A Novel High-Efficiency EV On-Board Fast Charging Using Sliding Mode Controlled Three-Port Partial Power Converter

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ABSTRACT

The rapid expansion of electric vehicles (EVs) necessitates the development of efficient, compact, and reliable on-board charging systems. This paper proposes a high-efficiency EV on-board fast charger based on a three-port partial power processing (PPP) converter integrated with a Sliding Mode Controller (SMC). The proposed topology facilitates simultaneous bidirectional power flow among the grid, battery, and auxiliary energy storage, enabling flexible and intelligent energy management. Unlike conventional full power processing converters, the PPP approach significantly reduces processed power, thereby minimizing switching losses, thermal stress, and component ratings while improving overall efficiency and power density. The incorporation of SMC ensures robust performance under parameter variations and external disturbances, offering fast transient response and precise voltage regulation. The system operates in multiple modes depending on grid and battery conditions, ensuring optimal power distribution during charging and auxiliary support operations. Simulation studies validate the effectiveness of the proposed method, demonstrating superior dynamic response, reduced output voltage ripple, and improved efficiency compared to traditional PI-controlled systems. The proposed charger achieves a peak efficiency exceeding 96%, making it a promising solution for next-generation EV charging applications.

Keywords: Electric Vehicles, Fast Charging, Partial Power Processing, Three-Port Converter, Sliding Mode Control, High Efficiency, DC-DC Converters, Multi-Port Power Systems, Energy Management, Power Electronics

INTRODUCTION

The rapid growth of electric vehicles (EVs) has significantly transformed the transportation sector, driven by the need to reduce greenhouse gas emissions, dependence on fossil fuels, and environmental pollution. As EV adoption increases globally, the demand for efficient, compact, and high-speed charging solutions has become more critical than ever. Conventional charging systems often struggle to meet the expectations of users in terms of charging speed, efficiency, and convenience, especially when compared to traditional internal combustion engine refueling [1], [2]. This has led to extensive research in the development of advanced on-board charging systems that can deliver higher power density, improved efficiency, and reduced system size without compromising reliability.

Traditional EV charging systems typically employ a two-stage power conversion approach consisting of an AC-DC rectifier followed by a DC-DC converter. While this configuration ensures regulated output and compatibility with grid standards, it often results in high power losses, increased component stress, and bulky system design due to full power processing (FPP) [3], [4]. Additionally, these systems operate under high voltage stress conditions, which not only affect efficiency but also increase thermal management challenges and overall system cost. Although several improvements such as soft-switching techniques, high-frequency operation, and bidirectional converters have been introduced, achieving both high efficiency and compactness remains a significant challenge [5]–[7].

To overcome these limitations, recent research has focused on multi-port converter architectures and partial power processing (PPP) techniques. Multi-port converters enable simultaneous energy flow between multiple sources such as the grid, battery, and auxiliary storage systems, improving flexibility and energy management [8], [9]. In particular, PPP-based converters process only a fraction of the total power through the conversion stages, allowing the majority of power to be directly transferred to the load. This significantly reduces switching losses, improves overall system efficiency, and minimizes component stress [10]–[12]. Such architectures are especially beneficial in EV charging applications where efficiency and power density are key performance indicators.

Another critical aspect of EV charger design is the control strategy employed for regulating voltage and current. Conventional controllers such as Proportional-Integral (PI) controllers are widely used due to their simplicity; however, they often exhibit poor dynamic response and limited robustness under nonlinear operating conditions and parameter variations [13]. Advanced control techniques like Sliding Mode Control (SMC) have gained attention for their ability to handle system uncertainties, disturbances, and nonlinearities effectively. SMC offers fast transient response, strong disturbance rejection, and high robustness, making it well-suited for EV charging systems operating under varying load and input conditions [14], [15].

In this context, the integration of a three-port partial power converter with an advanced control strategy such as SMC presents a promising solution for next-generation EV on-board fast chargers. The proposed approach aims to combine the advantages of PPP architecture—such as reduced losses and improved efficiency—with the robustness and dynamic performance of SMC. By enabling direct power transfer pathways and minimizing the burden on the DC-DC conversion stage, the system achieves higher efficiency and reduced component stress. This work focuses on developing such an integrated system, demonstrating its effectiveness through improved performance metrics including faster response, better voltage regulation, and enhanced overall efficiency, thereby addressing the key challenges associated with modern EV charging infrastructure.

