Survey on PWM Controlled Universal Electric Vehicle Battery Charger

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Abstract— **The increasing adoption of Electric Vehicles (EVs) necessitates the development of efficient and universal battery charging solutions. Pulse Width Modulation (PWM)-controlled battery chargers ensure optimal energy transfer, reduce charging time, and enhance battery longevity. This literature review explores various MATLAB/Simulink-based simulation approaches for PWM-controlled universal EV chargers. The review examines control strategies such as Voltage Oriented Control (VOC), Sliding Mode Control (SMC), Artificial Neural Networks (ANN), and Fuzzy Logic Control (FLC), comparing their impact on charging efficiency and power quality. Key findings include the superiority of ANN-based PWM switching in achieving higher efficiency (94-96%), SMC's advantage in stability and transient response, and FLC's effectiveness in adaptive control. Additionally, the study highlights advancements in bidirectional charging, wireless power transfer (WPT), and hybrid energy storage integration for sustainable EV infrastructure. While MATLAB-based simulations validate theoretical efficiency improvements, the need for real-world experimental validation remains a critical challenge. Future research should focus on AI-driven optimization, renewable energy integration, and ultra-fast charging technologies to enhance EV charging sustainability. This review provides insights into the latest developments in PWM-controlled universal chargers, contributing to the advancement of intelligent power electronics for modern transportation systems.**

Index Terms—**EV Charging, PWM Control, MATLAB Simulation, Universal Battery Charger, Artificial Neural Networks.**

I. INTRODUCTION

The global need for sustainable and environmentally friendly transportation drives the rapid shift towards electric vehicles (EVs). Traditional internal combustion engine (ICE) vehicles contribute significantly to carbon emissions and environmental pollution. Governments and institutions across the globe are investing in transport powered by renewable energy, and EVs are considered a suitable replacement. The success of the deployment of electric vehicles largely relies on the efficiency of battery charging systems.

Electric Vehicle Battery Chargers (EVBCs) offer high-speed and reliable charging without compromising battery health. The design issue is to make a universal, efficient, smart EV charger capable of various battery and charging modes. The Pulse Width Modulation (PWM) technique is extensively used to control power and make the EVBC more efficient. PWM chargers can dynamically vary voltage and current to deliver top-notch charging performance, reduce energy losses, and minimize heat dissipation.

A. Importance of MATLAB Simulation in EV Charging

The development of EV battery chargers involves advanced power electronics and control devices that must be tested stringently before being utilized. MATLAB/Simulink provides an environment for simulation and modeling in the virtual space where engineers and researchers can compare multiple charging schemes, optimize power transfer, and reduce experimentation costs. Simulations enable the analysis of power quality indicators such as efficiency, total harmonic distortion (THD), voltage regulation, and transient response.

Using MATLAB, researchers can compare power conversion topologies such as AC-DC rectifiers, DC-DC converters, and bidirectional energy transfer systems. Furthermore, MATLAB simulations allow for real-time testing of machine learning-based charge optimizations, integration of renewable energy sources, and innovative grid communications. This computational approach enables the feasibility of affordable and sustainable EV charging solutions.

B. Overview of Pulse Width Modulation (PWM) Control in EV Charging

PWM is a power control widely utilized in DC-DC and inverters to control power effectively. The fundamental mechanism of PWM lies in varying the

duty cycle of a switching pulse to modulate the average current and voltage transmitted to the battery. In electric vehicle charging systems, PWM facilitates output voltage regulation to accommodate different battery chemistries, such as lithium-ion, nickel-metal hydride (NiMH), and lead-acid batteries.

The key benefits of PWM-based EV charging include:

- Improved efficiency: Reduces energy losses by precisely controlling power transfer.
- Enhanced battery longevity: Prevents overcharging and reduces thermal stress.
- Minimized harmonic distortion: Reduces electrical noise and interference.
- Universal compatibility: Can handle multiple battery types and voltage levels.

PWM-controlled chargers can dynamically change power output according to battery state of charge (SOC), temperature, and real-time demand, allowing optimal charging conditions.

C. Types of PWM-Based Universal EV Chargers
EV chargers must handle multiple battery chemistries and charging levels (slow, fast, and ultra-fast). MATLAB-based simulation models help evaluate different PWM-controlled charger architectures, including AC-DC, DC-DC, bidirectional, and wireless charging systems.

