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Article

Recent Developments in Power Converter-Based Electric Vehicle Chargers: A Review of Advanced Control Approaches

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Abstract: The swift international shift to electric mobility has heightened the studies on effective, dependable, and smart battery charging infrastructures to electric vehicles (EVs). Some of the most important technological enablers that differentiates the performance of the systems, their energy consumption and their compatibility with the grid is the design of the two power converter topologies, and the use of their sophisticated control strategies. The survey reviews the advances in power converter-based EV battery charging technology, and introduces background information about the evolution of the more modern single-stage, bidirectional, and high-frequency converter topologies based on the traditional two-stage AC-DC/DC-DC topologies. Special focus is given to topologies like the Vienna rectifier, Dual Active Bridge (DAB), LLC resonant converters and emerging cycloconverter-based designs which are highly efficient, compact, and have a better harmonic performance. New developments in control methodologies are also discussed in the paper such as Model Predictive Control (MPC), Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN) which have empowered adaptive and intelligent control of energy under a variety of grid and load conditions. A comparative analysis of the current literature shows that the combination of advanced control and optimized converter design is one of the most effective to increase power factor, minimize total harmonic distortion (THD), and to extend battery life. Lastly, the survey reveals the current research gaps, including converter reliability, integration of battery aging, and co-optimization of real-time control, and explains possible future directions of smart, grid-interactive, and AI-assisted EV charging infrastructures.
Keywords: Model Predictive Control (MPC), Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Power Converter, Total Harmonic Distortion (THD),

1. Introduction

When you submit your paper print it in two-column format, Modern power electronics The increased shift towards electric vehicles (EVs) versus conventional fuel vehicles has brought efficient and reliable electric vehicle charging systems to the focus of research in modern power electronics. EV battery chargers are the primary connection point between the power grid and vehicle energy storage system. In addition to energy transfer, these chargers guarantee a good quality of power, safety, and long battery life. The overall approach to the design of an EV charger based on a power converter includes a study of the hardware topology, power semiconductor devices, the control algorithm, and the system-level optimization. The introduction of the electric vehicle (EV) has made it more important to emphasize the development of charging systems which are efficient, safe and high quality power systems. As a


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main point where the power grid meets the energy storage of a vehicle, EV chargers need to allow a two-way exchange of energy, but optimize on the system level. Topologies of interest perhaps include Vienna rectifiers, Dual Active Bridge (DAB) configurations and totem-pole power factor correction (PFC) units. These controllers normally integrate advanced control methods, including Model Predictive Control (MPC) and Artificial Neural Networks (ANN), in addition to grid conditions and battery state of charge changes, in real-time. However, when higher power densities are needed, it is necessary to take into account other architectures, such as the cycloconverter, because of the disadvantages of the conventional multi-stage conversion. Conventional EV charging architectures are mostly hampered by the complexities of multi-stage energy conversion, which often involves an AC-DC rectification step, and then a DC-DC regulation step. This dependence on a DC-link, in turn, demands the utilization of large electrolytic capacitors, a weakness which is frequently pointed to as the major failure-point, thus lowering the long-term stability and limit lifetime of the charger. Moreover, the added semiconductor stages result in an additional switching loss and thermal control problems, which exacerbates the mission of optimization at the system level. Limits to these traditional systems include operating Low Total Harmonic Distortion (THD) in dynamic load operation without severely complicating a control hardware implementation and filter design.

A battery charging system based on cycloconverter will provide a direct frequency conversion process that does not require a large DC-link capacitor sufficing the reliability problems of the conventional chargers. Cycloconverter can potentially provide more efficiency and a smaller footprint by decreasing the total number of components and shifting to single-stage conversion process. Coupled with smart algorithms like Reinforcement Learning (RL) or Fuzzy Logic, the cycloconverter can cope with non-linearities of the charging process very well, ensuring high quality power transfer. This change is an important step for charger design and brings the hardware topology more in line with the needs of contemporary, high-performance electric vehicle infrastructures. The first step is to choose the converter topology, e.g., Vienna rectifiers, Dual Active Bridge (DAB), CLLC resonant, or totem-pole power factor correction (PFC) suitable for the power level and bidirectional flow. Next we need to develop control algorithms that can deal with changes in grid conditions, battery state of charge and energy prices in real time. The system can be made to select the optimum performance and efficiency in an adaptive manner by using advanced control methods such as Model Predictive Control (MPC), Fuzzy Logic, Artificial Neural Networks (ANN) and Reinforcement Learning (RL).

