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Recent Developments in Electric Vehicle Onboard Charging Systems: Converter Topologies, Control Techniques, and Emerging Challenges

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Abstract- The rapid growth of electric vehicle (EV) adoption has led to a substantial rise in the need for high-performance and dependable charging solutions. Among these, the onboard charger (OBC) plays a vital role by transforming grid-supplied alternating current (AC) into direct current (DC) required for battery charging. Despite ongoing advancements, challenges such as current ripple, power losses due to switching, and thermal constraints continue to affect OBC performance and design efficiency.This review presents an overview of recent progress in EV onboard charging technologies, with particular attention to converter configurations, integrated charging structures, bidirectional power flow capabilities, and methods for mitigating current ripple. In addition, it explores emerging trends including chargers supported by renewable energy sources, security concerns in charging systems, and multifunctional charger designs.The study also highlights the significance of analyzing both high-frequency and low-frequency behaviors to enhance efficiency, maintain power quality, and ensure system reliability. Lastly, it identifies key research gaps—such as issues related to scalability, heat management, fault resilience, and cost-effectiveness—to provide direction for future innovations in onboard charger development.

Keywords: Electric Vehicles (EVs), Onboard Charger (OBC), Converter Topologies, Bidirectional Charging, Integrated Charging Systems, Current Ripple Reduction, Switching Losses, Thermal Management, Power Quality, High-Frequency Analysis, Low-Frequency Analysis, Renewable Energy Integration, Cybersecurity, Multifunctional Chargers, Fault Tolerance, Scalability.

I.INTRODUCTION

Electric vehicles (EVs) are increasingly reshaping the transportation landscape by providing a more sustainable and energy-efficient substitute for traditional internal combustion engine-based vehicles. Growing environmental concerns, along with global initiatives aimed at lowering greenhouse gas emissions, have accelerated the widespread adoption of EVs. As a result, there is a rising need for dependable and efficient charging systems that can operate under a variety of conditions. Among different charging options, onboard chargers (OBCs) play a crucial role by allowing EVs to be charged directly from standard AC supply sources, thereby reducing reliance on external charging stations and enhancing user convenience.

An onboard charger serves as an embedded power conversion unit that transforms alternating current (AC) from the electrical grid into a regulated direct current (DC) suitable for charging the vehicle's battery. Typically, the system consists of an AC–DC conversion stage with power factor correction (PFC) to ensure high-quality input current and compliance with grid requirements. This stage is followed by a high-frequency DC–DC converter responsible for controlling the output voltage and current while also providing electrical isolation between the grid and the battery. Key design objectives for OBCs include achieving high efficiency, compact size, lightweight construction, and robust performance. However, these goals are often limited by issues such as switching-related losses, electromagnetic interference, thermal constraints, and harmonic distortion.

A significant challenge in OBC design is the presence of current ripple, which can negatively impact battery health by introducing excess heat and stress within the cells, ultimately reducing their lifespan. Additionally, operating at high switching frequencies, while advantageous for minimizing the size of passive components, tends to increase switching losses and complicate thermal management. Effective heat dissipation and temperature regulation are therefore essential to ensure system reliability over time. At the same time, compliance with strict power quality standards requires the reduction of input current harmonics and improvement of the power factor, further increasing design and control complexity.

Recent progress in power electronics and advanced control techniques has enabled the development of improved solutions to address these challenges. Novel converter designs, including interleaved and resonant topologies, have been introduced to enhance efficiency and minimize ripple effects. Soft-switching methods are widely adopted to reduce switching losses and improve high-frequency operation. Furthermore, integrated charging configurations that merge propulsion and charging functions are being explored to reduce overall system size, cost, and complexity. The use of wide bandgap semiconductor technologies, such as silicon carbide (SiC) and gallium nitride (GaN), is also facilitating the development of high-efficiency, high-power-density charging systems.

This paper provides a comprehensive review of modern onboard charger technologies, with a focus on recent advancements in converter architectures, ripple reduction techniques, and system integration strategies. It also examines emerging concepts such as bidirectional charging and Vehicle-to-Grid (V2G) functionality, which enable EVs to exchange energy with the grid and support energy management systems.