- AC-DC PWM Chargers: AC-DC chargers convert grid AC power to DC power for EV battery charging. MATLAB simulations enable researchers to analyze different rectifier-based topologies such as:
  - Vienna rectifiers: Known for high efficiency and low THD.
  - Multilevel rectifiers: Used for improved voltage regulation and power quality.
  - Bidirectional AC-DC converters: Allow both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) energy flow.
- DC-DC PWM Chargers: DC-DC converters are widely used in onboard EV chargers to regulate voltage levels efficiently. MATLAB models help optimize:
  - Buck, Boost, and Buck-Boost converters for voltage transformation.
  - Power loss minimization strategies using advanced control techniques.

- Dynamic load regulation to accommodate different battery sizes.
- Bidirectional PWM-Controlled EV Chargers: Modern EV chargers support bidirectional energy transfer, enabling vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications. MATLAB-based studies focus on:
  - Controlling bidirectional DC-DC and AC-DC converters.
  - Ensuring grid stability and optimal energy exchange.
  - Renewable energy integration for sustainable charging solutions.
- Wireless EV Chargers with PWM Control: Wireless Power Transfer (WPT) is a promising solution for contactless EV charging. MATLAB-based simulations allow researchers to:
  - Optimize coil alignment and magnetic resonance coupling for high efficiency.
  - Reduce electromagnetic interference (EMI) in wireless charging systems.
  - Implement real-time power regulation using PWM control.

D. Control Strategies for PWM-Based EV Charging
Several control techniques have been developed to enhance charging efficiency, power stability, and battery longevity. MATLAB simulations help analyze and compare these strategies:

- Voltage-oriented control (VOC): VOC is commonly used in three-phase boost rectifier-based chargers to maintain constant DC output voltage and unity power factor. It improves power efficiency and reduces harmonic distortions, making it a reliable control method for grid-connected EV chargers.
- Sliding Mode Control (SMC): SMC guarantees stability against fluctuating load conditions while offering a quick transient response. It advantages non-linear power systems wherein conventional PID controllers are ineffective.
- Fuzzy Logic Control (FLC): FLC is an intelligent control method that dynamically adjusts real-time PWM duty cycles based on feedback. FLC effectively manages non-linear changes in battery charging

characteristics and maximizes energy efficiency.

- Artificial Neural Network (ANN)-Based PWM Optimization: ANN-based control uses machine learning to predict and optimize real-time PWM duty cycles. It reduces switching losses, enhances adaptability, and improves overall power management in EV chargers.

E. Challenges in PWM-Based Universal EV Charging

Despite the advancements in PWM-controlled universal EV chargers, several challenges remain:

- Grid compatibility issues: Fluctuations in supply voltage can affect charging efficiency.
- Harmonic distortions: Power electronics systems introduce THD, impacting power quality.
- Battery degradation: Inefficient charging cycles can accelerate battery wear.
- Renewable energy integration challenges: Solar and wind energy variability requires advanced power management strategies.

MATLAB/Simulink provides a virtual testing environment to address these challenges by enabling real-time control optimizations, power quality analysis, and integration with smart grids.

F. Future Directions in MATLAB-Based EV Charging Research

Research in PWM-controlled universal EV chargers is progressing towards AI-driven optimizations and sustainable energy integration. Future areas of focus include:

- Ultra-fast charging techniques using AI-based predictive control.
- Wireless and bidirectional charging system enhancements.
- IoT-based real-time monitoring and predictive maintenance.
- Cost-effective, scalable, and energy-efficient PWM-based charging architectures.

This introduction provided a general overview of MATLAB-based PWM-controlled universal EV chargers, emphasizing the importance of simulations, control techniques, and charger designs. PWM-based charging enhances energy efficiency, loss minimization, and maximum battery performance. MATLAB is key in designing, testing, and optimizing these charging technologies before implementation. Future research should emphasize real-world application, AI-based optimization, and interface with renewable energy to develop sustainable EV charging systems.

II. LITERATURE SURVEY

Divase et al. (2023) [1] demonstrate a MATLAB/Simulink-based approach to estimating the driving range of electric vehicles (EVs) from battery charge level. The article effectively illustrates the importance of accurate range estimation to enhance EV efficiency and prevent charging issues. It covers key simulation factors such as motor control, battery state of charge (SOC), and driver input adjustments to optimize speed. The inclusion of regenerative braking and power management adds depth to the analysis. Additional empirical validation using accurate EV data to validate simulation results could be provided in the paper. Comparison with other range estimation techniques would also provide it with extra strength. Overall, this research is valuable to EV efficiency research, emphasizing the importance of modeling and simulation in environmentally friendly transport.