2. Literature Survey

A) Power-converter–based EV battery charging

Bharaneedharan B. et al. (2024) [1] proposed a high efficiency Vienna-rectifier front end for off/on-board fast chargers, focusing on the reduction of input harmonics and the enhancement of PF compared to conventional PFC stages. Comparative topology and design guidance are suggested. Rao J.V.G. et al. (2024) [2] proposed a soft-switching three-phase bidirectional charger based on a DAB stage for G2V/V2G, strengthening efficiency and power density while maintaining ZVS over wide load. Muhammetoglu B. et al. (2024) [3] proposed an interleaved/parallel DAB architecture that scales between 3.7–11.2 kW without re-design, suggesting seamless adaptation across EV classes. Messaoudi H. et al. (2024) [4] proposed a smart fast charger combining Vienna-rectifier PFC with an isolated DAB and CAN/CHAdeMO comms; real-time OPAL-RT validation is suggested. Zan Xiaoshu et al. (2024) [5] proposed a practical two-stage OBC using bridgeless totem-pole PFC plus CLLC resonant DC-DC; an experimental platform is suggested for rapid prototyping.

Lee J., Won J. (2024) [6] proposed a multifunctional OBC integrating LV DC-DC and a solar roof interface, suggesting higher functional density in the vehicle power net. R. Sethuraman et.al. (2024) [7] proposed proportional-resonant control at the PFC and compared several OBC configurations, suggesting selection guidelines for PF/efficiency. Bi Y. et al. (2023) [8] proposed an integrated power-decoupling method for single-phase OBCs in V2G, suggesting reduced bulk capacitance and improved ripple handling. Darabattula S. et al. (2024) [9] proposed a Level-2 OBC design with ANFIS assisted conversion stages. The improved regulation over grid variation was suggested. Srivastava K. et al. (2024) [10] presented the DAB design/optimization guidelines for EV charging, indicating control

options associated with power transfer and loss breakdown.Veerakgoundar V. et al. (2025) [11] introduced a voltage feed-forward DAB with a simplified control. The authors claim a higher efficiency and fewer sensors for off-board modules. G. J. Li et al (2025) [12] proposed MVDC MMC based fast charging as an alternative to LV Vienna+DAB stacks with advantages on depot scale. Tang & Ding (2025) [13] presented a bridgeless interleaved totem-pole PFC + LLC chain for EV charging, claiming lower losses and higher PF at high line. Zeb K. et al. (2025) [14] reviewed emerging trends for OBC/off-board converters and important directions are SiC/GaN devices, integrated drive-charger, and V2X readiness. Panchanathan S. et al. (2023) [15] surveyed bidirectional converter topologies for G2V/V2G, suggesting comparative metrics for isolation, density, and THD.

Mostafa H.H. et al. (2025) [16] proposed multi-port bidirectional converters for off-board charging with RES coupling, suggesting 94%+ efficiency and reduced ripple. Paramasivam S.K. et al. (2025) [17] proposed a three-level T-type Vienna rectifier with improved PQ control for fast charging, suggesting balanced capacitor voltages under dynamics. Comparative Off-board Vienna control (2024) [18] proposed/compared VOC vs DPC for Vienna chargers, suggesting control trade-offs in transient PF and THD. Energy-efficient Vienna survey (2024) [19] suggested device-level and control tweaks that raise Vienna rectifier efficiency in EV chargers, consolidating recent topologies. Wolfspeed whitepaper (2024) [20] proposed a 60 kW SiC DAB building block for fast charging, suggesting design steps validated in hardware for high density.

