IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

ISI 2023-2024: (0.557) Arab Impact Factor: 1.51 SJIF 2024 = 5.274

Volume 3 | Number 2 | April-June 2025 | Pages 31-46

Article

Evaluating the Influence of EV Charging Patterns on Power Quality Metrics in Modern Electrical Grid

Tariq A. Mohamed[1*], Abdullah A. Buaod[2], Haytham Y. Mustafa[3], Saad. M. Saad[4]

[1]Faculty of Engineering, Omer Al-mukhtar University, El Beida, Libya
[2,3,4] Department of Electrical Technology, College of Electrical and Electronics Technology-Benghazi, Benghazi, Libya

[*]Corresponding author: **Tariq.mohamed@omu.edu.ly**

Received: February 01, 2025 Accepted: April 01, 2025 Published: April 08, 2025

Abstract: This paper indicates a comprehensive evaluation of the impact of electric vehicle (EV) charging on power quality parameters within contemporary electrical distribution networks, with a particular focus on transient behaviors and system stability under varying levels of EV penetration. Leveraging the IEEE 33-bus radial distribution system as a benchmark model, the study employs time-domain ETAP simulations to analyze load flow dynamics, voltage profile variations, and power loss distributions. A comparative investigation is conducted between scenarios with and without the integration of photovoltaic (PV) systems, further augmented by the implementation of Battery Management Systems (BMS) to enable dynamic load control and grid support. The simulation results reveal that the coordinated integration of PV and BMS significantly mitigates voltage deviations, reduces system losses, and enhances grid stability, particularly during peak demand periods. These findings underscore the pivotal role of distributed energy resources (DERs) and advanced energy management strategies in facilitating a resilient and sustainable EV charging infrastructure, which is indispensable for accommodating the anticipated growth in EV adoption.

Keywords: Electric Vehicle (EV) Charging; Grid Stability; Photovoltaic (PV) Systems; Battery Management System (BMS); Power Quality Metrics.

1. Introduction

Electric vehicle (EV) sales continue to exhibit robust growth, with projections indicating that global sales could reach approximately 17 million units in 2024, representing more than one in five vehicles sold worldwide. EVs are steadily advancing toward mass-market acceptance across an increasing number of countries, signaling a pivotal shift in the global automotive landscape. Although challenges such as tightening profit margins, volatile battery material prices, elevated inflation rates, and the gradual phase-out of purchase incentives in certain regions have raised concerns regarding the sector's growth trajectory, global sales data remain resilient [1-3]. During the first quarter of 2024, electric car sales recorded an approximate 25% increase compared to the same period in 2023, maintaining a consistent year-on-year growth trend observed since 2022. Market projections for 2024 suggest that electric vehicles could attain a market share of up to 45% in China, 25% in Europe, and over 11% in the United States [3,4], supported by intensifying competition among manufacturers, continued declines in battery and vehicle costs, and sustained policy interventions aimed at promoting the adoption of zero-emission vehicles.

As electric vehicle (EV) markets continue to expand rapidly, the necessity for an equally robust and accessible public charging infrastructure becomes increasingly critical. While the majority of EV charging currently occurs at residential and workplace locations, evolving consumer expectations are poised to demand equivalent levels of convenience, autonomy, and service quality for EVs as traditionally experienced with internal combustion engine vehicles. This transition underscores the imperative for widespread, reliable, and efficient public charging networks. By the end of 2021, the number of publicly accessible charging points worldwide had approached approximately 1.8 million units, with fast chargers comprising nearly one-third of this total. Notably, approximately 500,000 public chargers were installed in 2021 alone—a figure exceeding the cumulative total available in 2017—reflecting a significant acceleration in deployment efforts [4-6]. However, despite these advances, the growth rate of publicly accessible chargers decelerated to 37% in 2021, a decrease from 45% in 2020 and markedly lower than the average annual growth rate of nearly 50% recorded between 2015 and 2019. Within this expansion, fast charger installations increased by 48% in 2021, marginally higher than the 43% growth observed in 2020, whereas the deployment rate of slow chargers exhibited a pronounced slowdown, growing by only 33% compared to 46% the previous year [7-10]. These trends highlight both the significant progress achieved and the emerging challenges facing the EV ecosystem, particularly the need to sustain and accelerate the deployment of high-capacity, publicly accessible charging infrastructure to meet future demand and support the continued electrification of the transportation sector.

Power quality (PQ) has become a central concern in modern electrical grids, particularly as the integration of distributed energy resources (DERs), electric vehicles (EVs), and advanced power electronic devices continues to transform traditional grid operations [11-16]. Maintaining high standards of power quality is essential to ensuring grid reliability, efficiency, and stability in the face of increasingly dynamic and decentralized energy flows. Key PQ metrics include voltage profile stability, frequency stability, harmonic distortion, power factor, system losses, voltage unbalance, and event-driven reliability indicators. Voltage stability is critical to prevent equipment malfunctions and degradation [17-20], while frequency stability ensures system synchronism, especially under fluctuating renewable and EV loads. Harmonic distortion, caused by non-linear devices such as EV chargers and inverters, can lead to increased losses and equipment damage, making Total Harmonic Distortion (THD) a vital metric. Managing the power factor and reactive power is crucial for maintaining transmission efficiency and supporting voltage regulation, particularly as EV chargers impact network dynamics [21-24].

Additionally, minimizing system losses is essential to preserving network efficiency, with EV load concentrations potentially exacerbating feeder losses if not properly coordinated. Voltage unbalance, often resulting from uneven single-phase loads, can reduce three-phase equipment efficiency and lifespan. Thus, event-driven metrics such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) provide important measures of overall grid reliability [25-28]. In sum, the evolving landscape of electrification demands advanced monitoring systems, adaptive protection schemes, real-time control algorithms, and strategic DER and EV integration to uphold and enhance power quality across modern distribution networks. To provide a structured overview of the current state of research in this domain, Table 1 summarizes recent key studies that have examined the influence of EV charging patterns on power quality metrics in modern electrical grids. The table highlights the major findings of each contribution, offering valuable insights into the evolution of research approaches.

Table 1. summarizes recent key studies that have examined the influence of EV charging patterns on power quality metrics in modern electrical grids.

Ref.	Year	EV	findings
[29]	2025	√	▪ This study develops a stochastic EV modeling framework that captures the inherent uncertainties in EV charging behaviors, including variations in travel distances, arrival and departure times, and individual charging requirements. ▪ Stochastic processes, particularly Monte Carlo simulation techniques, are utilized to realistically model diverse real-world EV charging scenarios. A

			▪ backward–forward sweep load flow algorithm is then applied to assess the impact of these stochastic charging patterns on grid performance. ▪ Simulations reveal that uncontrolled EV charging, especially during peak hours and in areas with constrained grid capacity, can severely exacerbate grid stress. Comparisons with deterministic modeling underscore the necessity of coordinated and intelligent EV charging strategies to maintain grid resilience.
[30]	2025	√	▪ The study introduces a hybrid optimization approach, combining the Dollmaker Optimization Algorithm (DOA) and Contrastive Hypergraph Neural Network (CHGNN), referred to as the DOA-CHGNN technique, for optimizing the placement of Electric Vehicle Charging Stations (EVCS) with integrated Photovoltaic-Battery Energy Storage Systems (PV-BESS) in DC grids. ▪ The primary aim of the proposed strategy is to minimize voltage drops and THD while maximizing overall system efficiency; DOA is employed to optimize EVCS placement, while CHGNN is used to accurately predict dynamic EV load profiles. ▪ Simulation results, conducted within the MATLAB environment, demonstrate that the proposed DOA-CHGNN method achieves superior performance metrics—specifically, a THD of 0.9%, a total system cost of $5,520,000, an execution time of 0.41 seconds, and an efficiency of 98%—compared to other optimization methods like Jellyfish Search Algorithm (JSA), Hybridized Whale Particle Swarm Optimization (HWPSO), and Deep Neural Networks (DNN).
[31]	2025	√	▪ The study presents an artificial intelligence (AI)-integrated optimal charging framework designed to facilitate fast EV charging while alleviating grid stress by smoothing the "duck curve," effectively managing dynamic charging demands. ▪ Data collected from Caltech's Adaptive Charging Network (ACN) at NASA's Jet Propulsion Laboratory (JPL) site were categorized into daytime and nighttime patterns. Charging duration predictions were based on features such as start charging time and requested energy, enabling intelligent scheduling through AI-driven optimization strategies. ▪ The proposed AI-based strategy was evaluated under scenarios involving the integration of 1.5 million, 3 million, and 5 million EVs, demonstrating that without any control strategies, peak loads rise significantly (from around 22,000 MW without EVs to 35,000 MW with 5 million EVs). The implementation of the AI-driven optimization reduced peak demand by approximately 16% for 1.5 million EVs, 21.43% for 3 million EVs, and 34.29% for 5 million EVs.
[32]	2025	√	▪ To address this gap, the study proposes a procedure to estimate future power demand patterns for public car parks under a 2030 scenario, utilizing real-world data collected from various car parks across Italy. ▪ Monte Carlo simulations are employed to generate probabilistic daily power demand curves across different maximum charging power levels, ranging from 7.4 kW to ultra-fast charging, thus capturing the stochastic nature of EV charging behaviors. ▪ Results reveal substantial variability in power demand patterns depending on the type and location of car parks. City center car parks peak in the morning, while railway station and hospital car parks follow transportation and healthcare-related demand profiles. Business area car parks show a strong weekday demand concentration. Furthermore, ultra-fast charging can escalate peak grid demand by up to 210%.