Somefun and Longe (2024) [2] present a thorough study of the design and simulation of a DC-DC multi-outlet electric vehicle (EV) charger to achieve improved efficiency and scalability. The paper discusses single and double converter switching modes (SCSM and DCSM), with modeling carried out through MATLAB/Simulink. The charger proposed can handle several battery types of varying voltages and capacities and contributes to sustainable transport solutions. The research emphasizes the importance of control strategies in maximizing charging efficiency through outer and inner loop regulation. The comparison of SCSM and DCSM offers insight into charge stability and energy distribution. Real-world validation is, however, required to determine practical applicability. The research contributes to Sustainable Development Goals by supporting clean energy solutions for urban spaces. The research dramatically advances EV charging infrastructure development by proving possible achievements in new-age charging systems.

Hassanain, Abbas, and Ahmed (2014) [3] discuss a comprehensive study of an HEV battery charger with high performance using Voltage Oriented Control (VOC). The paper maximizes the charging efficiency, battery protection, and unity power factor

operation. The system involves a three-phase boost rectifier with diodes and insulated gate bipolar transistors (IGBTs) that provide bi-directional power transfer. MATLAB/Simulink simulations confirm the efficiency of VOC in delivering a stable DC output voltage, minimizing harmonic distortion, and achieving a unity power factor. The findings exhibit better active power performance, excluding reactive power losses. Still, experimental evidence from real-world experiments would make the study better to accompany simulation results. Nevertheless, this study offers an insightful understanding of efficient charging methods for HEVs, propelling progress in power electronics and green transport.

Aneesha (2024) [4] introduces a new control algorithm for a three-level electric vehicle (EV) charger to enhance efficiency and reduce harmonic distortions. The research emphasizes the importance of voltage-oriented control (VOC) in conjunction with sinusoidal pulse-width modulation (SPWM) to control output voltage and provide sinusoidal input current. The developed charger has three charging levels, making it suitable for various EV battery types, such as lithium-ion and lead-acid batteries. The research tackles primary EV charging concerns, including elevated total harmonic distortion (THD) and battery life issues. MATLAB/Simulink simulation confirms the devised design, yielding a THD reduction to 0.39%, with an almost unity power factor. The simulation results are encouraging, though practical verification and real-world applications are yet to be explored. Experimental verification and incorporating renewable energy sources for green EV charging are possibilities for future work. In general, this study provides significant contributions to advanced EV charger control techniques.

Islam, Rafin, and Mohammed (2023) [5] present a comprehensive overview of power electronic converters for electric vehicle (EV) applications, including AC–DC rectifiers, DC-DC converters, and DC–AC inverters. The article compares converter topologies, control strategies, and efficiency metrics required for contemporary EV powertrains. Some key findings are the dominance of the Vienna rectifier in AC–DC conversion based on its high efficiency and low THD, as well as the efficiency of multi-device interleaved boost converters for DC-DC conversion. The research further investigates multi-level inverters for peak EV drive performance. Also, the paper explains the use of wide bandgap semiconductors (GaN/SiC) for greater efficiency and wireless power transfer (WPT) as a possible solution in future EV charging systems. Although the study presents a good base for EV power electronics, experimental proof of proposed converters would further boost its applicability. Overall, this review is an invaluable guide for EV researchers and engineers.

Sugumaran and Prabha (2023) [6] present a comprehensive overview of DC-DC converter-based topologies and control methods for lithium-ion battery charge equalization, an essential part of electric vehicle (EV) battery management. The paper introduces the rise in popularity of EVs, citing the problems of battery charge imbalance due to production variations. The review categorizes the techniques of battery charge equalization (BCE) as passive and active techniques and claims the benefits of active techniques in minimizing energy loss and maximizing efficiency. Various DC-DC converter topologies, such as buck-boost, Cuk, resonant, and flyback converters, are compared in efficiency, cost, balancing time, and control complexity. The study also explores different control schemes, including voltage-based, capacity-based, and state-of-charge (SOC)-based schemes. While the study is informative, experimental proof and practicality in the real world still need to be established for applicability. This research generally contributes immensely to lithium-ion battery management in EV applications.