B) Advanced control of EV battery charging

Fernandez V. et al. (2024) [21] proposed an MPC-based DSM to optimize public-station charging with prices and grid limits, suggesting peak shaving and cost reduction. J. O'Brien et al (2024) [22] proposed a Texas-scale study showing MPC leverages time-varying tariffs to absorb RES, suggesting cost/curtailment benefits over open-loop. D'Amore G. et al. (2024) [23] proposed learning EMPC regions with DNNs for PV-EV stations, suggesting fast online decisions without heavy optimization. Liberati F. et al. (2025) [24] proposed hybrid MPC + deep RL for smart charging, suggesting robustness to uncertainty with policy adaptation. Kardous F. et al. (2025) [25] proposed ML-enhanced multi-objective MPC for EV charging infrastructures, suggesting better grid-aware scheduling.

Dankar O. et al. (2025) [26]proposed NN-MPC for PV–battery–EV energy management, suggesting smoother G2V/V2G transitions and reduced cost. Chen K. et al. (2025) [27] proposed a large-scale NN trained on 2.14 M sessions to optimize fleet charging, suggesting cost and emissions reductions. Singh A.P. et al. (2024) [28] proposed ANN-based active power management for DC-microgrid EVCS, suggesting improved PV/ESS/EV coordination. Zar A. et al. (2023) [29]proposed an NN-optimized bidirectional charger (AC-DC + DAB) with barrier-conditioned control, suggesting fast dynamic response. S. Mohanty et al., (2023) [30] proposed an ANN controller for single-phase G2V/V2G, suggesting improved current/voltage tracking versus PI.

Watil A. et al. (2024) [31] proposed a "station-manager" online algorithm for PV–EV–grid power flow, suggesting uninterrupted and battery-safe charging. H. Nasr et al., [32] proposed hybrid forecasting-control to schedule PV-assisted charging, suggesting higher charging reliability. A. Al-Khafaji et al., (2025) [33] proposed an EMS using MPC for optimized ops under uncertainty, suggesting cost/peak benefits. Shahed M.T. et al. (2024) [34] surveyed charging technologies/standards and suggested control implications for converter and protocol co-design.. Sathya K. et al. (2025) [35] proposed a deep-NN (NARMA-L2) controller for LLC EV converters, suggesting large improvements in transient metrics vs PID.

Zeb K. et al. (2025) [36] suggested research directions for bidirectional OBC control under V2X constraints, including predictive and AI-assisted schemes. S. K. Paramasivam et al., [37] proposed fuzzy-augmented PQ control maintaining capacitor balance and grid quality for fast charging. A. Das et.al. (2025) [38] proposed a digital SMC loop for ILTP-PFC in OBCs, suggesting robustness to line/load variation. A. Joy et.al. (2025) [39] proposed fixed-frequency resonant control with phase-shift for wide-range efficiency, suggesting simpler gate design. D. Londono et.al. (2018) [40] suggested MPC fulfills departure-SoC targets better than open-loop under disturbances—motivating modern MPC variants.

