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High-Efficiency Voltage Balancer having DC–DC Converter Function for EV Charging Station

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ABSTRACT: The growing popularity of electric vehicles (EVs) calls for the creation of scalable, dependable, and highly efficient charging infrastructure. Because of their reduced conversion stages and compatibility with distributed energy sources, bipolar DC bus architectures have become a popular solution. However, these systems' operational dependability, safety, and efficiency are seriously threatened by the voltage imbalance between the positive and negative rails. Furthermore, flexible DC–DC converters are required due to the large range of EV battery voltages. A novel high-efficiency voltage balancer (VB) with DC–DC converter functionality is presented in this paper. It was created especially to address these two issues. The suggested architecture ensures symmetrical bus voltage under dynamic load conditions by separating voltage balancing control (VBC) from load dependency, in contrast to traditional three-level converters. Reliability is increased by the design's improved conversion ratio, decreased voltage/current stress on components, and removal of problems like shoot-through faults. Robust performance across a range of load scenarios and efficiencies exceeding 97% are confirmed by simulation and experimental validation. Additionally, this paper assesses the role of cutting-edge DC–DC converter topologies in meeting a range of EV voltage requirements, including reconfigurable LLC resonant converters and multiport differential power processing systems. To maximize efficiency and guarantee smooth grid and renewable integration, intelligent control techniques are also covered, such as adaptive AI-based algorithms and model predictive control. This integrated strategy offers a framework for next-generation EV charging stations that is prepared for the future.

KEYWORDS: Electric Vehicle Charging, Voltage Balancer, Bipolar DC Bus, DC–DC Converter, Voltage Imbalance, Fast Charging, LLC Resonant Converter, Multiport Power Processing, Model Predictive Control, Renewable Integration.

I. INTRODUCTION

Electric vehicles (EVs) have become increasingly popular as a result of the global shift to sustainable transportation, making them a key element in initiatives to lower greenhouse gas emissions and reliance on fossil fuels. The demand for sophisticated charging infrastructure that can provide quick, effective, and dependable energy transfer is rising in tandem with the growth in EV penetration. Bipolar DC bus architectures are frequently used in modern EV charging stations, especially those intended for high-power or fast-charging applications, because they make it easier to integrate distributed energy resources like solar photovoltaics and reduce the number of power conversion stages needed. These bipolar systems do, however, have inherent problems with voltage imbalance, which can be caused by asymmetric power flow between the positive and negative rails, unequal loading, or component mismatches. The dependability and durability of charging infrastructure may be threatened by such imbalances, which can also result in decreased system efficiency, increased stress on power electronic components, and possible safety risks.[1]

The quick development of EV battery technologies has also led to a great variety of battery voltages and capacities, which calls for DC–DC converters that can handle wide output voltage ranges with strong control and high efficiency. The benefits of combining DC-DC conversion and voltage balancing into a single architecture are numerous and include decreased system complexity, lower expenses, and increased overall efficiency. This dual-purpose method optimizes power flow within the charging station by enabling simultaneous energy conversion and voltage regulation, doing away with the need for independent balancing circuits. The creation of high-efficiency voltage balancers with built-in DC–DC converter capabilities is essential to sustaining the upcoming generation of EV charging stations as transportation electrification grows, guaranteeing scalability, dependability, and smooth integration with smart grids and renewable energy sources.[2]

II. OBJECTIVES

To design a high-efficiency voltage balancer integrated with DC–DC converter functionality for EV charging stations.

- To analyze and address voltage imbalance issues in bipolar DC bus architectures.
- To develop and validate control strategies that enhance the performance, safety, and reliability of EV fast-charging systems.

III. METHODOLOGY

This study utilizes a qualitative research methodology that includes a comprehensive analysis of scholarly literature, technical standards, and recent developments in electric vehicle charging technology. Focus is directed on the examination of voltage balancing methodologies and DC–DC converter configurations. This literature-based methodology underpins the theoretical framework, delineates current limits, and directs the creation of a highly efficient, integrated solution appropriate for contemporary EV charging stations.

