demonstrates that Monte Carlo simulation is an effective approach for modeling the stochastic nature of electric vehicle charging loads. By incorporating probabilistic distributions of daily mileage, initial state of charge, and charging start time, Monte Carlo-based models are able to capture realistic charging behavior and load uncertainty under different operational scenarios. Recent empirical studies further confirm that Monte Carlo simulation is particularly suitable for capturing the inherent uncertainty of electric vehicle charging behavior. This approach enables probabilistic modeling of key stochastic factors such as daily driving mileage, initial state of charge, and charging start time, which strongly influence the temporal distribution of EV charging demand. By generating a large number of random charging scenarios, Monte Carlo-based methods provide realistic aggregated load profiles and offer valuable insights for charging infrastructure planning and distribution network impact assessment [13-19].

3. Types of Electric Vehicles (EVs)

There are several types of EVs, each with distinct characteristics and power sources. The Battery Electric Vehicle is a fully electric vehicle that operates exclusively on electrical energy stored in a battery pack. Unlike conventional vehicles, BEVs do not include an internal combustion engine and rely solely on electric motors for propulsion. The energy required to operate a BEV is supplied by a high-capacity rechargeable battery, which is charged by connecting the vehicle to the electrical grid through various charging levels, including AC Level 1, AC Level 2, and DC fast charging. The electric motor converts the stored electrical energy into mechanical energy, which drives the vehicle's wheels. BEVs are recognized for their environmental benefits, as they produce zero tailpipe emissions, contributing to the reduction of greenhouse gases and air pollution. Additionally, BEVs offer higher energy efficiency compared to internal combustion engine vehicles due to fewer energy conversion losses. From an operational perspective, BEVs have lower running costs because electricity is generally cheaper than fossil fuels, and the vehicles require less maintenance. The absence of components such as fuel tanks, exhaust systems, and complex engines reduces maintenance needs significantly. However, BEVs face several challenges, including limited driving range depending on battery capacity, longer charging times compared to conventional refueling, and the need for widespread charging infrastructure. Despite these challenges, advancements in battery technology and the expansion of charging networks continue to improve the practicality and adoption of BEVs globally. Examples of commercially available BEVs include the Tesla Model 3, Nissan Leaf, Hyundai Ioniq 5, and Chevrolet Bolt EV, which demonstrate the growing shift toward sustainable transportation [20].

The Hybrid Electric Vehicle is a vehicle that uses both an internal combustion engine and an electric motor to provide power. The battery in an HEV is charged in two main ways. First, it charges through regenerative braking, which means the vehicle captures energy when slowing down or braking and converts it into electricity stored in the battery. Second, the battery is charged by the internal combustion engine while the car is running. HEVs do not require external charging from the electric grid. Instead, the system automatically switches between the engine, the electric motor, or both, depending on driving conditions. For example, during low-speed driving or when starting the car, the electric motor provides power. During high speeds or heavy acceleration, the internal combustion engine provides more power, sometimes with assistance from the electric motor. HEVs are designed to improve fuel efficiency and reduce emissions compared to traditional vehicles. They help save fuel, especially in stop-and-go traffic where the electric motor is most effective. However, HEVs cannot run on electricity alone for long distances because the battery is smaller compared to plug-in hybrids or fully electric vehicles. Some popular examples of HEVs are the Toyota Prius, Honda Insight, Hyundai Ioniq Hybrid, and Ford Escape Hybrid. These vehicles offer better fuel economy and are more environmentally friendly than conventional gasoline vehicles while not requiring any external charging [21].

The Plug-in Hybrid Electric Vehicle uses both an internal combustion engine and an electric motor for power. Unlike Hybrid Electric Vehicles, the battery in a PHEV is larger and can be charged by plugging the vehicle into the electrical grid. This means the battery can be charged externally at home or public charging stations. PHEVs can drive on electric power alone for a certain distance, usually between 40 and 60 kilometers, before the internal combustion engine turns on to provide additional range. This allows drivers to use electricity for short trips and switch to gasoline for longer drives. Because of this dual power source, PHEVs offer greater fuel efficiency and lower emissions compared to traditional vehicles. Popular examples of PHEVs include the Toyota Prius Plug-in and the Mitsubishi Outlander PHEV [22].