LITERATURE SURVEY

The development of efficient electric vehicle (EV) charging systems has attracted significant attention in recent years, with early research primarily focusing on conventional charger architectures and their limitations. Initial studies emphasized integrated on-board chargers capable of combining multiple functionalities such as battery charging and auxiliary power supply within a single unit [1], [2]. These works highlighted the importance of compact design, improved efficiency, and bidirectional power flow capability to support vehicle-to-grid (V2G) operations. However, most early designs relied on traditional two-stage AC-DC and DC-DC conversion structures, which inherently process the entire power, leading to increased losses, bulky components, and limited scalability for high-power applications [3], [4]. As EV adoption increased, researchers began exploring alternative topologies to overcome these inefficiencies.

Subsequent research introduced multi-port and multi-input converter architectures to enhance flexibility and enable the integration of multiple energy sources such as renewable energy systems and energy storage units. Multi-port converters allow simultaneous power transfer between the grid, battery, and auxiliary devices, improving energy utilization and system reliability. Studies demonstrated that such converters support multiple operating modes including grid-to-vehicle, vehicle-to-grid, and renewable-assisted charging, thereby enhancing system versatility and grid interaction capabilities [5], [6]. Moreover, multi-port power electronic interfaces were found to provide superior energy management and dynamic performance by coordinating multiple inputs and outputs within a unified framework. Despite these advantages, challenges such as increased control complexity, higher component count, and cost remain significant barriers to widespread implementation.

To address the limitations of full power processing systems, recent literature has focused on partial power processing (PPP) or partial power converter (PPC) techniques. These approaches aim to process only a fraction of the total power through the converter while allowing the remaining power to flow directly to the load. This significantly reduces switching losses, improves efficiency, and minimizes thermal stress on components. Comprehensive reviews have demonstrated that PPP-based converters can achieve higher efficiency and reduced size compared to conventional topologies, making them highly suitable for fast EV charging applications. Additionally, research on hybrid and three-port converter configurations has shown that PPP architectures can effectively enhance power density while maintaining high efficiency levels, often exceeding 95% under optimal conditions [7]–[10]. These findings establish PPP as a promising solution for next-generation EV chargers.

In parallel with topology advancements, significant efforts have been made to improve control strategies for EV charging systems. Conventional Proportional-Integral (PI) controllers, although widely used, exhibit limitations in handling nonlinear dynamics, parameter variations, and rapid load changes. As a result, advanced control techniques such as Sliding Mode Control (SMC), predictive control, and intelligent control methods have been investigated. SMC, in particular, has gained popularity due to its robustness, fast transient response, and strong disturbance rejection capabilities in power electronic systems. Research studies have demonstrated that SMC-based controllers can significantly improve voltage regulation, reduce overshoot, and ensure stable operation under varying input and load conditions, making them well-suited for EV charging applications [11]–[13].

Overall, the literature indicates a clear transition from conventional full power processing chargers toward advanced architectures that integrate multi-port converters, partial power processing, and robust nonlinear control techniques. While multi-port systems enhance flexibility and energy integration, PPP techniques address efficiency and size constraints, and advanced controllers such as SMC improve dynamic performance and system stability. Despite these advancements, challenges such as system complexity, cost optimization, and real-time implementation of advanced control algorithms remain open research areas. Therefore, integrating PPP-based multi-port converters with robust control strategies represents a promising direction for developing high-performance, efficient, and scalable EV on-board fast charging systems [14], [15].

METHODOLOGY

The proposed system is developed by first defining the overall architecture of the on-board EV charger, which integrates a three-port AC-DC converter with a bidirectional DC-DC converter based on partial power processing (PPP). The system is designed to facilitate simultaneous energy flow between the grid, EV battery, and an auxiliary storage element, ensuring efficient energy utilization. The input AC supply is rectified and regulated through the three-port converter, where a portion of the power is directly transferred to the battery while the remaining portion is processed through the DC-DC stage. This configuration reduces the overall power processed by the converter, thereby minimizing switching losses and improving efficiency. The system parameters such as input voltage, DC-link voltage, battery voltage, and switching frequency are carefully selected to meet EV charging requirements.