IV. VOLTAGE BALANCING IN BIPOLAR DC BUS SYSTEMS

Bipolar DC Bus Architecture

Electric vehicle (EV) charging stations frequently use the bipolar DC bus architecture because of its effectiveness and adaptability in integrating dispersed energy sources and controlling power flow. A bipolar voltage supply system is essentially created by this architecture, which has two DC rails—a positive and a negative—referenced to a neutral midpoint. To accommodate the different voltage requirements of different EV battery systems, such a configuration enables EV chargers to connect directly across the full voltage between the positive and negative rails or between the positive or negative rail and the neutral point. By lowering the number of power conversion stages, the bipolar DC bus improves system efficiency overall and makes integrating energy storage and renewable energy sources easier. However, a major problem with bipolar DC bus systems is the voltage imbalance between the positive and negative rails. Uneven loading conditions brought on by different EV charging demands are usually the cause of this imbalance, which results in uneven voltage levels on the two rails. Unbalanced voltage can worsen system performance, put more strain on power electronics, and jeopardize safety. Advanced voltage balancing techniques have been proposed to address this, such as dual-output voltage balancers with model predictive control, which provide superior balancing capabilities while reducing the stress on switches from voltage and current and avoiding common problems like shoot-through faults. In bipolar DC bus-fed EV charging stations, these control techniques improve system robustness and stability while guaranteeing constant power quality. Therefore, a key component of dependable, effective, and scalable EV charging infrastructure is the bipolar DC bus architecture in conjunction with efficient voltage balancing.[3][4]

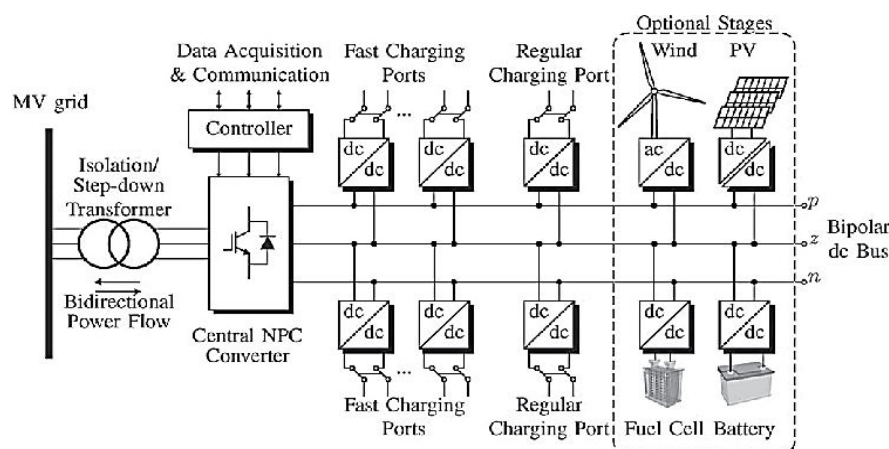


Fig :- Bipolar DC Bus[5]

Voltage Imbalance: Causes and Effects

The main causes of voltage imbalance in bipolar DC bus systems are irregular transmission line parameters, asymmetrical renewable energy generation, and unequal load distribution. Bus voltage imbalance can occur when the voltages on the two rails diverge due to different loads connected to the positive and negative rails or when power is distributed unevenly among the rails from distributed energy sources. Dynamic fluctuations in renewable energy resources and uncertainties in load consumption further exacerbate these imbalances. Reduced system efficiency, compromised operational reliability, elevated stress on power electronic devices, and deteriorated power quality are all consequences of voltage imbalance. Additionally, persistent imbalance can result in equipment failure and safety issues, particularly in high-power EV charging stations where stable voltage is essential for effective operation. Intelligent load management, coordinated control of dispersed sources, and sophisticated voltage balancing converters are being developed to address these problems and guarantee stable voltage regulation and dependable operation in bipolar DC microgrids.[6][7]