The Fuel Cell Electric Vehicle is an electric vehicle that generates electricity onboard using a fuel cell system. Instead of storing electricity in batteries like Battery Electric Vehicles, FCEVs produce electricity in real time through a chemical reaction between hydrogen and oxygen. Hydrogen gas is stored in high-pressure tanks inside the vehicle. When the vehicle operates, hydrogen reacts with oxygen from the air inside the fuel cell stack, producing electricity that powers the electric motor. The only by-product of this reaction is water vapor, which makes FCEVs environmentally friendly with zero harmful emissions. FCEVs refuel by filling the hydrogen tanks, which takes about 3 to 5 minutes - much faster than charging a battery electric vehicle. They also offer a long driving range, typically between 400 and 600 kilometers depending on the model and tank size. However, there are some challenges. Hydrogen refueling stations are still rare and expensive to build. Most hydrogen today is produced from natural gas, which can have environmental impacts unless produced using renewable energy. Also, storing and handling hydrogen requires special safety measures because hydrogen is highly flammable. The technology and hydrogen tanks are currently more expensive compared to batteries and traditional engines. Examples of FCEVs available on the market include the Toyota Mirai, Hyundai Nexo, and Honda Clarity Fuel Cell [23]. In conclusion, electric vehicles represent a diverse and evolving technology aimed at reducing reliance on fossil fuels and minimizing environmental impact. (BEVs) offer a fully electric solution powered solely by rechargeable batteries. (HEVs) blend traditional engines with electric motors, improving fuel efficiency without needing external charging. (PHEVs) provide flexibility by allowing external battery charging alongside conventional fueling. (FCEVs) use hydrogen fuel cells to generate clean electricity, emitting only water vapor. Together, these technologies contribute to a more sustainable transportation future, each with distinct benefits and challenges that continue to drive innovation and adoption worldwide.

4. Overview on EV Charging

Conductive Charging - This technique, which is popular in many nations, is utilizing a cable to connect EVs to a charging socket. Using a specialized CS, EV owners can use this common connection to charge their cars at home or in public. Onboard and off-board charging are the two categories of AC/DC plug-in charging, as seen in (Fig.1.). Onboard charging, utilized for slower charging and takes place only within the car. By moving the charger outside the EV, off-board charging, on the other hand, allows for faster charging. Standard charging (via cable) is used by well-known EV models like the Tesla Roadster, Chevy Volt, and Nissan Leaf. Inductive Charging- This is also known as Wireless charging, which transfers energy without connecting conducting cables between a source and a load. Another name for this is wireless charging, which moves energy between a source and a load without the need for conducting connections. With benefits including ease of use, dependability, and simplicity, this technique can also be used to charge EV batteries. A WC System uses two coils to more effectively transmit electricity and charge EVs. First, a rectifier and inverter are used to convert the grid's AC mains into high-frequency AC. The receiving coil, which is often placed below the vehicle, transforms the oscillating magnetic flux fields into HF AC. This high-frequency AC is converted into a continuous DC source that powers the EV's onboard batteries. To guarantee steady and secure functioning, the system has communication, power control, and battery management. The efficiency and safety of the charging process are further increased by using magnetic planar ferrite plates on both sides, or the transmitter and receiver, to improve the distribution of magnetic flux and reduce harmful leakage flux. There are two methods for charging an EV's battery pack: static and dynamic wireless charging systems [24].