II. LITERATURE REVIEW

A review of existing research highlights several shortcomings in current EV charging technologies. For example, PWM-controlled SRT DC/DC converters and dual active bridge (DAB) converters based on SiC MOSFETs are often studied without sufficient analysis of their thermal performance and long-term operational reliability. In a similar vein, three-phase non-isolated charger configurations require more detailed examination of their fault-tolerant capabilities. Bidirectional onboard chargers also tend to overlook the practical design challenges associated with single-stage conversion structures. Moreover, emerging approaches such as onboard self-heating mechanisms, cybersecurity in charging infrastructures, and solar-integrated multifunctional chargers frequently fail to address key considerations like cost viability and adherence to regulatory standards.

Additionally, research focusing on current ripple reduction and photovoltaic (PV)-assisted charging systems often lacks attention to real-world implementation barriers and economic practicality. Important factors such as scalability, transient performance, and system resilience under fault conditions remain inadequately addressed. These limitations point to the necessity for more comprehensive and application-driven investigations in the field of EV charging system design.

In this regard, incorporating both high-frequency and low-frequency analysis into literature reviews is essential for a more complete understanding of EV charging systems. Assessing system behavior across different frequency domains offers valuable insights into efficiency, thermal performance, and dynamic response. Such an integrated perspective enables better identification of design trade-offs, enhances system stability, and contributes to the development of more efficient, reliable, and optimized charging technologies.

III. METHODOLOGY

This study adopts a systematic and analytical approach to review and evaluate recent developments in electric vehicle (EV) onboard charger (OBC) technologies. The methodology begins with an extensive survey of existing literature, including journal articles, conference papers, and technical reports related to converter topologies, control strategies, and charging architectures. Relevant studies are selected based on their contribution to efficiency improvement, power density enhancement, ripple mitigation, and overall system performance.

Following the literature collection, the selected works are categorized into key areas such as AC–DC power factor correction techniques, DC–DC converter topologies, bidirectional charging systems, and integrated charging architectures. A comparative analysis is then carried out to assess the performance of different approaches in terms of efficiency, thermal behavior, switching losses, and power quality. Special attention is given to identifying the advantages and limitations of each topology and control method.

In addition, both high-frequency and low-frequency analyses are considered to better understand system dynamics, electromagnetic effects, and thermal characteristics. This dual-frequency perspective helps in evaluating the trade-offs between efficiency, component size, and operational stability. Emerging technologies, including wide bandgap semiconductor devices and renewable-energy-assisted charging systems, are also examined to assess their potential impact on future OBC designs.
Finally, research gaps are identified by critically analyzing the limitations of current studies, particularly in areas such as scalability, fault tolerance, thermal management, and economic feasibility. Based on these observations, potential directions for future research are proposed to support the development of more efficient, reliable, and cost-effective onboard charging systems for electric vehicles.

Overview of EV Onboard Charger Architecture

An electric vehicle onboard charger (OBC) is generally designed with two primary power conversion stages that work together to ensure efficient and reliable battery charging. The first stage is the AC–DC conversion unit with power factor correction (PFC), which converts the input alternating current from the grid into a stable direct current output. This stage is responsible for maintaining a high power factor and minimizing harmonic distortion to comply with grid standards. Among the various configurations, boost PFC converters are commonly preferred due to their relatively simple control structure and high efficiency.

The second stage is the DC–DC conversion unit, which further processes the DC output to provide a controlled voltage and current suitable for charging the battery pack. This stage also ensures galvanic isolation between the grid and the vehicle, enhancing safety and system reliability. To achieve improved efficiency and higher power density, advanced converter topologies such as resonant converters and dual active bridge (DAB) converters are widely implemented. Together, these two stages form the core architecture of an EV onboard charger, balancing performance, safety, and efficiency requirements.

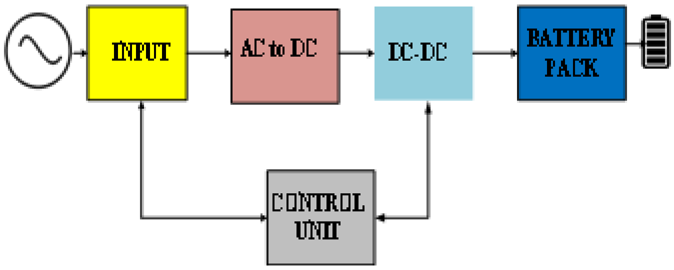

Fig 1:: Block diagram of onboard charging system for EVs

IV. CONTROL METHODS

Control strategies play a crucial role in ensuring the efficient, stable, and reliable operation of electric vehicle (EV) onboard chargers (OBCs). These methods are primarily designed to regulate output voltage and current, maintain a high power factor, reduce harmonic distortion, and minimize switching losses across different operating conditions.