Voltage Balancing Control (VBC) Strategies

In bipolar DC bus systems, voltage balancing control (VBC) techniques are crucial for preserving equal voltage levels on the positive and negative rails, particularly in situations with unbalanced loads. Voltage balancers based on dual-active-bridge converter topologies or buck-boost converter topologies are common methods that control the differential voltage by redistributing power among the rails.[8][9] In order to improve resilience against communication delays and system disruptions, advanced control frameworks—like hierarchical and coordinated secondary control—use feedback from both local and estimated voltage data. To accomplish full-domain current balancing and bus voltage regulation, these tactics might also include adaptive control algorithms and power line communication. [10][11] Autonomous voltage balancing with coupled inductors is one recent advancement that enables self-balancing operation without the need for additional control loops or components. [12] All things considered, these VBC techniques guarantee the steady, effective, and dependable operation of EV charging stations and bipolar DC microgrids.

V. DC-DC CONVERTER TOPOLOGIES FOR EV CHARGING STATIONS

Requirements for EV Charging DC-DC Converters

Electric vehicle (EV) charging stations' DC-DC converters must adhere to strict specifications in order to operate effectively, safely, and adaptably. In order to handle the various battery voltages of various EV models, which frequently range from 200 V to more than 1000 V, they must support a broad output voltage range. Low energy loss has a direct impact on thermal management and operating costs, making high efficiency especially important for fast-charging applications. Vehicle-to-grid (V2G) and vehicle-to-home (V2H) services depend more and more on the ability to transfer power in both directions. To protect users and avoid ground loops, galvanic isolation is usually necessary, particularly in high-power installations. Additionally, converters need to be compact and have a high power density in order to fit into small station footprints while still performing well thermally. In order to serve numerous vehicles at once and adjust to future demand, charging stations must also be scalable and modular. Maintaining output voltage stability, managing dynamic loads, and improving reliability under changing grid and load conditions all require sophisticated control strategies.[13][14] [15]

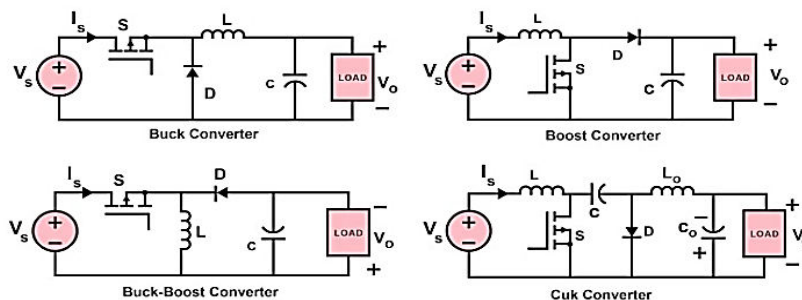


Fig :- Basic DC-DC converter circuit diagrams.[16]

State-of-the-Art Topologies**LLC Resonant Converters**

LLC resonant converters' high efficiency, superior power density, and adaptability over a broad output voltage range make them popular in EV charging stations. In contemporary charging systems, advanced control techniques like the Remora Levy Optimizer (ReLyO) further improve voltage regulation and reduce losses, allowing for 99% efficiency and dependable operation.[17]

Multi-Stage and Multiport Converters

EV charging stations are increasingly using multi-stage and multiport DC–DC converters to increase efficiency, lower infrastructure costs, and allow multiple vehicles to be charged simultaneously. By allowing bulk power transfer through a main converter while auxiliary converters handle partial power for each port, multiport converters—such as those with differential power processing or ring-connected dual active bridge topologies—reduce component ratings and system costs. Because of their fault tolerance, scalability, and flexible power flow management capabilities, these architectures are ideal for fast-charging stations and integration with distributed energy resources.[18][19]

Isolated DC–DC Converters

In order to guarantee safety and adherence to legal requirements, isolated DC–DC converters are crucial components of EV charging stations because they offer galvanic isolation between the grid and automobiles. These converters, which include dual active bridge (DAB) topologies and modular multilevel converter (MMC)-based topologies, facilitate the simultaneous charging of several vehicles with varying battery voltages and allow for an efficient medium-voltage DC grid connection. By lowering transformer stress and naturally balancing submodule capacitor voltages, advanced modulation techniques such as quasi-two-level (Q2L) modulation increase efficiency and dependability. High-frequency transformer-based designs and SiC-based three-port converters are other recent innovations that simplify system design and lower component count while achieving high power density and efficiencies of up to 98.2%.[20][15][14]