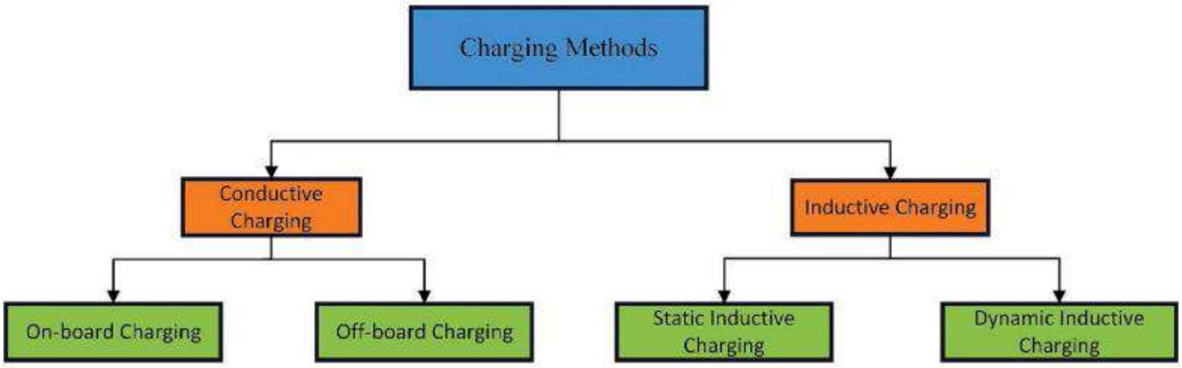

Fig.1. Charging methods of EVs [25].

5. Impacts of Electrical Vehicles on Grids

Charging patterns and load curves alter as a result of power demands being redistributed via grid-connected electrical charging stations. Users' demands and their patterns of peak and off-peak demand are reflected in the grid load curve [26]. Regulations do not apply to voltage levels. As more people need to be charged, the demand for power is rising. TOU can be implemented into the system to lessen the negative effects on the grid. Time of Use is referred to as TOU. With this type of tariff structure, charges are set for peak and off-peak times based on the division of the day into four sections. It is one of the demand-side management strategies that lowers bills by promoting efficient energy consumption. Power plants schedule their output in accordance with daily electricity demand peaks in order to meet such demands. In the meantime, the power grid plans the supply of electricity and the installation of numerous transmission and distribution devices based on the demands of the power load. A portion of the machinery must be inactive or operating at low load during off-peak hours. Costs are higher during load-peak periods since all equipment is in operation [27]. In the past, lower costs were achieved by using only a small amount of infrastructure for distribution, transmission, and generating in order to balance supply and demand. Therefore, it is reasonable and feasible to charge varied rates for power during different usage hours, according to economic principles. The implementation effect indicates that the leverage of the energy price market is significantly impacted by TOU pricing. It has the capacity to increase the economic benefits of a whole power system while ensuring that supply and demand balance is maintained by reducing excessive energy growth during peak hours and increasing power consumption during the valley time [28]. By shifting power use from peak hours to a flat part of the day, known as the valley period, the TOU pricing structure will promote the usage of electric vehicles. In order to reduce power production costs and preserve supply and demand equilibrium, electric utilities will alter consumers' consumption habits through TOU pricing [29].