In this context, Khan [33] conducts a detailed investigation into the impacts of large-scale electric vehicle (EV) penetration on low-voltage distribution networks, with particular emphasis on the influence of charging times, charging methods, and EV operational characteristics. The study examines several charging scenarios to assess the effects of EV integration on key grid performance indicators, including power demand, voltage profiles, power quality, and overall system adequacy. A lookup-table-based charging strategy is proposed to facilitate a systematic analysis of large-scale EV deployment impacts. The results reveal that both bus voltages and line currents experience significant deviations during periods of intensive EV charging and discharging. Specifically, residential grid voltage sag increases were observed, ranging approximately from 1.96% to 1.77%, 2.21%, 1.96% to 1.521%, and 1.93% across four distinct EV charging profiles. The findings of this study provide valuable insights that can be utilized in the development of optimized EV charging and discharging strategies aimed at minimizing adverse effects on voltage stability and line current performance within distribution networks. Several studies [34-36] critically examined the challenges associated with the integration of electric vehicles (EVs) into electrical networks and evaluates strategies for their effective mitigation. The research demonstrates that through the implementation of coordinated and synergistic operating strategies, combined with the deployment of advanced technologies and intelligent control systems, the adverse impacts of large-scale EV integration on grid stability and power quality can be significantly alleviated. The development and widespread adoption of these strategic frameworks and technological innovations are pivotal to ensuring the reliability and quality of power supply as EV penetration continues to surge.

In this direction, the rapid proliferation of electric vehicles (EVs) presents both unprecedented opportunities and significant challenges for modern electrical distribution networks. As EV adoption accelerates, the associated charging demand introduces new complexities in grid operation, particularly affecting power quality metrics such as voltage stability, frequency regulation, and system losses. Unlike traditional load profiles, EV charging patterns are inherently stochastic, characterized by high variability in time, location, and intensity, thereby imposing dynamic and often unpredictable stresses on existing infrastructure. This study focuses on evaluating the influence of EV charging behaviors on the performance of electrical grids, with particular emphasis on key power quality indicators under varying penetration levels. Using the IEEE 33-bus radial distribution system as a representative model, detailed simulations are conducted to assess load flow variations, voltage deviations, and energy losses arising from different EV integration scenarios. Furthermore, the analysis explores the effectiveness of incorporating distributed energy resources (DERs)—specifically photovoltaic (PV) systems and Battery Management Systems (BMS)—in mitigating adverse impacts and enhancing overall grid resilience. Through systematically investigating the interplay between EV charging patterns and power quality outcomes, this research aims to provide critical insights into the operational challenges and strategic solutions necessary for developing robust, adaptive, and sustainable grid architectures capable of supporting the future electric mobility landscape.

2. Modeling EV Charging Impact Using IEEE 33-Bus System

This study investigates the impact of electric vehicle (EV) charging on the performance of an IEEE 33-bus distribution network. The study employs a combination of data-driven modeling and power system simulation techniques to analyze the network's behavior under varying EV penetration levels.

A. Data Collection and Preparation:

i. Load Profile: A 24-hour load profile for the IEEE 33- bus system was obtained from [Source of Load Profile Data]. This profile represents the typical daily load demand on the network, including variations in residential, commercial, and industrial loads.

ii. Electrical Vehicle Profile: An EV charging profile was developed based on [source of EV charging data or methodology for creating profile]. This profile incorporates factors such as:

- EV Penetration Level: The number of EVs connected to the grid at different times of the day.
- Charging Behavior: Charging times, charging rates, and state-of-charge (SoC) requirements of EVs.
- Charging Station Locations: The locations of EV charging stations within the 33-bus system.

- Data Format: Both the load profile and EV profile were prepared in CSV format for easy integration into the simulation software.

B. ETAP-Based Transient Load Flow and Dynamic Analysis

- ETAP Software: The study utilizes the Electrical Transient Analysis Program (ETAP) software for power system simulation. ETAP provides a comprehensive platform for modeling and analyzing power systems, including load flow analysis, short-circuit analysis, and transient stability studies.
- Model Development: The IEEE 33-bus test system was modeled in ETAP, including all components such as generators, transformers, lines, and loads. The load profile and EV profile were imported into the model to simulate the impact of EV charging on the network.

C. Time-Domain Load Flow Analysis

- Simulation Parameters: The time-domain load flow analysis was performed over a 24-hour period with a suitable time step to capture the dynamic behavior of the system.
- Performance metrics:
  - Voltage Profile: The voltage at each bus in the system was monitored throughout the simulation period to assess voltage deviations and potential voltage violations.
  - Electrical Losses: Power losses within the network were calculated to evaluate the impact of EV charging on system efficiency
  - Voltage Drop: Voltage drop across each line segment was analyzed to identify potential bottlenecks and areas of concern.

D. Data Analysis and Results

i. Data Extraction: Simulation results, including voltage profiles, electrical losses, and voltage drop data, were extracted from ETAP and processed for analysis.

ii. Visualization: The results were visualized using appropriate graphical tools, such as line charts, bar charts, and heatmaps, to effectively present the findings.

iii. Analysis: The impact of EV penetration levels on system performance was analyzed, with particular focus on:

- The magnitude and duration of voltage deviations.
- The distribution of electrical losses within the network.
- The identification of critical areas with significant voltage drops.

Thus, this study investigated the impact of electric vehicle (EV) charging on the IEEE 33-bus distribution network using data-driven modeling and ETAP-based dynamic simulations. A 24-hour load profile and EV charging behavior model were developed to capture real-world system dynamics, including variations in load demand and EV penetration levels. Through time-domain load flow analysis, key performance indicators—such as voltage profiles, power losses, and voltage drops—were assessed. The results revealed that increased EV charging demand leads to higher voltage deviations and system losses, particularly around clustered charging station locations. However, the integration of photovoltaic (PV) systems and Battery Management Systems (BMS) significantly improved voltage stability and reduced losses. The findings highlight the need for optimized EV charging strategies, demand-side management, and intelligent control frameworks to maintain grid resilience and operational efficiency in the context of growing EV adoption.

3. Results and Dissections

The Results and Discussion section comprehensively examines the IEEE 33-bus test system topology, with a particular emphasis on evaluating grid performance under two distinct scenarios: with and without the integration of photovoltaic (PV) systems. This assessment aims to elucidate the impacts of PV deployment on the operational characteristics, reliability, and efficiency of the distribution network.