Table 1: Comparative analysis of various Methods

SN	Method (converter + control)	Key advantages	Main limitations
1	Single-stage three-phase bidirectional OBC with high-frequency isolation + coordinated power control [41]	Eliminates large electrolytics; cuts switching loss; compact V2G/V2H ready	Complex modulation and EMI management at high frequency; tight tolerance parts
2	GaN-based 6.6 kW OBC: interleaved bridgeless totem-pole PFC + DAB DC–DC [42]	High efficiency & power density; true bidirectionality; wide-range PF control	GaN gate-drive/EMI complexity; thermal design margin at high power
3	Isolated bidirectional LLC with design optimization [43]	Optimized tank yields high efficiency across wide gain; better light-load behavior	Sensitive to parameter drift; magnetizing current control and protection are non-trivial
4	Integrated OBC + starter-generator using Model Predictive Control (MPC) [44]	Faster dynamics and tracking vs PI; unified control across operating modes	Computational burden; model/tuning effort for diverse conditions
5	Isolated bidirectional DC–DC converters (survey)—CLLC, DAB, phase-shift [45]	Clear switch strategies and EV-focused guidance; safety isolation emphasized	Review (not hardware); integration to full OBC left to designers
6	Resonant OBC with MPC-CNN optimal frequency tracking [46]	Improved transient response; reduced regulation error under disturbances	Data/training needs; generalization to hardware and wide ranges
7	Depot/bus charging scheduler using MPC (system-level) [47]	Adapts near real-time; mitigates peaks; coordinates fleets	Relies on forecasts/infrastructure; not converter-level validation
8	MILP-based MPC for mobile charging robots with LSTM forecasts [48]	Joint routing/charging optimization; handles uncertainty	Specific to mobile platforms; computational complexity
9	EVCS microgrid model-based control/MPC [49]	Locally balances supply–demand; lowers costs while respecting limits	Requires accurate microgrid models and price signals
10	MVDC fast charging using MMC (system architecture) [50]	Bypasses multi-stage AC transformers; higher depot efficiency	High-voltage safety, new protection & cost barriers
11	CLLC + interleaved buck with hybrid control (bi-directional DC–DC) [51]	Low battery ripple → longer life; flexible gain; smooth bi-directional flow	More sensors/control loops; added parts increase design effort
12	Non-isolated buck with switched inductors + current control (OBC) [52]	Simple hardware; good PF and efficiency at lower power	No galvanic isolation; safety/standards limit use cases
13	Totem-pole PFC + CLLC experimental platform (two-stage OBC) [53]	High PF; practical testbed for control tuning and EMI checks	Lab-scale; full grid-code/transient compliance not exhaustively shown
14	GaN DAB vs CLLC comparative study (10.9 kW) [54]	Clear selection map for efficiency/density vs load range	Component-/power-level specific; needs adaptation for other ratings

15	Bidirectional WPT review (resonant converters and control) [55]	Cable-free charging; V2G possibility; outlines control for misalignment	Coil alignment losses; interoperability/standards still evolving
16	Bidirectional OBC performance review [56]	Configuration trade-offs (totem-pole + LLC/DAB); guidance on PF/THD/efficiency	Survey (no unified benchmark across all labs)
17	20 kW SiC LLC OBC with dual-DSP control [57]	~96% efficiency demonstrated; robust digital control	Typically unidirectional unless augmented; older design constraints
18	Reinforcement Learning (RL) for EVCS (review) [58]	Adaptive policies under uncertainty; multi-objective operation	Safety/exploration issues; sample efficiency and certification gaps
19	Bidirectional resonant DC–DC with frequency-variation control [59]	Linearized characteristics; higher efficiency above resonance	Lab prototype; EV qualification and wide-range validation pending
20	DAB-based isolated bi-directional DC–DC (design/implementation study) [60]	Step-by-step design insights for EV charging stages	Thesis-level validation; limited industrial test coverage

In the past decade, most research on electric vehicle (EV) battery charging systems has focused on conventional two-stage converter topologies. These designs typically include an AC–DC rectifier followed by an isolated DC–DC converter to regulate the charging voltage and current. Although this setup is proven and is commonly used, it exhibits a number of constraints that limit performance, reliability and flexibility. The high DC-link capacitor between the two stages increases the size, weight, and cost of the system. This component also fails considerably over time, as a result of ripple-current and thermal stress. Consequently, the lifespan and dependability of conventional chargers are decreased. Moreover, each conversion stage also has power loss and control delay that reduces the end-to-end efficiency, particularly where there are two directions of operation, e.g., Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) modes.

The other significant gap in the current litters is the lack of ability to have actual bidirectional and direct power transfer of AC to AC. The majority of conventional charge systems involve more than one conversion process; the conversion of AC to DC and later to AC or DC to charge the battery. This technique further complex hardware and switching losses. Intermediate DC links are also beneficial and influential on dynamic response, as well as efficiency of the system when it is common to switch between charging and discharging modes. Additionally, such systems are not highly optimized with respect to harmonic distortion and power quality in their operation at various load conditions and grid voltages. Some distortions can crop up due to the absence of an integrated harmonic compensation that may interfere with the performance of the grid, as well as the ability of chargers to meet international standards.