6. Literature Review

The study first describes the power topologies used in EV charger installations and then examines how different charger topologies impact grid performance. The impact of electric vehicles on grid power quality, electrical system components, and the grid performance indicator is also covered in detail. A brief review of the numerous assessments and research projects carried out to ascertain the impact of rising electric vehicle penetration on the electrical grid's distribution side Various approaches to strengthening the existing structure and enhancing grid performance are discussed [30]. The impact of battery charging on the grid, considering both conventional and smart charging models, has been studied, and the same model has been utilized to introduce the concept of Vehicle-to-Grid [31]. Regarding the distribution of EV chargers at various operating locations, various findings have been presented. The author also concentrated on various interruptions brought on by electric vehicle charging. The author has also concentrated on several viewpoints that can be examined in subsequent research [32]. In order to assess the impact of EV charging on the grid during peak and off-peak hours, a model was developed and validated through real-time simulation. Three distinct charge types have been depicted, and their combinations have been examined [33]. The role of charging stations in grid availability has been studied, and a model has been developed to analyze the system's availability, maintenance, and reliability. Because charging station dependability is so important, it has an impact on how well PEV stations operate. According to the author of this study, load shedding is a significant problem in some nations and, as a result, users have less hours for charging, which is a major difficulty with availability. The author has ultimately come to the conclusion that dependability and availability decline with time [34]. The study has identified multiple challenges and issues associated with electric vehicle charging in India, affecting both the power grid and overall infrastructure [35]. The social, economic, technological, and environmental elements influencing the Uzbekistan electric car market are being examined [36]. In addition to covering various charging technologies, standards, and optimization strategies, the study has provided several recommendations to minimize peak load on the grid [37]. In recent modeling-based studies, Monte Carlo simulation has been widely adopted to analyze large-scale EV charging load uncertainty under real-world operating conditions. Such studies demonstrate that charging demand typically exhibits multi-peak characteristics, often concentrated around midday and nighttime periods. These findings highlight the importance of probabilistic approaches for accurately forecasting EV charging loads and supporting grid-aware smart charging strategies [38]. Monte Carlo simulation is employed to capture the stochastic nature of EV charging behavior, including random arrival time, initial SOC, and charging duration. Multiple charging scenarios are generated to obtain realistic aggregated EV load profiles [39]. The study provides a brief overview of the obstacles and challenges faced by electric vehicles in India, and further highlights Vehicle-to-Grid (V2G) as an innovative concept that can be utilized as an additional power source[40]. Several elements and their effects on the power system have been mentioned in Airport's "Impact of electric vehicle charging on the power grid" (2021). Additionally, it has been examined to determine whether the current power grid can meet the charging demands from electric vehicles [41]. The study discusses various power quality issues, employing a Simulink model for their assessment and measurement. The influence of simulation-based e-mobility data has been analyzed using several random parameters. Furthermore, a case study on a retail mall has been carried out to evaluate power demand and perform a comprehensive financial analysis [2,42]. An overview of optimal charging approaches and the deployment of different pricing schemes has been presented. In addition, dynamic pricing strategies have been recommended to enhance the management of electric vehicle charging. The NREL (2020) study highlights the importance of employing different modeling techniques aimed at minimizing infrastructure needs, mitigating peak demand charges, and optimizing onsite energy generation. The author of this study discussed an energy modeling process that examined the potential effects of EV charging on building load profiles and infrastructure requirements in mixed-use communities [43].

7. Replacement with Distributed Energy Resources

Distributed Energy Resources, including solar photovoltaic systems, battery energy storage systems, and other localized generation sources, play a significant role in mitigating the negative impacts of electric vehicle charging on the distribution network. Despite the growing adoption of EVs, the absence of DER integration can lead to challenges such as local peak load increases, voltage drops, and transformer overloading, particularly in residential and commercial areas with high EV penetration. DERs contribute to addressing these challenges by providing localized energy generation and storage, thereby reducing the dependency on the centralized grid during peak charging periods. For example, solar PV systems installed at homes, commercial buildings, or EV charging stations can supply renewable energy directly to EVs, especially during daylight hours. This reduces the instantaneous demand on the grid and helps in flattening peak loads. Furthermore, battery energy storage systems complement solar generation by storing excess energy during low-demand periods or high solar production and discharging it when EV charging demand increases, typically during evening peaks when solar output is low. This load shifting helps maintain voltage stability, reduces stress on distribution transformers, and mitigates line congestion. Integrating DERs with smart energy management systems enables dynamic coordination between EV chargers, solar generation, and battery storage. For instance, during periods of high grid demand or low voltage, the system can prioritize the use of stored energy or local PV generation to supply the EV chargers, effectively acting as a peak-shaving mechanism. Additionally, DERs can support islanding modes during grid outages, allowing critical EV charging infrastructure to remain operational. In broader terms, DERs contribute to enhancing the resilience, reliability, and sustainability of the distribution network in the presence of increasing EV loads. The integration of DERs, particularly solar PV combined with battery storage, offers a highly effective solution to local grid issues caused by EV charging. It not only supports the transition to clean energy but also ensures that the distribution network can accommodate higher EV penetration without significant infrastructure upgrades [43]. Recent studies show that integrating distributed energy resources, such as solar photovoltaic systems and battery energy storage, with EV charging stations effectively mitigates peak load growth and enhances voltage stability in distribution networks. When coordinated through smart energy management systems, DER-supported EV charging can significantly reduce grid stress and defer costly network reinforcements [44].