Bidirectional and Modular Topologies

Bidirectional and modular topologies are increasingly vital in EV charging stations, enabling both charging and discharging (V2G) operations and supporting flexible, scalable infrastructure. Bidirectional converters, such as full-bridge modular dual active bridge designs, allow energy flow in both directions and achieve high efficiency, while modular architectures simplify expansion, centralize control, and reduce component count. These features enhance fault tolerance, adaptability, and integration with multiple energy sources, making them optimal for modern, high-power EV charging systems.[21][22][23]

VI. HIGH-EFFICIENCY VOLTAGE BALANCER WITH DC–DC CONVERTER FUNCTION

The development of a high-efficiency voltage balancer (VB) with a DC–DC converter function is essential for contemporary EV charging stations, especially those that use bipolar DC bus architectures. Three-level (TL) DC–DC converters, which function as both fast chargers and voltage balancers, are frequently used in conventional bipolar DC-bus-fed charging stations. However, because the output load power determines the balancing capability, these TL converters are naturally constrained in their voltage balancing control (VBC) range. This restriction may cause the bipolar DC bus to experience ongoing voltage imbalances, particularly when there are multiple vehicles charging at once or when load conditions change. A high-efficiency VB that not only completes the DC–DC conversion necessary for rapid charging but also offers reliable, independent voltage balancing has been proposed as a solution to these limitations. In contrast to traditional TL converters, the suggested VB architecture maintains bus voltage symmetry under all load circumstances since it places no limitations on the VBC range. This is accomplished by using a topology that puts less strain on the semiconductor switches from voltage and current, increasing conversion ratio and efficiency. Additionally, by avoiding common problems like shoot-through faults, the design improves operational safety and reliability.[1]

The high-efficiency VB functions as a charger and a balancer in practice by blending in perfectly with the power electronics of the charging station. Wide output voltage ranges can be handled effectively by it, meeting the various charging needs of contemporary EVs. Based on simulation and experimental results, this method maintains high efficiency (often above 97%) over the entire operating range in addition to achieving superior voltage balancing.

Because of its dual functionality, the system is less complicated, has fewer components, and is more reliable overall.[24]

VII. CONTROL STRATEGIES

Control strategies are essential to EV charging stations' dependable, effective, and adaptable operation, particularly as these systems increasingly incorporate renewable energy sources and cater to dynamic, nonlinear loads. Ensuring optimal power converter performance, maintaining power quality, managing energy flows, and providing reliable voltage and current regulation under a range of grid and load conditions are the main objectives of control strategies.[25]

Power converters in charging stations have historically had their output voltage and current controlled by conventional control techniques, such as proportional-integral (PI) and proportional-resonant (PR) controllers. These methods work well for basic regulation, but they might not work well for rapidly fluctuating loads, grid disruptions, or integrating variable renewable energy sources. Strategies for adaptive control have been developed to overcome these constraints. Model predictive control (MPC), least mean square with exponential function (LMSEXF), and artificial intelligence-based controllers are examples of adaptive control algorithms that dynamically modify control parameters in real time in response to system disturbances and changes in order to preserve stability and reduce harmonics.[26]

Grid-tied photovoltaic (PV) assisted EV charging stations, for instance, have effectively used LMSEXF-based control to reduce power quality problems like harmonics and voltage fluctuations that result from the variable nature of both PV generation and EV charging loads. In order to ensure quick and accurate compensation for disturbances and maintain grid current harmonics within IEEE 519 standards, the LMSEXF controller adjusts its step size based on the error magnitude. Results from experiments and simulations validate this adaptive approach, which significantly improves system robustness and power quality.[27]