A. IEEE 33-BUS TEST SYSTEM TOPOLOGY

Figure 1 illustrates the IEEE 33-bus radial distribution test system, a benchmark model extensively employed for the evaluation of power flow algorithms and the development of distributed energy resource (DER) integration strategies. The topology comprises 33 buses (designated as B1 to B33) interconnected by distribution lines (L1 to L33), forming a medium-voltage network characterized by its radial structure and absence of closed loops. Each bus is associated with electrical loads that simulate residential, commercial, and industrial energy consumption profiles. Notably, specific buses such as B18 and B33 exhibit higher load concentrations and are situated at greater electrical distances from the substation, rendering them more susceptible to voltage drops. In the present study, the IEEE 33-bus test system serves as a foundational model for assessing the integration of electric vehicle (EV) charging stations at buses B20, B28, and B11, alongside photovoltaic (PV) systems deployed at buses B22, B33, and B11. The analysis focuses on the impacts of these integrations on power losses and voltage profiles under varying load conditions.

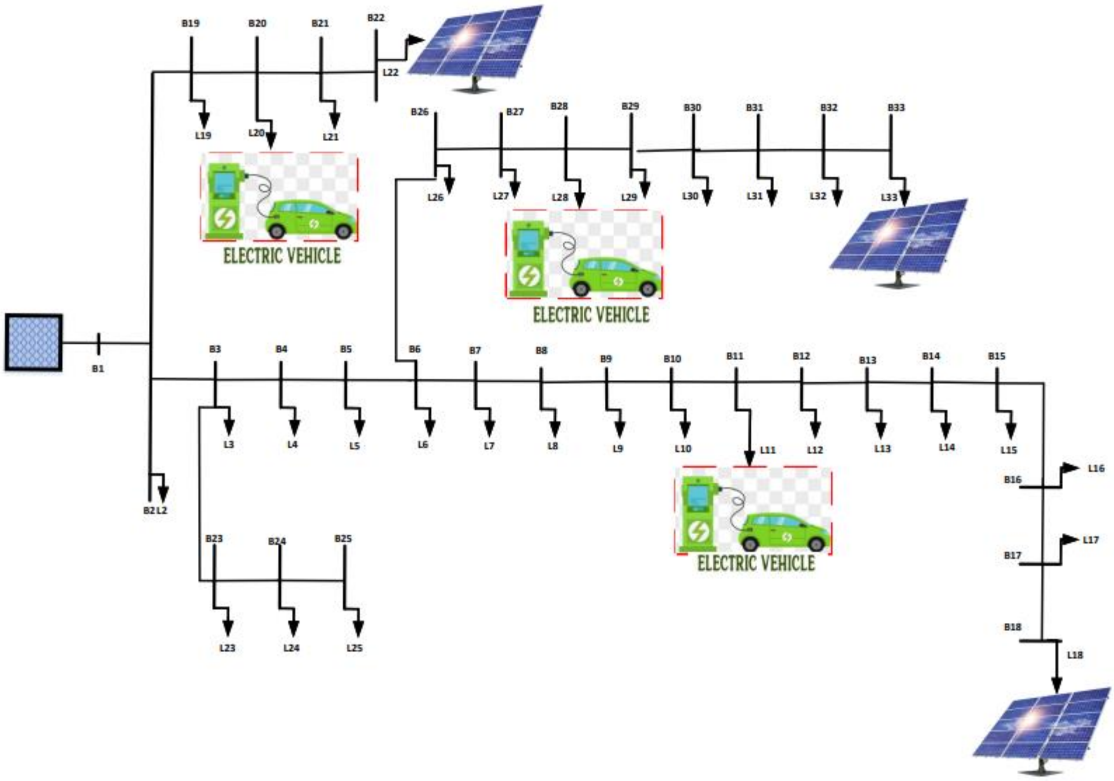

Figure 1. IEEE 33-bus radial distribution test system.

Figure 2 depicts the proposed analytical framework designed to demonstrate and implement voltage profile assessment under varying levels of electric vehicle (EV) penetration, providing a comprehensive technical analysis of the dynamic characteristics of the IEEE 33-bus distribution system. Within this framework, a detailed model of a 4 MW grid-following inverter-based photovoltaic (PV) system is incorporated to facilitate time-domain load flow simulations conducted over a 24-hour period, thereby capturing the system's dynamic operational behavior. The framework integrates a 24-hour load profile with corresponding EV charging patterns, accounting for temporal variations in residential, commercial, and industrial loads as well as the diverse charging behaviors of EVs under different scenarios, including varying penetration rates and charging schedules. This approach enables a systematic evaluation of the IEEE 33-bus distribution network's performance, particularly in terms of voltage stability and load management, under dynamic EV integration conditions.

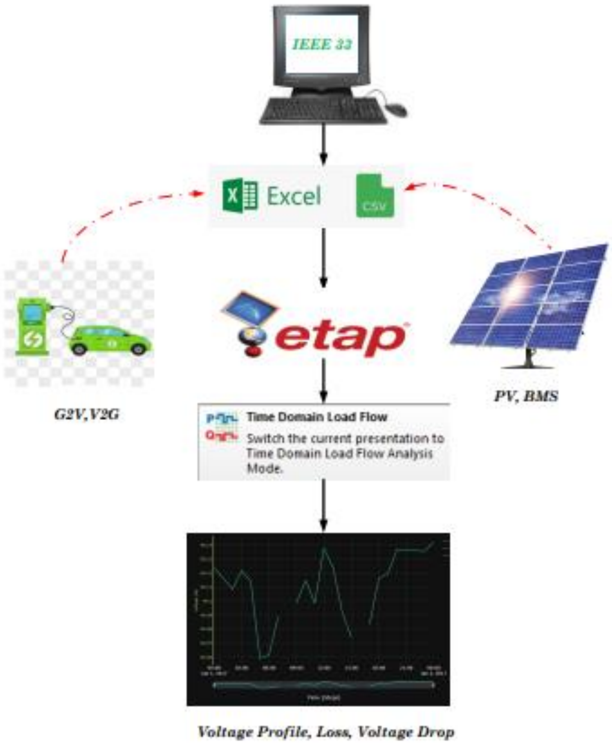

Figure 2. Framework of Proposed Scheme.

B. *Assessing Grid Performance with And Without PV Integration*

i. Without PV

Figure 3 presents the distribution of grid power losses over a 24-hour period, with particular emphasis on the influence of increasing electric vehicle (EV) loads on feeder loss characteristics. The analysis reveals a marked escalation in peak demand between 5:00 AM and 9:00 AM, predominantly driven by the operation of EV charging stations under Grid-to-Vehicle (G2V) mode, which substantially amplifies line losses, particularly along extended feeder sections. In contrast, the deployment of Vehicle-to-Grid (V2G) strategies commencing at 7:00 PM enables power redistribution across the network, contributing to a notable reduction in overall system losses.

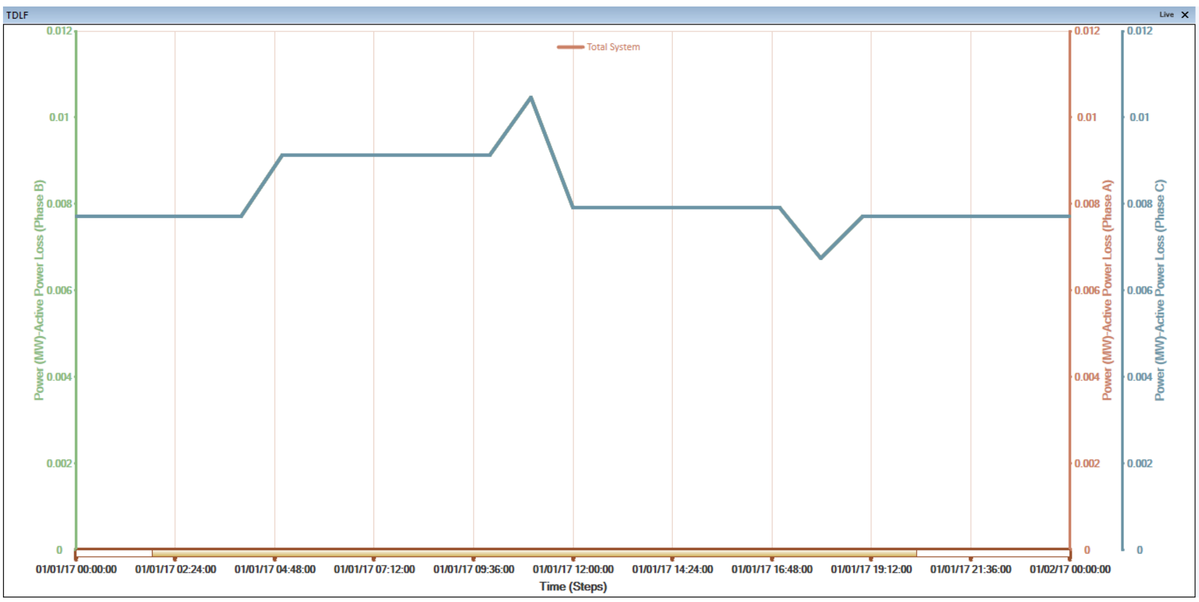

Figure 3. Grid Loss Distribution Over a 24-hour Period.