8. IEEE Bus System IEEE 33 Bus System

The IEEE test systems are standardized network models developed by the Institute of Electrical and Electronics Engineers for power system analysis and research. These models are widely used to benchmark simulation results, compare different methodologies, and validate technical solutions in a controlled and repeatable environment. The IEEE 33-bus distribution test system is widely adopted in the literature as a benchmark network for evaluating the impacts of electric vehicle charging on distribution grids. Previous studies employ this test system to analyze voltage deviations, power losses, and load growth under different EV penetration scenarios. The IEEE 33-bus system is highly relevant for analyzing distribution-level challenges such as voltage deviations, power losses, and load growth due to EV integration. The IEEE 33-bus system serves as an effective platform for simulating various scenarios involving different levels of EV penetration, DER deployment, and smart charging strategies. Using this system, previous studies assess how EV charging impacts voltage profiles, power losses, and peak load conditions. It also evaluates how the integration of DER - such as solar PV and battery storage - can mitigate these impacts. The use of the IEEE 33-bus system allows the findings to be standardized, credible, and comparable with another research in the field. It provides valuable insights that can be translated into practical strategies for enhancing the reliability, efficiency, and resilience of distribution networks facing increased EV adoption [8,45,46].

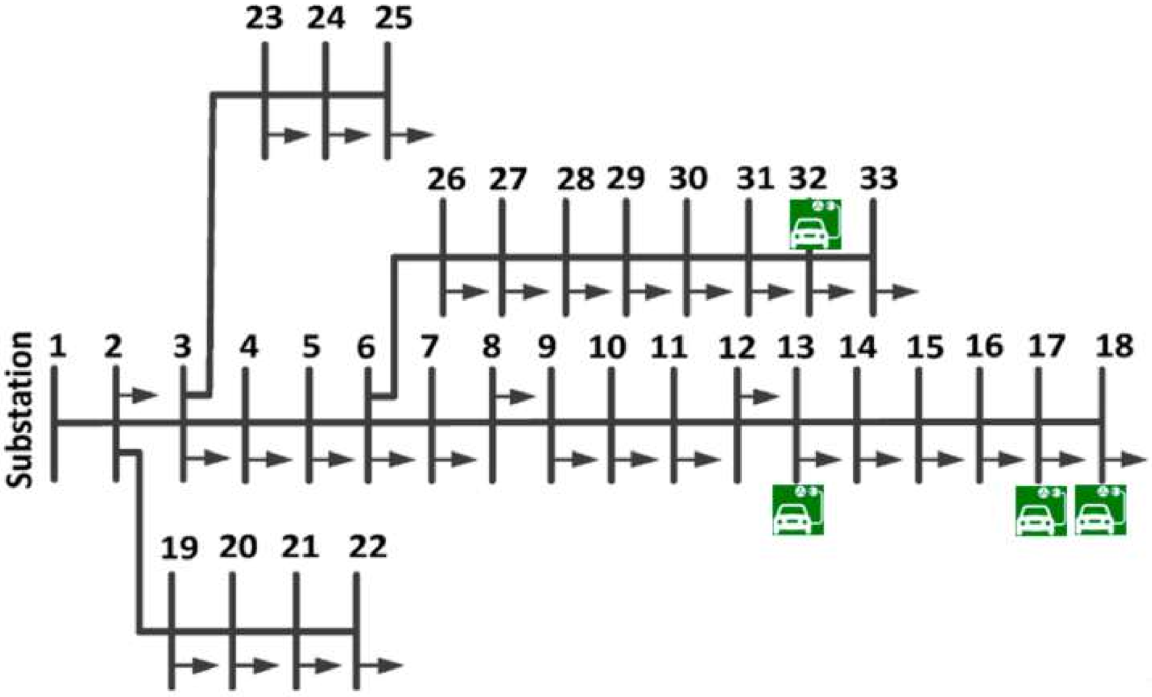

Fig. 2. Placement of EVCS on the IEEE 33 bus network [8,47].