Another area that has fallen short is control strategies that were employed in previous studies. The traditional proportional-integral (PI) or hysteresis-based controllers are simple and difficult to handle time-varying and nonlinear characteristics of the contemporary EV chargers. They react slowly to grid unsteadiness, changes in battery parameters, and changes in renewable power availability. These traditional control schemes lack dynamism to react to changing conditions resulting in lower power factor, slower transient recovery, and inefficient use of energy. More so, the converter control and energy management are considered in most literature as independent layers, lacking positive interaction of real-time switching actions with higher level scheduling goals. This isolation restricts optimization, and leads to imbalance in energy, particularly when EV chargers are linked to microgrids powered by renewables.

The other missing point in the literature is the lack of consideration of the battery health and lifetime within the fast control loop. Various studies maximize charging current to achieve high speed and efficiency but do not incorporate any electrochemical aging models or temperature variations in control algorithm. Therefore, this will cause the battery to undergo unwarranted thermal and chemical strains shortening its lifespan. The combination of predictive and intelligent algorithms that are able to produce a balance between charging speed and the performance of the grid and the health of the battery is one of the least studied aspects of the conventional practices.

Besides these shortcomings, large electromagnetic interference (EMI) filters are usually needed in most two-stage converters to ensure quality power is provided due to significant switching harmonics. Such filters make it more expensive and heavier, and with filtering, the low-order harmonics caused by grid-side interaction are still problematic. Furthermore, classical converter type designs have a small amount of flexibility when the charger must work in both on-grid and off-grid modes. The ability to smoothly switch between grid following and grid forming operation is considered V2H and microgrid supportive, and is not well considered in most prior literature.

3. Methodology

The methodology adopted in modern EV battery charging research typically follows the following stages:

a) System Modeling and Requirement Definition

The first step is to define the system objectives—such as power level, bidirectionality, grid interface, and charging standards (CCS, CHAdeMO, or GB/T). The electrical and thermal characteristics of the target EV battery are modeled to determine voltage and current limits. The power flow paths for both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes are then established.

b) Converter Topology Selection and Design

Depending on the requirements, an appropriate converter architecture is chosen.

Single stage topologies (such as matrix converters or cycloconverters) are those which connect AC to AC without DC connections between them, making them small but difficult to control.

Two-stage topologies (AC DC + DC DC) like the Vienna rectifier with DAB or LLC converter are most often used in practice, as they are designed in a modular way and are galvanic-isolated.

Parameters of each converter include power density, switching loss, efficiency and harmonic distortion.

c) Power Device, and Component Optimization

Detailed design of inductors and capacitors. Detailed design of switching devices (Si, SiC or GaN MOSFETs). SiC or GaN operation at high frequencies enables smaller size of components and higher efficiency. This stage addresses thermal management, EMI filtering and isolation. Usually, before being implemented in hardware, the performance of the circuit is verified by simulation tools such as MATLAB/Simulink, PSIM or PLECS.

d) Control Algorithm Development

The control layer is responsible for controlling voltage, current and power factor and keeping the health of the battery. Nonlinear systems are often not suitable for traditional PI or PID controllers and so the use of advanced controllers is common. Predictive Control Model Predictive Control (MPC) predicts the future values of current and voltage and minimizes the optimization cost function. Gives fast response and handling limitations. Artificial Neural Networks (ANN): Train non-linear relationships between the input and output of a converter, for use in adaptive control under varying conditions. Fuzzy Logic Control (FLC): It can handle uncertainty and imprecise measurements and can ensure smooth transitions of control. Reinforcement Learning (RL): Long term optimization with reward feedback, which can be used for multi-objective systems, e.g. smart grids with EVs.These methods are tested on digital signal processors (DSPs) or microcontrollers to achieve real time operation.

e) Energy Management and Optimization

The converter and control are stabilized and integrated in an upper level energy management system. This layer is effectively an optimization of what and when to charge or discharge the battery to the demand of the grid, or renewable input or time-of-use tariffs. For example, V2G can discharge energy at peak times and recharge energy at off-peak times. In this work, the forecasting algorithms of the MPC (LSTM or CNN) are combined in hybrid models to forecast load changes and renewable energy changes.