In charging stations with multiple sources and ports, hierarchical and coordinated control frameworks are also becoming more popular. These frameworks usually use a primary control layer for quick local regulation, a secondary layer for distributed converters to share voltage and current, and occasionally a tertiary layer for system-wide optimization, like grid interaction or economical dispatch. Energy management systems (EMS) that use optimization algorithms, like Mixed-Integer Linear Programming (MILP) or nature-inspired algorithms, are used in renewable-integrated stations to schedule charging, control energy storage, and optimize station profitability while maintaining grid stability.[28]

Droop control strategies are employed in microgrid-connected stations to autonomously balance power among multiple converters or virtual synchronous generators (VSGs), enhancing system reliability and reducing complexity. VSG-based control can also provide virtual inertia and damping, improving the stability of low-inertia microgrids that host large numbers of EV chargers.[29] Human-Driven Instruction-Based Optimization (HDIBO) and similar hybrid approaches leverage both algorithmic precision and human insights to iteratively optimize control parameters, dynamically responding to real-world complexities such as fluctuating renewable output, varying EV demand, and changing electricity prices. These methods are shown to outperform traditional genetic algorithms and particle swarm optimization in terms of stability and efficiency.[28] The integration of real-time dynamic power management using model predictive control (MPC) further enhances performance in grid-connected PV-EV charging stations, enabling predictive scheduling of charging and discharging events, and proactive mitigation of grid disturbances.

VIII. CASE STUDIES

High-Efficiency Voltage Balancer in a Bipolar DC Bus EV Charging Station

Bipolar DC bus EV charging stations, which are becoming more and more popular due to their effective connection to distributed generation and fewer conversion stages, have a major advancement in the form of a high-efficiency voltage balancer (VB) with an integrated DC–DC converter function. Typically, a three-level (TL) DC–DC converter that doubles as a fast charger controls the voltage balancing between the positive and negative rails in conventional systems. Nevertheless, when EVs are charged at variable or low loads, a TL converter's voltage balancing control (VBC) range is naturally constrained by the power of its output load, rendering it inadequate to handle voltage imbalance. This restriction may result in longer-lasting voltage imbalances, more strain on power electronic parts, and decreased system performance. A novel high-efficiency VB design has been put forth to address these issues and get around the

limitations of TL converters. In addition to being a quick charger, the suggested VB has strong voltage balancing capabilities that don't restrict the VBC range. Regardless of the quantity or charging state of connected EVs, the VB can maintain voltage symmetry across the DC bus by severing the balancing function from the charging load. In comparison to traditional designs, the architecture improves efficiency and increases conversion ratio by putting less strain on the semiconductor switches through lower voltage and current. Further improving reliability, the design also steers clear of common problems like shoot-through faults. Results from experiments and simulations have shown how effective this strategy is, demonstrating that even in situations with uneven or fluctuating loads, the suggested VB can maintain balanced DC bus voltages. Because of its increased efficiency and conversion ratios, the system is a good fit for contemporary high-power charging stations that need to consistently service a variety of vehicles with varying charging needs. For the next generation of scalable and reliable EV charging infrastructure, the solution's integration of the voltage balancing and DC–DC conversion functions simplifies system architecture, lowers the number of components, and improves operational reliability.[1]

Reconfigurable LLC Converter for Wide Voltage Range Charging

Modern and future electric vehicle (EV) charging stations require a wide output voltage, and a reconfigurable LLC resonant converter is a state-of-the-art solution to meet these needs. Because next-generation powertrains may need up to 1200 V, and EVs currently typically run at 400 V and 800 V, charging infrastructure needs to be able to effectively deliver a wide range of output voltages. Conventional LLC converters, despite their reputation for efficiency and compactness, have trouble maintaining high performance over such a broad output range because of their increased switching frequency span and voltage gain limitations. In response to these issues, reconfigurable LLC converters with creative stacked structures on the primary and secondary sides—like stacked half-bridges, diodes, and capacitors—have been developed recently. With this design strategy, the voltage stress on switches and diodes is cut in half, greatly increasing efficiency and dependability. To further improve operational stability, the converter self-balances the voltage across the stacked capacitors. Through a variety of inverter and rectification techniques, the converter can accommodate low, medium, and high voltage charging situations while maintaining a broad output voltage range, as experimental prototypes have shown up to an 8:1 ratio. Reconfigurable LLC converters minimize losses and maintain soft-switching across the voltage range by operating efficiently over a narrow switching frequency range, in contrast to conventional LLC converters that rely on wide-span pulse frequency modulation.[2][30]