The power loss profile depicted in Figure 3 underscores the imperative of optimizing EV charging schedules and integrating distributed generation resources to improve network efficiency and reliability. Figures 4 and 5 respectively depict the EV charging demand curve and its subsequent impacts on voltage profiles and voltage drops across the distribution network. Furthermore, Figure 6 illustrates the variability of daily EV charging patterns, which are predominantly shaped by user behavior and state-of-charge (SoC) requirements. The transient responses to dynamic EV load fluctuations are evaluated through ETAP-based simulations, with voltage profiles captured at discrete time intervals. These profiles reveal the system's dynamic behavior under varying load conditions, facilitating the identification of critical buses where voltage thresholds may be violated, thus necessitating the activation of protective schemes to maintain network integrity.

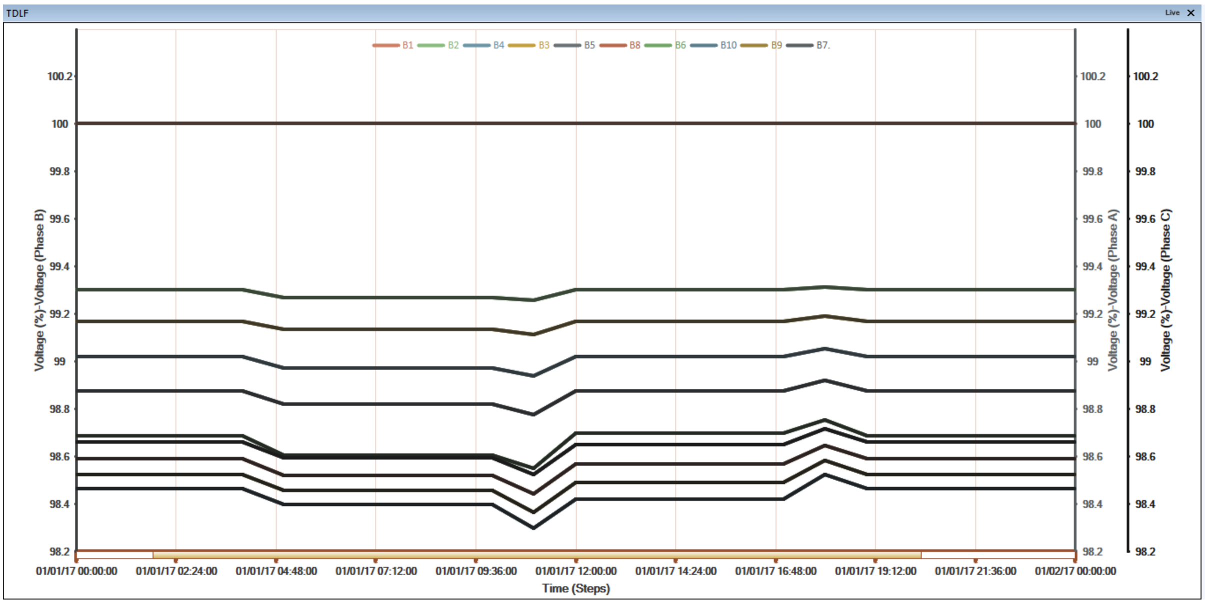

Figure 4. Gird Bus Voltage Profile without PV and BMS System.

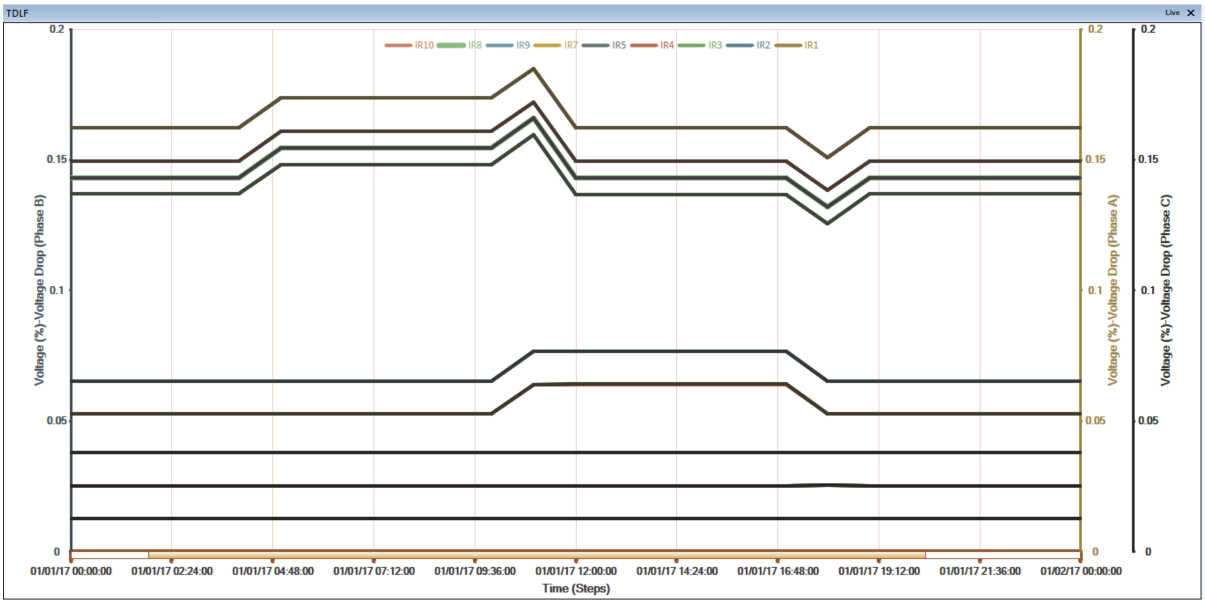

Figure 5. Gird Bus Voltage Drop without PV and BMS System.

These transient vulnerabilities may result in delayed protection system responses, thereby underscoring the necessity for advancements in adaptive relay coordination and settings. As observed in Figure 6, significant evening charging peaks originating from the three charging stations—CS1, CS2, and CS3—are evident, typically coinciding with the return of users to their residences and the subsequent connection of their electric vehicles (EVs) to the grid. This behavior induces substantial load spikes and pronounced voltage depressions, predominantly due to the operation of the Grid-to-Vehicle (G2V) mode at these stations.

Moreover, off-peak periods beginning at approximately 2:00 AM exhibit markedly reduced demand levels, particularly at buses B20, B28, and B11, where vehicles continue to operate under G2V mode within an extended eight-hour charging window, as illustrated in Figure 7 through the corresponding grid power loss profiles. This decline in system load during off-peak hours presents a strategic opportunity for the implementation of load-shifting techniques aimed at enhancing system efficiency. The occurrence of pronounced load peaks further highlights the critical importance of implementing demand-side management (DSM) initiatives and introducing time-of-use (ToU) tariff structures to incentivize charging during off-peak intervals. Additionally, the deployment of advanced Battery Management System (BMS) strategies can play a pivotal role in mitigating demand variability, thereby contributing to improved voltage stability and overall grid resilience during peak load periods.

i. With PV

A comparative analysis is conducted between scenarios with and without photovoltaic (PV) system integration to evaluate improvements in voltage support and reductions in power losses. Battery Management Systems (BMS) were implemented for six PV system batteries—two batteries at each of the nodes B22, B33, and B18—establishing a coordinated Grid Support Mechanism. Under this framework, PV inverters dynamically regulate their output in response to real-time variations in solar irradiance and grid demand, while continuous voltage monitoring at the battery-associated buses facilitates effective mitigation of power loss issues. As illustrated in Figure 7, the integration of PV systems yields a significant reduction in voltage deviations and feeder losses, particularly at critical nodes, during periods when EV charging stations located at B28, B20, and B11 operate under Grid-to-Vehicle (G2V) mode, specifically between 5:00 AM and 2:00 PM. The BMS configuration, in conjunction with real-time voltage measurements, enables dynamic switching between charging and discharging states of the batteries. As shown in Figure 8, when the voltage at the battery buses exceeds 98.5% of the nominal value, the BMS triggers a transition to the charging state, thereby enabling the batteries to contribute active power to the grid, enhancing system voltage stability and reducing dependency on centralized generation.