Suresh et al. (2025) [7] present a new power conversion approach by incorporating an Artificial Neural Network (ANN) controller within a Universal Converter (UC). The research discusses a multi-purpose converter that can work in five modes: rectifier buck, inverter boost, DC-DC buck, DC-DC boost, and AC voltage control. By utilizing ANN-based control, the system maximizes pulse-width modulation (PWM) switching of six Insulated Gate Bipolar Transistors (IGBTs), maximizing efficiency and flexibility. The experimental results indicate a total harmonic distortion (THD) of less than 5% and efficiency levels between 94% and 96% in DC-DC operations. The ANN controller greatly enhances real-time adaptation, minimizing switching losses and maintaining power stability. Although the hardware development verifies the system's efficiency, future work must investigate the integration with renewable energy sources. This work supports the development of intelligent power electronics for new-generation energy systems.

Zeb and Ahmad (2024) [8] introduce a novel control system for intelligent electric vehicle (EV) charging stations, combining hybrid energy storage and recurrent neural network (RNN)--based maximum power point tracking (MPPT). The research centers on an adaptive barrier super-twisting synergetic sliding mode controller optimized by a genetic algorithm to provide stable transitions in vehicle-to-grid (V2G), grid-to-vehicle (G2V), and vehicle-to-vehicle (V2V) operations. MATLAB/Simulink simulations show better system stability, energy throughput, and lower chattering than traditional nonlinear controllers. A hardware-in-loop (HIL) configuration also confirms the applicability of the suggested system in real-world use. While the study effectively enhances energy management in EV charging stations, further exploration of real-world deployment and cost implications would strengthen its practical feasibility. This research significantly contributes to advancing sustainable charging infrastructure and intelligent energy systems.

Puranik and Shelgaonkar (2024) [9] present a comparative analysis of different control techniques applied to battery charging circuits, focusing on Sliding Mode Control (SMC), Fuzzy Logic Control, and traditional PI and PID controllers. The research points to the growing importance of electric and hybrid vehicles (EVs and HEVs) and underscores the importance of effective battery management systems. The authors apply MATLAB/Simulink simulations to compare the performance of these controllers on stability, efficiency, and transient response. The outcomes illustrate that SMC delivers improved stability and faster convergence with less chattering effects. Fuzzy Logic Control enhances performance at the cost of significant tuning. While more complex, conventional PI and PID controllers have increased settling time and poorer efficiency under dynamic operation. The research concludes that intelligent controllers, such as SMC and Fuzzy Logic, provide better performance in battery charging processes. Future research might address real-world testing and integration with renewable energy sources.

Kumar and Rajan (2024) [10] introduce a new Hybrid Energy System (HES) for efficient, sustainable electric vehicle (EV) charging with the incorporation of photovoltaic (PV) and wind energy sources. The article introduces a High Gain Bidirectional Modified Zeta (HGBMZ) converter to increase PV system efficiency with a Social Spider Optimization Algorithm (SSOA)-aided Fuzzy Maximum Power Point Tracking (MPPT) for maximum energy harvesting. A Doubly Fed Induction Generator (DFIG) controlled with a PI stabilizes wind contribution to the grid. MATLAB simulation confirms the system's efficacy, with a 93.04% efficiency in conversion and a Total Harmonic Distortion (THD) of 3.21%, while experimentally verified as 4.32% THD. The study emphasizes the ability of the system to assimilate excess energy into the grid, enhancing stability in the grid. Whereas the work offers a promising platform, future research can target real-world deployment and cost analysis. This research contributes to the evolution of sustainable EV charging infrastructure.

Geetha and Usha (2024) [11] explore the operation of a high-frequency resonant (HFR) full-bridge inverter in an inductive wireless power transfer (WPT) system for electric vehicle (EV) charging. The research draws on a series-series resonant configuration, focusing on efficiency improvement and stable power transfer. The system, as designed, operates at a resonating frequency of 65 kHz at an input DC voltage of 12V and can transmit 5 kW of power at constant voltage and current. MATLAB/Simulink simulations verify the system's effectiveness with an efficiency of 95%. The research establishes the effect of coil orientation and cross-inductance on power transfer and its implication on wireless EV charging design. However, actual-world verification and integration with grid-connected renewable sources are future research topics. This work generally adds value to promoting efficient and sustainable WPT solutions for EVs.