Fig. 2 illustrates the single-line diagram of the IEEE 33-bus radial distribution test system with the integration of electric vehicle charging stations. The system consists of 33 buses connected in a radial configuration, with the main supply coming from the substation at Bus 1. The distribution network branches out into several feeder lines serving different load points. Several studies reported in the literature consider the placement of EV charging stations at different buses of the IEEE 33-bus system in order to investigate localized voltage drops and network stress. Typical placement locations include mid-feeder and end-feeder buses, which are more sensitive to increased charging demand. These buses are strategically selected due to their positions in the network where voltage drops and load impacts are more sensitive to increased demand. The arrows in the diagram indicate the direction of power flow from the substation through the feeders to the respective buses. Each line segment represents a distribution line connecting the buses. The network includes multiple laterals, such as the branches serving Buses 19–22, Buses 23–25, and Buses 26–30, contributing to the overall load distribution. This configuration is commonly used to analyze the impacts of EV charging load on voltage profiles, line losses, and overall network reliability. The inclusion of EV charging stations at different points in the network allows for evaluating how EV demand affects both upstream and downstream nodes in the distribution system. The IEEE 33-bus distribution test system is frequently adopted in the literature as a benchmark network to evaluate the impacts of electric vehicle charging and smart charging strategies on voltage profiles and power losses. In review studies, the IEEE 33-bus system is primarily used as an illustrative platform to compare different charging and control approaches reported in existing research [8,47].

9. Pricing Schemes

Electric vehicle integration into power distribution networks presents significant challenges, including peak load increases, voltage instability, and network congestion. One of the most effective demand-side management approaches to mitigate these issues is the implementation of various electricity pricing schemes that influence consumer charging behavior. This section explores different pricing mechanisms - Time-of-Use, Real-Time Pricing, Critical Peak Pricing, and Peak Time Rebate - their advantages, limitations, and suitability for managing EV charging demand [48].

Time-of-Use pricing is a simple and widely adopted strategy that divides the day into distinct time periods, typically including peak, shoulder, and off-peak hours. Electricity prices are higher during peak demand periods and lower during off-peak times. ToU encourages users to shift their electricity consumption, including EV charging, to cheaper off-peak periods to reduce costs. However, while ToU is straightforward and easy for customers to understand, it presents significant limitations in the context of widespread EV adoption. When a large number of EV users respond similarly to the price signal by shifting charging to the off-peak period, it can unintentionally create a secondary peak during these hours. This load clustering can overwhelm the grid during times originally intended for lower demand, reducing the overall effectiveness of the strategy. Furthermore, ToU pricing does not adapt to real-time grid conditions, limiting its responsiveness to unexpected demand fluctuations or supply shortages.

Real-Time Pricing is a more dynamic pricing mechanism where electricity prices fluctuate frequently - hourly or even every 15 minutes - based on real-time supply and demand conditions in the power grid. RTP provides a highly accurate reflection of grid stress, allowing customers to adjust their EV charging behavior according to actual grid needs. The primary advantage of RTP is its ability to incentivize users to charge their vehicles when electricity is most abundant and least expensive, thereby reducing peak demand and improving grid efficiency. However, implementing RTP requires a sophisticated communication and control infrastructure to continuously relay price signals to consumers. Another major challenge is the complexity and unpredictability of RTP pricing, which may cause confusion and discomfort among users who may struggle to determine the optimal times for charging. Additionally, lack of consumer awareness about real-time grid conditions can limit the effectiveness of RTP-based programs [48-50].