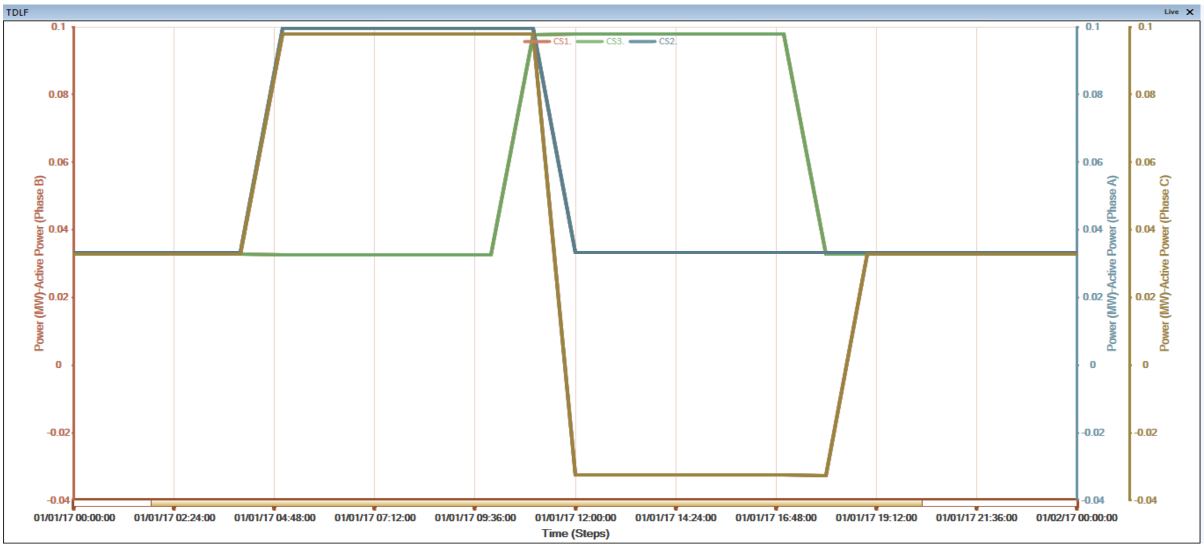

Figure 6. Load Profile of Three Charging Stations in The Grid without PV and BMS System.

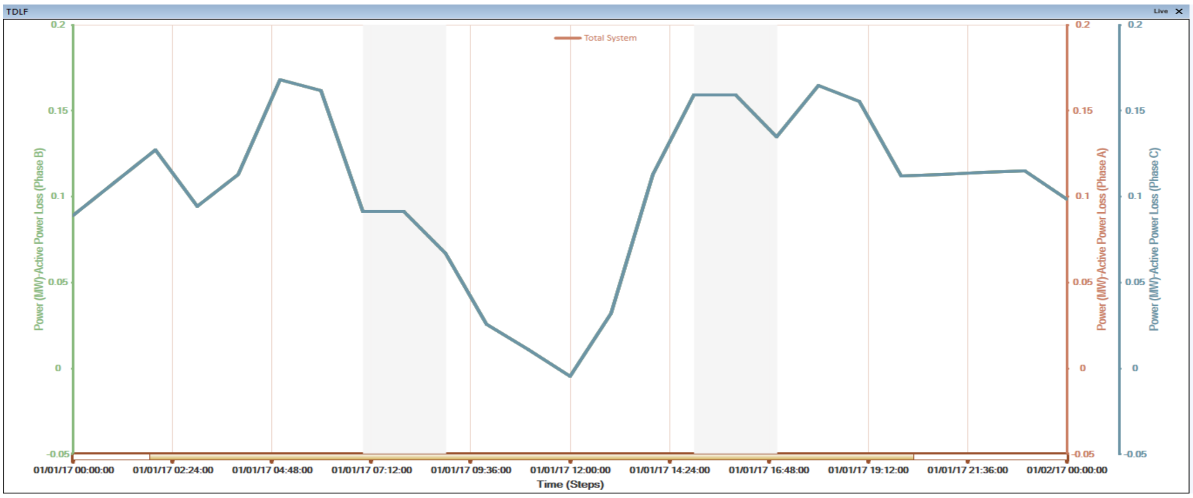

Figure 7. Power losses in the grid.

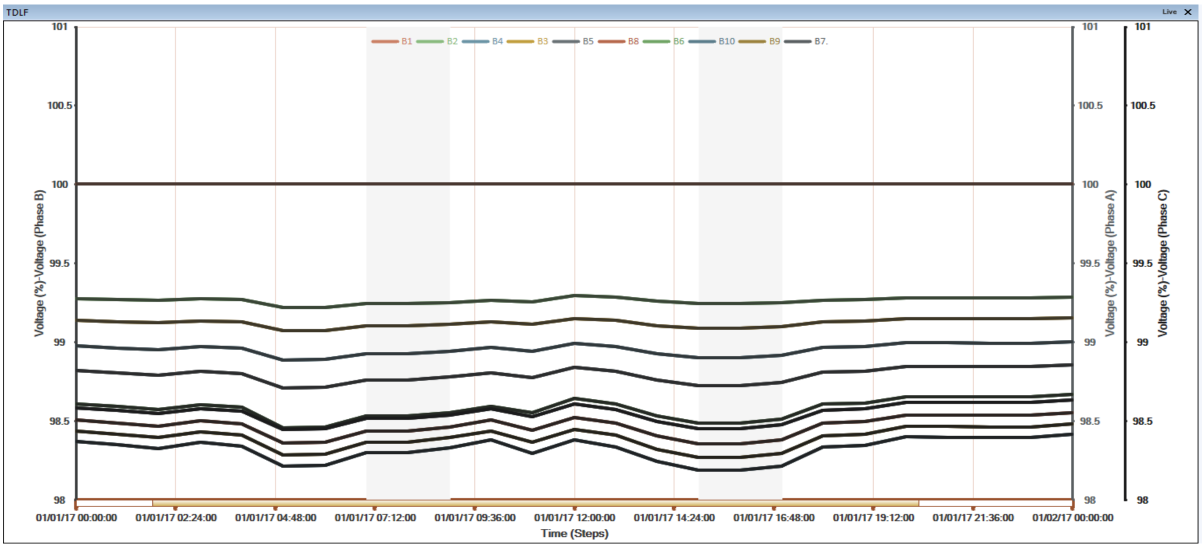

Figure 8. Gird Bus Voltage Profile with PV and BMS System.

Conversely, when the voltage at the battery buses falls below 97.8% of the nominal value, the Battery Management System (BMS) initiates a transition to the discharging state, permitting the batteries to draw active power from the grid to maintain operational equilibrium. The deployment of the Dynamic BMS strategy further enhances the stability of voltage profiles, underscoring the critical role of smart inverter technologies in modern distribution networks. Figure 9 illustrates the variations in active power profiles across the IEEE 33-bus system over a 24-hour simulation period encompassing electric vehicle (EV) charging activities. The proposed BMS framework effectively manages excess power absorption during peak demand periods and provides reactive power support during voltage sag events, thereby reinforcing system resilience. Moreover, the coordinated switching strategy between Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operational modes, as detailed in Figure 10, facilitates the bidirectional flow of power between EV batteries and the grid. This dynamic interaction, contingent upon the state of charge and operational conditions of the EV batteries, significantly contributes to the stabilization of both active and reactive power within the network. Additionally, the strategic optimization of EV charging station placement emerges as a vital consideration for achieving a more balanced load distribution across the distribution system, thereby enhancing overall grid performance and mitigating localized congestion.