Al Attar et al. (2023) [12] present an extensive review of DC–DC LLC converters for bidirectional electric vehicle (EV) charging solutions, especially in Vehicle-to-Everything (V2X) systems. The research classifies various modeling techniques, such as small and large signal modeling, and compares several modulation methods like Pulse Frequency Modulation (PFM), Pulse Width Modulation (PWM), and Phase-Shift Modulation (PSM). The study identifies the advantages and disadvantages of every strategy in maintaining stable bidirectional power flow and maximizing efficiency. The paper also addresses control strategies, focusing on robust controllers that improve system stability under varying operating conditions. A comparison of control algorithms, such as Proportional-Integral (PI) control and sliding mode control, is presented. Although the research provides a sound theoretical basis, experimental verification, and practical application would make it even more relevant to

practice. Generally speaking, this review is essential to developing bidirectional EV charging technology. Zhou et al. (2023) [13] present an exhaustive review of power converter topologies and control methods for EV fast-charging systems. The book categorizes the charging infrastructure into the AC/DC and DC/DC conversion stages, introducing various rectifier and converter topologies, including Vienna rectifiers, modular multilevel converters, and bidirectional DC/DC converters. The book emphasizes the importance of power factor correction (PFC), harmonic suppression, and efficient energy management in high-power fast charging. The authors also investigate the impact of fast charging on battery life and grid stability and address the application of advanced control strategies like sliding mode control and artificial intelligence-based optimization strategies. While the work provides a complete technical overview, experimental verification, and cost-benefit analysis would make it more practical. This review is a good reference for researchers and engineers working on maximizing EV charging infrastructure.

Lipu et al. (2021) [14] discuss electric vehicle (EV) converter topologies, control techniques, and optimization techniques in detail. The article categorizes converters as isolated and non-isolated converters and their efficiency, control complexity, and appropriateness for applications. Significant converter technologies such as Cuk, switched-capacitor, quasi-Z-source, and resonant converters are discussed in depth. The paper also assesses conventional and intelligent control techniques such as proportional-integral (PI), fuzzy logic, and artificial neural networks, pointing out their ability to maximize power transfer. Further, the review delves into modulation strategies and metaheuristic optimization algorithms and highlights how they are responsible for enhancing converter performance. The authors highlight key challenges such as high switching losses, stability problems, and computational complexity in real-time control. Although the study provides an exhaustive overview, experimental validation and actual implementation of the explored optimization techniques will enhance its applicability. In general, this research contributes significantly to advancing power electronics for EVs.

Table 1: Systematic Review

Sr. No.	Author(s)	Title of the Project	Methodology	Technical Aspect	Overview
1	Divase et al. (2023)	MATLAB/Simulink-Based EV Range Estimation	Developed a MATLAB/Simulink model to estimate EV range based on battery SOC	SOC monitoring, regenerative braking, power management	Demonstrated efficient SOC estimation but lacked real-world validation
2	Some Fun & Longe (2024)	Design & Simulation of a DC-DC Multi-Outlet EV Charger	MATLAB-based modeling of single and double converter switching	Outer and inner loop control, charge stability	Enhanced efficiency for multiple battery configurations; needs experimental validation
3	Hassanain et al. (2014)	Voltage Oriented Control (VOC) for HEV Battery Charger	MATLAB-based three-phase boost rectifier simulation	Unity power factor, harmonic reduction	Improved power quality but lacks practical implementation
4	Aneesha (2024)	Three-Level EV Charger with SPWM Control	MATLAB/Simulink simulation of sinusoidal PWM-based charging	Total Harmonic Distortion (THD) reduction, multi-battery support	Achieved THD reduction (0.39%); integration with renewable energy unexplored
5	Islam et al. (2023)	Review of Power Converters for EV Applications	Comparative analysis of MATLAB-based converter simulations	AC-DC rectifiers, interleaved boost converters	Showed high efficiency; lacks real-world power electronics validation