In the AC–DC stage, control techniques are mainly focused on power factor correction (PFC). Conventional approaches such as average current mode control and peak current mode control are widely used due to their simplicity and effectiveness in shaping the input current to follow the grid voltage. In addition, digital control methods are increasingly being adopted, offering improved flexibility, faster response, and better adaptability to varying load and grid conditions.For the DC–DC stage, various control strategies are implemented depending on the converter topology. Voltage-mode and current-mode control are commonly used for regulating the charging profile, ensuring that the battery is charged safely under constant current (CC) and constant voltage (CV) modes.

Advanced control techniques, such as phase-shift control in dual active bridge (DAB) converters, enable efficient bidirectional power flow and precise power regulation.To further enhance performance, modern OBC systems incorporate intelligent and adaptive control methods, including model predictive control (MPC), fuzzy logic control, and artificial intelligence (AI)-based approaches. These techniques improve dynamic response, reduce current ripple, and optimize efficiency under varying operating conditions. Additionally, soft-switching control strategies are employed to reduce switching losses and electromagnetic interference, particularly in high-frequency applications. Overall, the selection of an appropriate control method depends on system requirements such as efficiency, complexity, cost, and reliability. Advanced control strategies continue to evolve, playing a key role in addressing the challenges associated with next-generation EV onboard charging systems.

V. RESULTS

Based on the comparative analysis of recent onboard charger (OBC) technologies, several expected performance outcomes can be projected. Advanced converter topologies, particularly interleaved and resonant configurations, are anticipated to achieve higher efficiency levels, typically in the range of 94–98%, due to reduced switching and conduction losses. The incorporation of soft-switching techniques and wide bandgap devices such as SiC and GaN is expected to further enhance efficiency while enabling operation at higher switching frequencies, thereby reducing the size of passive components and improving overall power density.

In terms of power quality, the use of improved power factor correction (PFC) strategies is likely to maintain a power factor close to unity (0.98–0.99) and significantly reduce total harmonic distortion (THD), ensuring compliance with grid standards. Current ripple mitigation techniques, including interleaving and advanced filtering methods, are expected to reduce output ripple by 20–40%, contributing to improved battery health and longer lifespan.

Thermal performance is projected to improve through optimized heat dissipation methods and efficient control strategies, although thermal management will remain a critical design constraint at higher power levels. Additionally, bidirectional charging systems and integrated architectures are expected to demonstrate enhanced functionality, supporting Vehicle-to-Grid (V2G) operations with high conversion efficiency and stable dynamic response.

Overall, the estimated results suggest that modern OBC systems can achieve higher efficiency, improved reliability, and better power quality compared to conventional designs. However, trade-offs between cost, complexity, and performance will continue to influence practical implementation, highlighting the need for balanced and application-oriented design approaches.

VI. CONCLUSION

This paper provides a detailed review of recent progress in electric vehicle (EV) onboard charger (OBC) technologies, examining a wide range of converter topologies, integrated charging configurations, and techniques for reducing current ripple. It highlights how ongoing advancements in power electronics have led to notable improvements in efficiency, power density, and overall system performance, enabling the development of more compact and effective onboard charging solutions tailored to modern EV requirements.

However, despite these advancements, several important challenges persist. Thermal management remains a significant issue, as higher power densities and switching frequencies contribute to increased heat generation, which can negatively impact component durability and lifespan. Additionally, concerns related to long-term reliability, scalability to higher power levels, and cost efficiency continue to limit widespread implementation. Practical aspects such as system response during transients, fault-handling capability, and performance under real operating conditions also require further investigation to ensure dependable and resilient operation.

Looking forward, future work should focus on the adoption of advanced semiconductor technologies, including silicon carbide (SiC) and gallium nitride (GaN), to further improve efficiency and minimize losses. There is also a need for more robust fault-tolerant control strategies and comprehensive analysis across both high- and low-frequency domains to better understand system behavior under diverse conditions. Ultimately, a comprehensive design perspective that balances performance, cost, reliability, and compliance with standards will be essential for the development of next-generation onboard chargers and for supporting the continued expansion of electric mobility.

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