In the absence of photovoltaic (PV) system support, power losses tend to escalate during periods of elevated electric vehicle (EV) charging demand, thereby exacerbating inefficiencies, particularly along extended feeder systems. However, the integration of PV generation, combined with the operational control provided by the Battery Management System (BMS), results in a substantial reduction in these losses, especially during daylight hours, owing to localized energy production and the consequent minimization of power transfer distances. The performance of the PV systems is inherently modulated by temporal variations in solar irradiance, as illustrated in Figure 11. These fluctuations necessitate the precise and adaptive operation of the BMS, which assumes a pivotal role in sustaining optimal state-of-charge (SoC) thresholds within the PV battery banks. Through dynamic management strategies, the BMS ensures efficient charging processes while simultaneously safeguarding the battery systems against overcharging and deep discharge conditions. Consequently, the energy performance outcomes for the PV battery banks are significantly enhanced, contributing to improved grid stability and reliability.

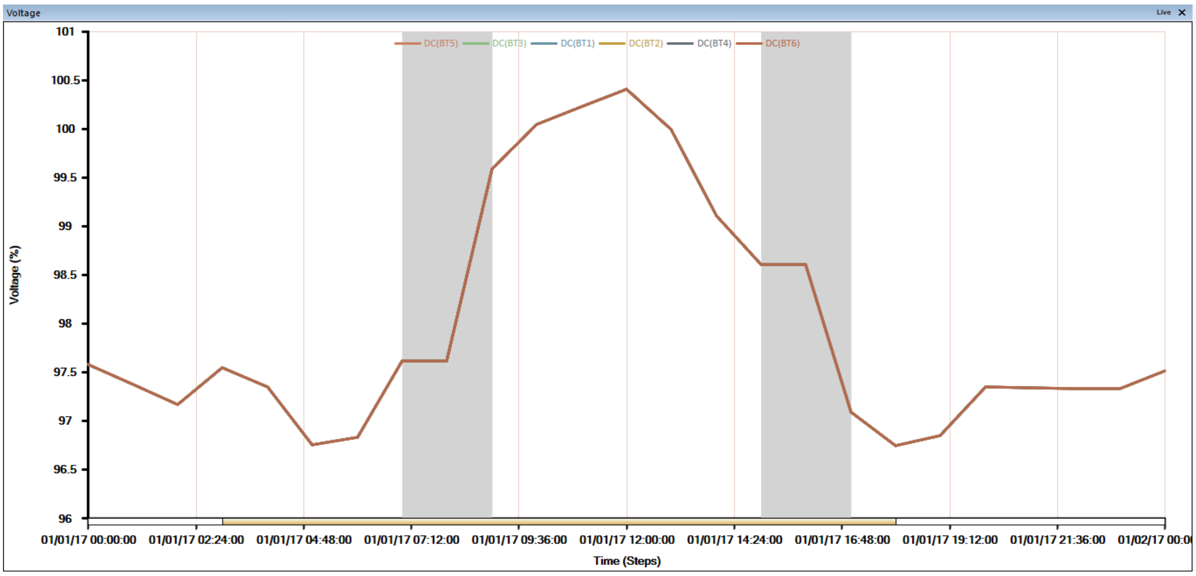

Figure 9. PV Battery Bus Voltage Profile with PV and BMS System.

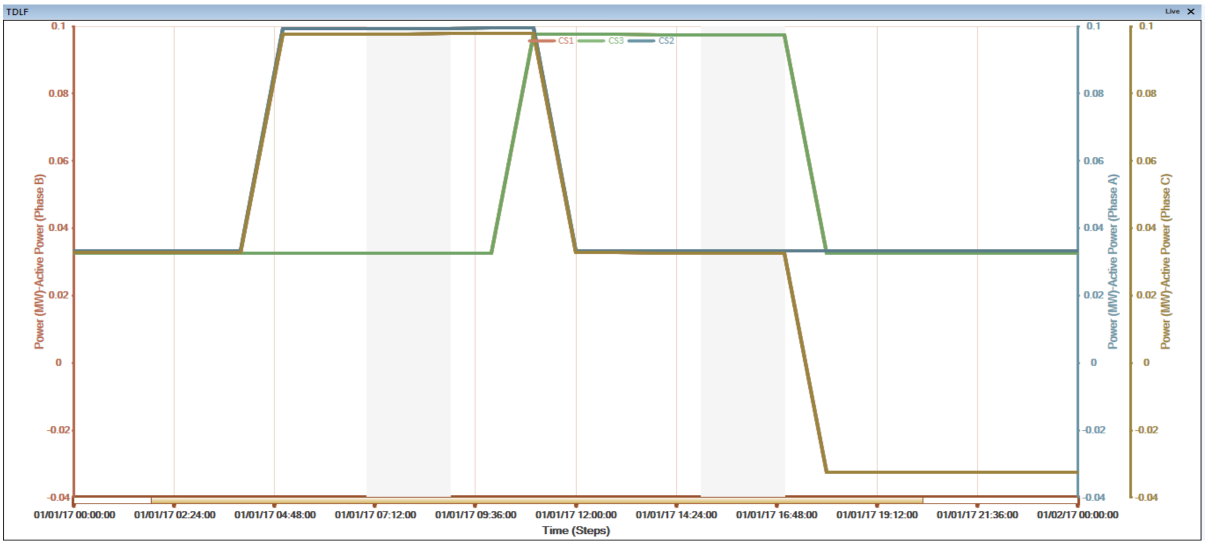

Figure 10. Load Profile of Three Charging Stations in The Grid without PV and BMS System.

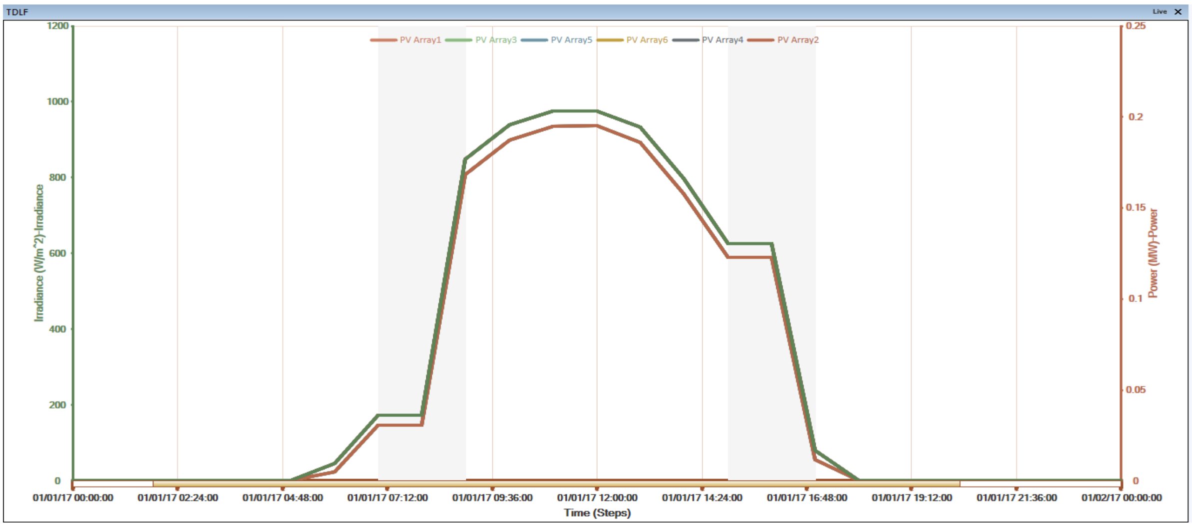

Figure 11. Irradiance Profile for 24-Hour Period.

The voltage profile results obtained through ETAP simulations, as depicted in Figure 12, substantiate the rationale for implementing the BMS-driven grid support mechanism within time-domain load flow analyses to enhance transient voltage stability. Moreover, the dynamic interaction between the BMS and PV inverters emerges as a critical factor in optimizing the distribution of reactive power across the network.