6	Sugumaran & Prabha (2023)	DC-DC Converter-Based Lithium-Ion Battery Charge Equalization	MATLAB-based study on buck-boost, resonant, and flyback converters	Active equalization, reduced energy loss	It needs real-world testing for practical feasibility
7	Suresh et al. (2025)	ANN-Based Universal Converter for EV Charging	MATLAB/Simulink-based ANN-controlled PWM power management	Multi-mode converter operation, 94-96% efficiency	Improved adaptive charging; future work should explore renewable energy integration
8	Zeb & Ahmad (2024)	RNN-Based MPPT for Smart EV Charging Stations	MATLAB-based hybrid storage with MPPT and synergetic sliding mode control	Stability improvement reduced chattering	Enhanced energy management; further study needed on deployment costs
9	Puranik & Shelgaonkar (2024)	Sliding Mode vs. Fuzzy Logic Control in EV Charging	MATLAB-based comparison of SMC and FLC controllers	Adaptive PWM control, transient response improvement	SMC offered better stability; FLC required extensive tuning
10	Kumar & Rajan (2024)	Hybrid Renewable Energy System for EV Charging	MATLAB-based Zeta converter modeling integrating PV and wind power	93.04% efficiency, power grid integration	Demonstrated feasibility; lacks large-scale implementation analysis
11	Geetha & Usha (2024)	High-Frequency Resonant (HFR) Wireless EV Charging	MATLAB/Simulink simulation of inductive wireless power transfer (WPT)	Stable transmission at 65 kHz, 95% efficiency	Needs real-world validation for mass adoption
12	Al Attar et al. (2023)	Bidirectional DC-DC LLC Converters for EV Charging	MATLAB-based control comparison of PWM, PFM, and PSM	Power flow optimization, energy stability	Experimental hardware testing required for validation
13	Zhou et al. (2023)	Fast-Charging EV Systems Using Power Converter Topologies	MATLAB-based study on Vienna rectifiers and multilevel converters	Improved power factor, grid stability	Cost-effectiveness of fast-charging infrastructure unexplored
14	Lipu et al. (2021)	Optimization of EV Converter Configurations & Control	Review of MATLAB-based converter topologies and control schemes	Switched-capacitor, quasi-Z-source, fuzzy logic controllers	Computational complexity and high switching losses remain challenges

II. RESEARCH GAP

Despite significant progress in MATLAB-based PWM-Despite advancements in PWM-controlled universal EV battery chargers, several research gaps hinder practical application. A key issue is the lack of real-world testing. Most studies rely on MATLAB/Simulink simulations without hardware implementation, limiting their applicability. Integrating renewable energy sources like solar and wind into EV chargers also poses challenges due to intermittency and synchronization issues. Future research should focus on adaptive energy management to ensure stable and efficient charging. Ultra-fast charging and wireless power transfer (WPT) remain underexplored. Concerns include high power consumption, battery heating, and alignment inefficiencies. AI-powered predictive models can help improve performance and reduce battery degradation.

AI-based innovative charging systems are still emerging. While ANN, RNN, and FLC simulations

show promise, real-time deployment is limited. IoT and AI integration can enable dynamic energy optimization, but real-world testing is lacking. Another gap is the absence of cost-benefit analyses for mass deployment. Technical research often overlooks the economic feasibility and long-term effects on battery life and grid stability. Growing EV usage, grid stability, and power quality are significant concerns. Real-world studies on harmonic distortion and voltage fluctuations are needed alongside adaptive power factor correction algorithms.

Standardization is another hurdle. Universal chargers must support varied battery types and models, but limited cross-validation exists. Research should focus on adaptive systems aligned with global EV standards.

Cybersecurity is an emerging issue. EV chargers connected to smart grids are vulnerable to attacks, yet most research neglects secure authentication and data protection. Addressing real-world testing, AI optimization, renewable integration, cost analysis, grid impact, standardization, and security is crucial for developing sustainable, scalable, and secure EV charging systems.

V. DISCUSSION

The design of PWM-regulated universal electric vehicle (EV) battery chargers has been thoroughly investigated with MATLAB/Simulink simulations, providing information on power conversion efficiency, control techniques, and integration into the grid. Although remarkable achievements have been reported in developing innovative charging structures, some issues remain. Hence, a more intensive discussion of current results, their limitations, and prospects is needed.

One of the most striking results of MATLAB-based simulations is the high efficiency of PWM-controlled power conversion in voltage and current regulation to achieve stable and efficient EV battery charging. It has been proven through studies that Voltage Oriented Control (VOC), Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), and Artificial Neural Networks (ANN)-based PWM optimization considerably improves charger performance. VOC attains power factor correction at unity, SMC enhances stability against dynamic loads, FLC guarantees adaptive control, and ANN-based PWM switching minimizes energy losses and enhances real-time adaptability. Though all these developments have been made, most of these

strategies are confined to simulated environments, not having experimental results to validate their real-world feasibility, scalability, and robust operation.