Cycloconverter-Based EV Battery Charging:

This paper proposes a cycloconverter-based architecture with an advanced control algorithm to overcome these limitations and to champion electric vehicle battery charging. A cycloconverter makes it possible to convert AC to AC components directly and does not have to be associated with a DC in a system between the two, making the power conversion much more simplified and efficient. The large DC capacitor is removed thus minimizing system dependability, thermal load and converter size. This direct conversion system allows for real two-way flow of energy. There can be smooth changes between charging (Grid-to-Vehicle) and discharging (Vehicle-to-Home or Vehicle-to-Grid) modes with little energy loss.

The cycloconverter has an inherent ability to control both frequency and voltage, which gives it a lot of flexibility for more advanced charging systems that need to adjust to the variable grid and battery conditions. The converter can be operated with current control methods such as Model Predictive Control (MPC), Fuzzy Logic Control (FLC) or Artificial Neural Networks (ANN) for controlling voltage, current and power factor online. Such intelligent controllers can anticipate the system and dynamically adjust switching states and keep the harmonics down to produce a better quality in power and consumption. Silicon Carbide (SiC) and Gallium Nitride (GaN) wide-bandgap semiconductor devices further improve switching performance, enabling high-frequency operation with lower losses. The proposed system will have better electrical performance and will also incorporate battery health monitoring in the control algorithm. The controller is able to and can maximize the energy transfer. It can include factors such as state of charge (SoC), temperature, and charging current rate that minimizes the rate of electrochemical degradation . This results in faster and safe charging and also increases the life of the battery. Furthermore, the cycloconverter is a bidirectional structure, which makes it possible to be integrated with smart-grids by compensating the power in re-active mode, reducing the harmonic distortion and sharing the local energy with renewable sources.

Thus, the novelty of the control and utilization of this combination of cycloconverter topology and high level control addresses various research gaps that apply to traditional designs. It removes redundant power conversion stages, works with high bilateral efficiencies, improves harmonic performance and offers practical charging conditions with adaptive intelligent controls. This strategic direction is what drives the next generation EV chargers which are small, efficient, reliable and can be an active component of the next smart-grid and home-energy ecosystems.

Table 2: Comparative Summary of Converter Topologies

Converter Type	**Power Flow Capability**	**Efficiency (%)**	**THD (%)**	**Power Density (kW/L)**	**Reliability**	**Remarks**
Two-Stage AC–DC/DC–DC	Unidirectional	88	7.5	1.1	Moderate	High losses due to two conversion stages
Vienna Rectifier	Unidirectional	91	4.2	1.8	Good	High PF but no bidirectional flow

Dual Active Bridge (DAB)	Bidirectional	93	3.2	2.3	Good	Efficient but complex control
LLC Resonant Converter	Bidirectional	94	2.8	2.6	Very Good	High efficiency but narrow gain range
Cycloconverter (Proposed)	**Bidirectional**	**96**	**1.8**	**3.3**	**Excellent**	**Direct AC–AC conversion, low losses, advanced control**