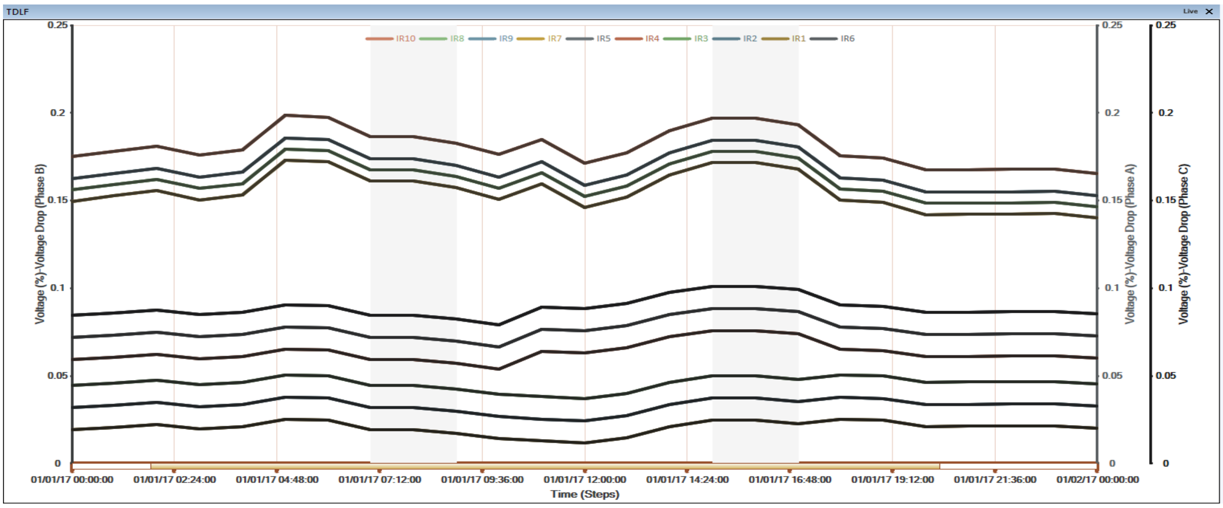

Figure 12. Voltage Drop Profile of Different Buses in The Grid with PV and BMS System.

This coordinated operation is exemplified by the effective load balancing achieved during peak demand periods, facilitated through the strategic discharge of EV batteries back into the grid. Further insights are provided in Figure 13, which presents the state-of-charge (SoC) profile of one of the PV battery systems as managed through BMS control inputs, demonstrating the system's responsiveness to dynamic grid conditions.

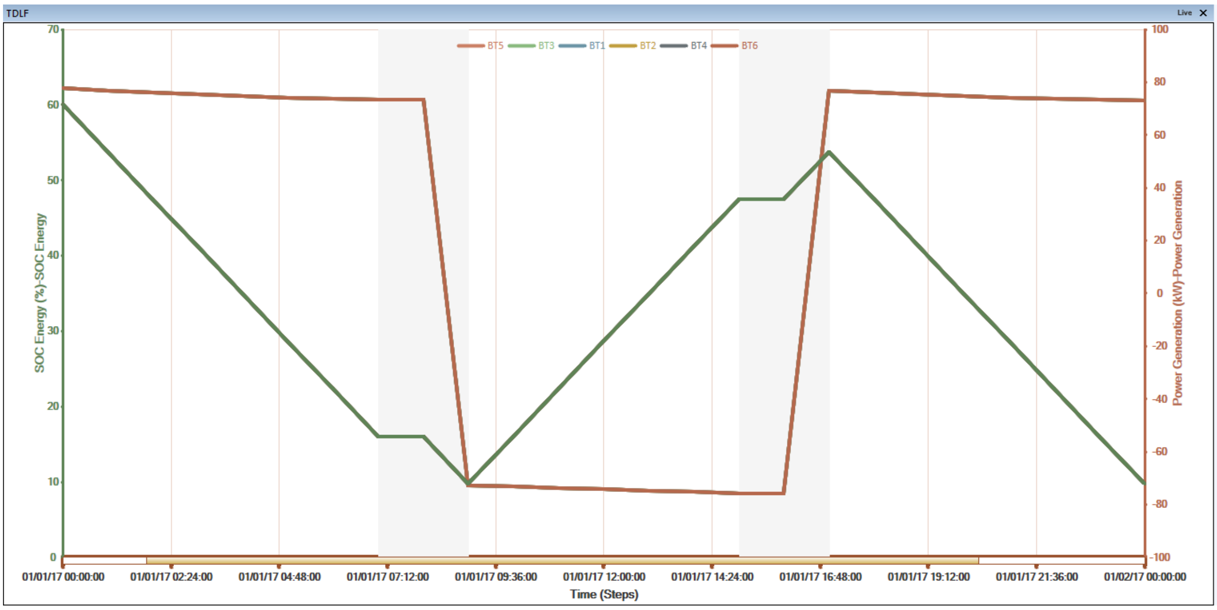

Figure 13. State of Charge of One of PV battery systems Based on BMS Inputs.

4. Conclusion

This study systematically evaluates the critical role of electric vehicle (EV) charging behavior in influencing grid stability, operational performance, and overall system efficiency. Through detailed simulation scenarios conducted on the IEEE 33-bus distribution system, the results clearly demonstrate that the strategic integration of photovoltaic (PV) systems, coupled with Battery Management Systems (BMS), significantly mitigates voltage sag phenomena, reduces active power losses, and promotes a more balanced load distribution across the network. These enhancements are particularly vital in the context of increasing EV penetration, where heightened and irregular charging demand places substantial strain on conventional distribution infrastructures. The findings highlight that PV generation, when synchronized with dynamic BMS strategies, not only provides localized support to mitigate transient voltage disturbances but also alleviates the burden on upstream network elements by reducing power transfer distances. The BMS's voltage-responsive operational framework ensures adaptive control over battery charging and discharging processes, thereby enabling real-time voltage regulation and contributing to the grid's dynamic resilience against fluctuating demand and generation patterns. Given the promising outcomes observed, future research should intensively focus on the development of advanced optimization techniques for BMS configuration, particularly multi-objective strategies that balance SoC preservation, grid support, and lifecycle extension of storage assets. Additionally, the deployment of intelligent enabling algorithms for demand-side management (DSM)—such as real-time load forecasting, predictive EV charging scheduling, and adaptive time-of-use tariff systems—will be pivotal in further enhancing grid reliability, operational efficiency, and economic viability in high-EV, high-renewable penetration scenarios. Moreover, expanding the scope to include stochastic modeling of EV user behavior, solar irradiance variability, and network contingencies would provide a more holistic framework for designing robust, scalable solutions for future smart grids.

Author Contributions: Author has contributed significantly to the development and completion of this article.

Funding: This article received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The author would likes to express their sincere gratitude to Omer Al-mukhtar University, Libya for their invaluable support and resources throughout the course of this research.

Conflicts of Interest: The author(s) declare no conflict of interest.

ORCID
Tariq A. Mohamed https://orcid.org/0009-0003-5238-3576
Abdullah A. Buaod https://orcid.org/0009-0003-3467-9402
Haytham Y. Mustafa https://orcid.org/0009-0005-3059-1379
Saad M. Saad https://orcid.org/0000-0002-8867-0521

References

[1] R. Peng, J. H. C. G. Tang, X. Yang, M. Meng, J. Zhang, and C. Zhuge, "Investigating the factors influencing the electric vehicle market share: A comparative study of the European Union and United States," *Appl. Energy*, vol. 355, no. 122327, p. 122327, 2024.

[2] S. Wang and L. Shi, "EV diffusion promotion analysis under different charging market structure," *Technol. Forecast. Soc. Change*, vol. 208, no. 123730, p. 123730, 2024.

[3] W.-L. Shang, J. Zhang, K. Wang, H. Yang, and W. Ochieng, "Can financial subsidy increase electric vehicle (EV) penetration---evidence from a quasi-natural experiment," *Renew. Sustain. Energy Rev.*, vol. 190, no. 114021, p. 114021, 2024.