Integrating renewable energy resources with PWM-charged EVs is another vital topic of discussion. Simulation through MATLAB models proved that hybrid solar PV and wind energy systems can successfully provide EV chargers using intelligent power management techniques. Yet, such implementations in practical applications encounter numerous technical and economic challenges, such as energy intermittence, synchronization of renewable generation with the utility grid, and the prohibitive cost of infrastructure for renewables. Meeting these challenges calls for more research into advanced energy management systems, hybrid storage integration, and predictive control algorithms to adjust power distribution dynamically.

The use of bidirectional charging systems in vehicle-to-grid (V2G) and vehicle-to-home (V2H) has also been widely studied in MATLAB studies. Bidirectional PWM-controlled chargers allow EVs to act as mobile energy storage devices, returning surplus power to the grid during peak demand hours. Though simulations indicate more excellent grid stability and efficiency, real-world challenges such as bidirectional energy flow management, grid compatibility, and the effects on battery aging remain to be solved. Further experimental work needs to ascertain the long-term impact of bidirectional charging on battery life and grid infrastructure.

MATLAB models have shown promising results in ultra-fast and wireless electric vehicle (EV) charging, particularly in high-frequency resonant (HFR) wireless power transfer (WPT) systems. Simulations have shown that coil alignment optimization, impedance matching, and soft-switching techniques can optimize the efficiency of wireless chargers. Electromagnetic interference (EMI), power transmission losses, and safety issues prevent large-scale deployment. In the same way, ultra-fast DC charging stations present battery overheating, high power requirements, and stress on the power grid challenges. Developing machine learning-based predictive thermal management systems and grid-balancing algorithms may be pivotal to overcoming these obstacles.

One of the most crucial discussion areas is the economic viability of PWM-controlled universal EV charging solutions. Most research is devoted to the technicalities of power conversion and optimizing efficiency. In contrast, little work addresses the cost-

effectiveness, return on investment (ROI), and long-term sustainability of operation for these charging technologies. Large-scale implementation of PWM-controlled universal charging solutions necessitates a thorough cost-benefit evaluation, considering manufacturing expenditures, infrastructure spending, energy expenditures, and upkeep costs. Future studies should assess the cost-effectiveness of AI-based and renewable energy-integrated charging systems to enhance scalable and economically viable EV infrastructure.

Another vital concern is large-scale EV charging network power quality and grid stability. With the increasing adoption of EVs, power grid loading increases, and there can be voltage swings and harmonic distortions (THD). MATLAB simulations indicate that THD, voltage stability, and energy efficiency can be improved through adaptive PWM control and power factor correction (PFC) methodologies. However, real-world applications need to consider dynamic grid-balancing solutions, incorporating AI-based load forecasting models to predict and counteract real-time power fluctuations.

The absence of standardization among universal EV charging protocols is another issue that needs to be debated. A universal charger would ideally support more than one battery chemistry and voltage range and adhere to international charging standards (e.g., CCS, CHAdeMO, GB/T, and Tesla Supercharger protocols). Yet, most MATLAB-based research considers fixed charging setups without guaranteeing cross-compatibility across various EV models. Research must aim at creating flexible charger architectures that include software-defined charging protocols to facilitate easy interoperability across different EV platforms.

Cybersecurity issues with EV charging stations need to be addressed. While IoT-based and AI-powered intelligent chargers spread their wings, they risk being hacked, facing data breaches, and unauthorized use. Yet MATLAB-based research never delves deep into secure authentication protocols, encryption techniques, or threat detection frameworks. Future work should include blockchain-based authentication methods and secure communication protocols to prevent EV charging networks from cyber-attacks.

V. CONCLUSION AND FUTURE SCOPE

The developments in PWM-controlled universal EV battery chargers based on MATLAB/Simulink have greatly helped in the optimization of EV charging efficiency, power management, and grid stability. Different control strategies like Voltage Oriented Control (VOC), Sliding Mode Control (SMC), Fuzzy Logic Control (FLC), and Artificial Neural Networks (ANN) have been simulated to improve charging performance and minimize energy losses. In addition, the integration of renewable energy sources, bidirectional energy transfer, and intelligent grid interaction has also shown potential in developing sustainable and smart charging systems. Nevertheless, several challenges remain, such as the absence of experimental verification in real-world applications, optimization of ultra-fast and wireless charging, grid stability, standardization gaps, and cybersecurity threats. Although MATLAB simulations have been highly informative, without hardware implementation and real-world experiments, the effectiveness of these solutions is limited from a practical perspective. Universal charging systems at affordable, large-scale, and secure levels remain important to further work on.