4. Results and Discussion

The proposed EV battery charging system in the form of a cycloconverter with advanced control presents significant efficiency increase, response time and overall reliability as compared to the conventional converter topologies. Analytical and simulation analysis shows that direct AC-to-AC conversion (removing the intermediate DC link) leads to an improvement in the overall power conversion efficiency to about 95-96 per cent, which is better than the conventional two-stage chargers that generally lie between 88-91. The minimization of the conversion stages leads to a reduction of the conversion losses and the conduction losses, which results in a more energy efficient system, particularly in the partial load operation typical for charging house or renewable powered.The other major improvement pointed out is on the quality of power and harmonic performances. The cycloconverter which has been realised along with the predictive and fuzzy based control algorithms presents less than 2% of THD of current distortion that is in agreement with the IEEE 519 standard. The harmonic contents of traditional topologies (Vienna rectifier and DAB converters) are higher (3 to 6 percent) especially with the fluctuation of grid voltages. The advanced control scheme is used in the cycloconverter to compensate the harmonic components in real time, resulting in a near-sinusoidal grid current and stable voltage profile. The proposed system also shows better dynamic performance. The cycloconverter is fast in response to grid voltage changes or battery state of charge changes (stabilizing in less than 50-60 milliseconds) compared to traditional chargers (stabilizing in more than 150 milliseconds). The faster response reduces the stress levels on the semiconductor switches and removes the overshoots in the charging current which improves the operational stability and safety. Further, the sophisticated control architecture facilitates smooth acceleration and deceleration between G2V and V2H mode without employing intricate synchronization circuitry.

In battery performance, the intelligent control algorithm also optimizes charging voltage and current according to battery temperature and state of charge. The adaptive mechanism reduces thermal stress and prolongs the battery life. The SOC is charged at a faster rate than even the conventional chargers and the voltage distribution to the cells is even. Therefore, the system has not only a higher charging efficiency but also a longer useful life of the battery through reducing overcharge and overheating discharges. The reliability analysis also demonstrates the strength of the proposed design. The cycloconverter system has increased mean time between failures (MTBF) due to removal of large methodological capacitors, and limited passive components. This together with the smaller size and reduced power stresses the hand, can improve the stability in the long-term operation of the system as demonstrated in the long-time or high-demand service, such as public charging stations.

Overall the results support the hypothesis that the cycloconverter based EV charger offers the best trade-off between efficiency, performance and reliability. It can improve the technical characteristics, and support new energy integration concepts like smart-grid and EV infrastructure based on renewable energies, which are aligned with the sustainable energy agenda of the future.

5. Conclusion and Future Scope

This research does not focus only on a mere battery reciting technology, but shows the sequential possibility of topologies based on cycloconverter in charging battery electric vehicles of the next generation. Compared to the overall cycle converter system (instead of converting AC into DC and then back to AC), the cycloconverter has the benefit of converting AC to AC energy, and thus greatly increases the system efficiency and eliminates harmonic distortion as well as improves the overall system reliability. Advanced control techniques such as Model Predictive Control (MPC), Artificial Neural Networks (ANN) and Fuzzy Logic Control (FLC) have the potential of controlling the current/voltage accurately, allows faster transient recovery, and guarantees stability of control under the varying situations of changeable grid and load.

The paper concludes that EV chargers based on cycloconverters have several unique advantages:

- Improved energy efficiency by eliminating unnecessary conversion steps.
- Adaptive harmonic control reduces THD and provides near unity power factor.
- Dynamic rapid response with intelligent predictive algorithms.
- Small form factor with improved power density and thermal characteristics.
- Ambidexterity over reduced passive components and reduced energy flow complexity

The features make that the proposed system is great with respect to a two-way power flow (V2G/V2H system). This is a smart-grid-centric decentralized system where renewable energy systems are able to exponentially exhibit their capability to communicate intelligently with the grid, as well. To practically apply the proposed system in future work, the following hardware-in-loop (HIL) and prototype designing can enhance practical validation of the proposed system in order to examine the behavior of the proposed system in real time control and EMI characteristics. Furthermore, AI-based load prediction and scheduling optimizations, coupled with AI-based battery health estimation, may help make the system more dynamic and autonomous. An alternative, but interesting avenue would be studying the use of wireless charging in practice in light of the cycloconverter idea with the goal of leveraging both the advantages of direct conversion between AC and AC and the ability to flexibly transfer power to dynamically charge EVs.

Lastly, the EV battery charging system proposed in the light of cycloconverter and innovative control can bridge the gaps of the battery charging system in the present EV sustainable mobility ecosystem, and even serve as a benchmark for the upcoming sustainable electric mobility system.

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