[4] M. Khaleel *et al.*, "Electric vehicles in China, Europe, and the United States: Current trend and market comparison," *Int. J. Electr. Eng. and Sustain.*, pp. 1–20, 2024.

[5] M. N. Vivekananda, P. A. Shidlyali, and V. V. Malgi, "Enhancing EV market forecasting accuracy: Integrating machine learning with ARIMA models," in *2024 IEEE International Conference on Communication, Networks and Satellite (COMNETSAT)*, 2024, pp. 445–450.

[6] Z. N. Bampos, V. M. Laitsos, K. D. Afentoulis, S. I. Vagropoulos, and P. N. Biskas, "Electric vehicles load forecasting for day-ahead market participation using machine and deep learning methods," *Appl. Energy*, vol. 360, no. 122801, p. 122801, 2024.

[7] H. J. Kim and M. K. Kim, "Spatial-temporal graph convolutional-based recurrent network for electric vehicle charging stations demand forecasting in energy market," *IEEE Trans. Smart Grid*, vol. 15, no. 4, pp. 3979–3993, 2024.

[8] S. Obrador Rey, L. Canals Casals, L. Gevorkov, L. Cremades Oliver, and L. Trilla, "Critical review on the sustainability of electric vehicles: Addressing challenges without interfering in market trends," *Electronics (Basel)*, vol. 13, no. 5, p. 860, 2024.

[9] A. Jannesar Niri, G. A. Poelzer, S. E. Zhang, J. Rosenkranz, M. Pettersson, and Y. Ghorbani, "Sustainability challenges throughout the electric vehicle battery value chain," *Renew. Sustain. Energy Rev.*, vol. 191, no. 114176, p. 114176, 2024.

[10] R. D. Mishra, S. K. Dash, M. S. Hossain, and A. S. Pillai, "Deep learning insights into India's electric vehicle market: A comparative approach to EV sales forecasting using neural networks," in *Lecture Notes in Electrical Engineering*, Singapore: Springer Nature Singapore, 2024, pp. 61–74.

[11] M. Y. Artemenko, V. V. Chopyk, V. M. Mykhalskyi, and I. A. Shapoval, "Power quality assessment and improvement of grid-tied distributed generation systems," in *Electric Vehicles and Distributed Generation - Microgrid*, New York: River Publishers, 2025, pp. 89–146.

[12] A. Alsharif *et al.*, "Impact of electric Vehicle on residential power distribution considering energy management strategy and stochastic Monte Carlo algorithm," *Energies*, vol. 16, no. 3, p. 1358, 2023.

[13] M. Khaleel, Z. Yusupov, N. Yasser, and H. J. El-Khozondar, "Enhancing Microgrid Performance through Hybrid Energy Storage System Integration: ANFIS and GA Approaches", *Int. J. Electr. Eng. and Sustain.*, vol. 1, no. 2, pp. 38–48, Jun. 2023.

[14] M. Khaleel, S. A. Abulifa, and A. A. Abulifa, "Artificial intelligent techniques for identifying the cause of disturbances in the power grid," *Brilliance*, vol. 3, no. 1, pp. 19–31, 2023.

[15] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, "Impact of mechanical storage system technologies: A powerful combination to empowered the electrical grids application," in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2022.

[16] S. Choudhury and G. K. Sahoo, “A critical analysis of different power quality improvement techniques in microgrid,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 8, no. 100520, p. 100520, 2024.

[17] B. H. Alajrash, M. Salem, M. Swadi, T. Senjyu, M. Kamarol, and S. Motahhir, “A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration,” *Energy Rep.*, vol. 11, pp. 5350–5371, 2024.

[18] M. Khaleel, N. El-Naily, H. Alzargi, M. Amer, T. Ghandoori, and A. Abulifa, “Recent progress in synchronization approaches to mitigation voltage sag using HESS D-FACTS,” in *2022 International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS)*, 2022.

[19] Y. Nassar and M. Khaleel, “Sustainable development and the surge in electricity demand across emerging economies,” *Int. J. Electr. Eng. and Sustain.*, pp. 51–60, 2024.

[20] M. Khaleel *et al.*, “The impact of SMES integration on the power grid: Current topologies and nonlinear control strategies,” in *New Technologies, Development and Application VII*, Cham: Springer Nature Switzerland, 2024, pp. 108–121.

[21] M. Almamoori, M. Almaktar, M. Khaleel, F. Mohamed, and A. Elbreki, “Assessing STATCOM-enabled reactive power control in fragile power transmission systems: A case study perspective,” *Math. Model. Eng. Probl.*, vol. 11, no. 8, pp. 2019–2028, 2024.

[22] A. Alsharif, A. A. Ahmed, M. M. Khaleel, A. S. Daw Alarga, O. S. M. Jomah, and I. Imbayah, “Comprehensive state-of-the-art of vehicle-to-grid technology,” in *2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2023.

[23] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, “Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, no. 100223, p. 100223, 2023.

[24] S. Rajkumar, R. Balasubramanian, and P. Kathirvelu, “A comprehensive review on supraharmonics—the next big power quality concern,” *Smart Grids and Energy*, vol. 9, no. 1, 2024.

[25] M. N. Dehaghani, T. Korõtko, and A. Rosin, “AI applications for power quality issues in distribution systems: A systematic review,” *IEEE Access*, vol. 13, pp. 18346–18365, 2025.

[26] M. Khaleel, Z. Yusupov, M. Elmnifi, T. Elmenfy, Z. Rajab, and M. Elbar, “Assessing the financial impact and mitigation methods for voltage sag in power grid,” *Int. J. Electr. Eng. and Sustain.*, pp. 10–26, 2023.

[27] A. Abodwair, M. Guneser, M. Khaleel, Y. Nassar, H. El-Khozondar, and A. Elbaz, “Feasibility assessment of hybrid renewable energy based EV charging station in Libya,” *jsesd*, vol. 13, no. 2, pp. 311–349, 2024.

[28] M. M. Khaleel, M. R. Adzman, and S. M. Zali, “An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM,” *Energies*, vol. 14, no. 21, p. 7073, 2021.

[29] J. James and Jasmin, “Stochastic modeling of electric vehicle charging and impacts on the grid,” *Electric Power Syst. Res.*, vol. 246, no. 111659, p. 111659, 2025.

[30] C. S. Subash Kumar, R. Saravanan, S. Sankarakumar, and G. Srinivas, “Optimizing power quality and placement of EV charging stations in a DC grid with PV-BESS using hybrid DOA-CHGNN approach,” *Electric Power Syst. Res.*, vol. 245, no. 111595, p. 111595, 2025.

[31] U. Jamil, R. J. Alva, S. Ahmed, and Y.-F. Jin, “Artificial intelligence-driven optimal charging strategy for electric vehicles and impacts on electric power grid,” *Electronics (Basel)*, vol. 14, no. 7, p. 1471, 2025.

[32] S. L. Shimi, R. A. de Oliveira, A. Kumar, and P. Kumar, "Impacts due toVehicle-to-gridand solar photovoltaic integration with the grid: A review," *Smart Electric and Hybrid Vehicles*. Wiley, pp. 55–70, 05-Feb-2025.

[33] M. Khan *et al.*, "Integration of large-scale electric vehicles into utility grid: An efficient approach for impact analysis and power quality assessment," *Sustainability*, vol. 13, no. 19, p. 10943, 2021.

[34] A. Srivastava, M. Manas, and R. K. Dubey, "Integration of power systems with electric vehicles: A comprehensive review of impact on power quality and relevant enhancements," *Electric Power Syst. Res.*, vol. 234, no. 110572, p. 110572, 2024.

[35] M. Abuqila, Y. Nassar, and M. Nyasapoh, "Estimation of the Storage Capacity of Electric Vehicle Batteries under Real Weather and Drive-mode Conditions: A Case Study", *WAUJPAS*, vol. 3, no. 1, pp. 58–71, Mar. 2025.

[36] A. Abodwair, M. Guneser, M. Khaleel, Y. Nassar, H. El-Khozondar, and A. Elbaz, "Feasibility Assessment of Hybrid Renewable Energy Based EV Charging Station in Libya", *jsesd*, vol. 13, no. 2, pp. 311–349, Nov. 2024.