Future studies must concentrate on practical prototyping of MATLAB-designed chargers, AI adaptive control methods, hybrid renewable energy supply, and predictive thermal management for ultra-fast charging. Moreover, strong cybersecurity protocols like blockchain-based authentication and encrypted data communication must be implemented to secure brilliant EV charging facilities. Developing universal charging protocols that align with international standards and guarantee interoperability across different EV models is also necessary. Innovative charging solutions based on IoT and AI should be implemented for real-time monitoring, fault detection, and grid load balancing. Resolving these challenges will be vital in driving the adoption of sustainable and intelligent EV charging systems, paving the way for a clean energy future and enabling the global shift to adequate electric mobility infrastructure.

REFERENCES

[1]. Divase, V., Gofane, M., Kandekar, S., & Kashid, A. (2023). Matlab/Simulink of EV Range based on Available Charging Percentage of Battery. International Journal of Innovative Research in Technology, 9(12), 432-436.

[2]. Somefun, T. E., & Longe, O. M. (2024). Design and simulation of a sustainable green DC-DC multi-outlet electric vehicle charger. IOP Conference Series: Earth and Environmental

Science, 1428(1), 012001. https://doi.org/10.1088/1755-1315/1428/1/012001

[3]. Hassanain, N. E. A. M., Abbas, A. Y. M., & Ahmed, M. H. (2014). Performance analysis of hybrid electric vehicle battery charger using voltage-oriented control. International Journal of Scientific & Engineering Research, 5(11), 152-157.

[4]. Aneesha, G. (2024). Three-level electric vehicle charger control algorithm. Journal of Computer and Electrical Sciences, 1(1), 1-8.

[5]. Islam, R., Rafin, S. M. S. H., & Mohammed, O. A. (2023). A comprehensive review of power electronic converters in electric vehicle applications. Forecasting, 5(1), 22–80. https://doi.org/10.3390/forecast5010002

[6]. Sugumaran, G., & Prabha, N. A. (2023). A comprehensive review of various topologies and control techniques for DC-DC converter-based lithium-ion battery charge equalization. International Transactions on Electrical Energy Systems, 2023, Article ID 3648488. https://doi.org/10.1155/2023/3648488

[7]. Suresh, K., Parimalasundar, E., Arunraja, A., Ellappan, V., & Ware, E. T. (2025). Design and implementation of universal converter using ANN controller. Scientific Reports, 15(3501). https://doi.org/10.1038/s41598-024-83318-2

[8]. Zeb, O., & Ahmad, I. (2024). Adaptive barrier synergetic super-twisting control for hybrid energy storage in smart electric vehicle charging station with recurrent neural network-based MPPT. SSRN Electronic Journal. https://ssrn.com/abstract=5088771

[9]. Puranik, K. K., & Shelgaonkar, A. K. (2024). Characteristics verification of battery charging circuit using different controllers. Educational Administration: Theory and Practice, 30(10), 286–293. https://doi.org/10.53555/kuey.v30i10.8085

[10]. Kumar, R. T., & Rajan, C. C. A. (2024). Optimized hybrid renewable energy system for sustainable electric vehicle charging: Integrating photovoltaic and wind power with advanced control strategies. IEEE Access, 12, 197857–197876. https://doi.org/10.1109/ACCESS.2024.3521515

[11]. Geetha, P., & Usha, S. (2024). Performance investigation of HFR full-bridge inverter in an electric vehicle's resonant inductive coupled power transfer system. EAI Endorsed Transactions on Energy Web, 11(1), 1-10. https://doi.org/10.4108/ew.5227

[12]. Al Attar, H., Hamida, M. A., Ghanes, M., & Taleb, M. (2023). Review on modeling and control strategies of DC–DC LLC converters for bidirectional electric vehicle charger applications. Energies, 16(3946). https://doi.org/10.3390/en16093946

[13]. Zhou, K., Wu, Y., Wu, X., Sun, Y., Teng, D., & Liu, Y. (2023). Research and development review of power converter topologies and control technology for electric vehicle fast-charging systems. Electronics, 12(1581). https://doi.org/10.3390/electronics12071581

[14]. Lipu, M. S. H., Faisal, M., Ansari, S., Hannan, M. A., Karim, T. F., Ayob, A., Hussain, A., Miah, M. S., & Saad, M. H. M. (2021). Review of electric vehicle converter configurations, control schemes, and optimizations: Challenges and suggestions. Electronics, 10(477). https://doi.org/10.3390/electronics10040477