Critical Peak Pricing imposes significantly higher electricity prices during a limited number of critical peak events, usually occurring a few times per year when the grid experiences extreme demand or stress. Outside of these critical periods, customers are charged regular ToU rates. CPP is generally more effective than ToU in controlling peak demand because the high price during critical hours strongly incentivizes consumers to reduce or defer their EV charging. Unlike RTP, CPP events are infrequent, making it easier for customers to adjust their behavior when compared to dealing with constant price variability. Nonetheless, CPP has its drawbacks. The primary challenge lies in the unpredictability of critical peak events. Customers may face uncertainty about when these events will occur, and if notification systems are inadequate, users may not have enough time to react. Furthermore, the sudden imposition of high prices during CPP events can be perceived as punitive, particularly if customers have limited flexibility to shift their charging times [50].

Peak Time Rebate is a pricing mechanism that offers consumers a financial reward for voluntarily reducing their electricity usage during peak periods, rather than penalizing them with higher rates. Under PTR, customers are given a baseline consumption level, and any reduction below that baseline during peak hours qualifies them for a rebate [51,52]. The advantage of PTR is that it uses positive reinforcement rather than punitive price increases, making it more acceptable and attractive to consumers. It encourages voluntary participation in demand reduction and reduces customer resistance often associated with CPP or RTP models. However, the success of PTR depends on several factors, including the accuracy of baseline consumption calculations and the attractiveness of the rebate offered. If the financial incentive is not compelling enough, customers may be less motivated to change their behavior. Additionally, PTR requires reliable measurement and verification systems to track consumption and administer rebates fairly [53,54].

In conclusion, while ToU pricing is easy to implement and understand, it can lead to unintended secondary peaks when most EV users shift their load to off-peak hours. This makes ToU less effective for large-scale EV load management. In contrast, CPP is more effective at mitigating peak loads because it applies strong price signals during the most critical times. However, it comes with the challenge of unpredictability in when peak events occur. RTP offers the highest level of grid responsiveness and economic efficiency, allowing for precise demand shaping according to real-time conditions. Nevertheless, its reliance on advanced infrastructure and the cognitive burden placed on consumers limit its widespread adoption. PTR offers a more customer-friendly approach, leveraging positive incentives rather than penalties, but its effectiveness depends heavily on how attractive and well-structured the rebate program is. Given these observations, relying solely on ToU is often impractical in modern grids with high EV penetration. A more effective approach involves combining different pricing mechanisms - for example, ToU with CPP or RTP supplemented by PTR incentives - to balance grid reliability, customer flexibility, and operational efficiency. Recent literature indicates that dynamic pricing mechanisms, such as real-time pricing and critical peak pricing, are more effective than static time-of-use tariffs in mitigating peak demand caused by large-scale EV charging [55].

10. Conclusion

The widespread deployment of electric vehicles presents both substantial challenges and promising opportunities for power distribution networks. This research demonstrates that uncoordinated EV charging may cause severe operational issues, including peak load escalation, voltage fluctuations, transformer congestion, and increased power losses. To mitigate these impacts, the coordinated application of smart charging methodologies, demand-side management strategies, and distributed energy resources is essential. The reviewed literature consistently indicates that uncoordinated EV charging can significantly increase peak demand, cause voltage instability, and overload distribution network components. Numerous studies employing benchmark test systems, such as the IEEE 33-bus network, highlight the effectiveness of smart charging strategies, distributed energy resources, and dynamic pricing mechanisms in mitigating these impacts. Additionally, the adoption of dynamic electricity pricing mechanisms, including Real-Time Pricing, Critical Peak Pricing, and Peak Time Rebate schemes, is shown to be more effective than conventional Time-of-Use tariffs in shaping consumer charging behavior and achieving improved load balancing. Furthermore, Monte Carlo simulation results emphasize the importance of realistically representing stochastic user behavior when designing and planning robust EV charging infrastructures. Overall, the findings highlight that a comprehensive framework combining advanced charging technologies, adaptive pricing policies, and grid-supportive energy resources is crucial for maintaining the reliability, efficiency, and sustainability of future distribution networks with high levels of EV penetration. Such an integrated approach not only contributes to decarbonization objectives but also improves grid flexibility and economic efficiency.

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