The viability of this strategy has been confirmed, for instance, by a prototype that has a 400 V input and a 200–800 V output at 500 W. It achieves high efficiency and efficient soft-switching at all operating points. As demonstrated by two-stage 11 kW prototypes, advanced designs also include dual secondary sides and interleaved buck converters, which achieve peak efficiencies above 97% and deliver over 95% efficiency over a 150–1000 V output range. These characteristics give reconfigurable LLC converters the flexibility and efficiency needed for the quickly changing EV landscape, making them incredibly well-suited for both on-board and fast DC charging stations.[31]

Multiport Differential Power Processing for Fast Charging

Architectures for multiport differential power processing (DPP) are becoming a very popular and economical option for quick EV charging stations. In these systems, the majority of the power transfer is handled by a primary DC–DC converter, and the partial power delivered to each charging port is managed by auxiliary converters, which are rated at a fraction of the total power. This method greatly lowers the necessary converter size and cost, permits multiple vehicles to be charged simultaneously, and improves system efficiency overall. Unlike traditional full-power converter configurations, the auxiliary converters only process the differential power, reducing losses. Furthermore, the architecture provides built-in fault tolerance because every port can be controlled separately. In real-world fast-charging scenarios, this topology's efficacy has been confirmed by case studies and practical hardware prototypes, which show that it can maintain high efficiency and flexible power flow management.[18]

IX. CHALLENGES AND FUTURE DIRECTIONS

- **Scalability and Standardization :-** As EV battery voltages continue to rise, converters must support even wider output ranges and higher power levels. Standardized modular designs will be crucial for scalability and interoperability.
- **Control Complexity :-** Advanced control strategies are needed to manage multi-mode, multiport, and reconfigurable architectures while ensuring stability, efficiency, and fault tolerance.

- **Integration with Renewable Energy and Grid Support :-** Future charging stations will increasingly integrate renewable energy sources and provide grid support functions (e.g., V2G). Voltage balancer/converter systems must adapt to bidirectional power flow and variable input sources.
- **Cost Reduction and Reliability :-** Ongoing research focuses on reducing system cost through component integration and simplification, while maintaining or improving reliability and safety.

X. CONCLUSION

Electric vehicles' (EVs') quick global adoption necessitates the creation of sophisticated, dependable, and efficient charging infrastructure. Strong voltage balancing and adaptable DC–DC conversion solutions are essential components of this infrastructure, especially in systems that use bipolar DC bus architectures. The limitations of traditional three-level (TL) DC–DC converters, which tie voltage balancing capacity to load power and frequently result in ineffective and unreliable operations under dynamic load conditions, have been examined in this paper along with the difficulties presented by voltage imbalance in bipolar systems. A high-efficiency voltage balancer (VB) with an integrated DC–DC converter function has been suggested and assessed in order to address these drawbacks. Regardless of the quantity or charging condition of connected EVs, this innovative design allows consistent bus voltage symmetry by separating the voltage balancing control (VBC) from the charging load. The architecture exhibits high energy conversion efficiency—often surpassing 97%—reduced voltage and current stress on semiconductor switches, and improved reliability through shoot-through fault avoidance. These enhancements not only improve operational performance but also decrease the number of components and complexity of the system, which lowers costs and increases scalability. The study also examined state-of-the-art DC–DC converter topologies, such as multiport differential power processing systems and reconfigurable LLC resonant converters. These architectures offer enhanced power density, broad voltage adaptability, and the flexibility needed to future-proof charging stations against changing EV powertrain specifications. When coupled with intelligent control strategies, such as human-in-the-loop optimization, adaptive and model predictive controls, and others, the modern EV charging station becomes a smart, scalable, and energy-efficient hub that can integrate renewable energy sources and interact with the grid.

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