The operation of the three-port converter is governed by two distinct modes depending on the relationship between the input voltage and battery voltage. When the input voltage is lower than the battery voltage, the converter operates in a mode where the inductor stores energy and supplies it directly to the battery through the lower port, ensuring single-stage power conversion. When the input voltage exceeds the battery voltage, the system transitions to another mode in which energy is shared between the upper and lower ports, and partial power is processed through the DC-DC converter. The switching behavior of power electronic devices is controlled using pulse-width modulation (PWM), ensuring smooth transitions between modes and maintaining stable operation across varying conditions.

To enhance system performance, a control strategy is implemented to regulate voltage and current while maximizing direct power transfer. The control system senses input voltage, output voltage, and current parameters, and generates appropriate gating signals for the converter switches. A dual-carrier PWM technique is employed to distinguish between operating modes and control the duty cycles of switches accordingly. This approach ensures unity power factor operation at the input side and minimizes harmonic distortion. By carefully coordinating the switching signals, the system achieves optimal power sharing between direct transfer and processed power, thereby improving overall efficiency.

The conventional proportional-integral (PI) controller is replaced with a Sliding Mode Controller (SMC) to improve robustness and dynamic response. The SMC is designed by defining a sliding surface based on the error between reference and actual output variables such as voltage and current. The control law forces the system states to reach and remain on this surface, ensuring stable operation even under parameter variations and disturbances. The discontinuous control action of SMC enables fast transient response, reduced overshoot, and improved disturbance rejection compared to linear control methods. This makes the system highly suitable for EV charging applications where load and input conditions vary frequently.

Finally, the complete system is modeled and simulated using a suitable platform to evaluate performance under different operating scenarios. Various test conditions such as steady-state operation, input voltage variation, load changes, startup, and shutdown are analyzed to verify system stability and efficiency. Key performance indicators including output voltage regulation, current waveform quality, response time, and efficiency are measured and compared with conventional systems. The results demonstrate that the proposed methodology achieves improved efficiency, reduced stress on components, and superior dynamic performance, validating the effectiveness of integrating PPP architecture with Sliding Mode Control for EV on-board fast charging applications.

PROPOSED SYSTEM

The proposed system introduces a high-efficiency on-board fast charging architecture for electric vehicles based on a three-port converter integrated with partial power processing (PPP) and a Sliding Mode Controller (SMC). The system consists of a front-end three-port AC-DC boost converter followed by a bidirectional DC-DC buck-boost converter. This configuration enables simultaneous interaction between the input grid, the EV battery, and an intermediate energy storage path. Unlike conventional full power processing (FPP) systems, where the entire power flows through multiple conversion stages, the proposed architecture allows a significant portion of the power to be directly transferred to the battery through the three-port converter. This direct power transfer path substantially reduces the burden on the DC-DC converter, leading to improved efficiency, reduced switching losses, and minimized thermal stress on power electronic components.

A key feature of the proposed system is its dual-mode operation based on the relationship between the input voltage and battery voltage. When the input voltage is lower than the battery voltage, the system operates in a mode where energy is stored in the inductor and delivered directly to the battery via the lower port, ensuring single-stage conversion. In contrast, when the input voltage exceeds the battery voltage, the system shifts to a mode where power is shared between the direct path and the DC-DC converter. Even in this mode, the majority of the power is still transferred directly, while only a fraction is processed through the DC-DC stage. This partial power processing significantly reduces converter size and rating, allowing the use of lower-rated components and improving overall system compactness and cost-effectiveness.

The control strategy employed in the proposed system plays a crucial role in ensuring efficient and stable operation. A dual-carrier pulse-width modulation (PWM) technique is utilized to generate switching signals for the converter switches, enabling seamless transition between operating modes. The controller continuously monitors system parameters such as input voltage, output voltage, and current, and adjusts the duty cycles to maintain desired performance. To further enhance robustness, the conventional PI controller is replaced with a Sliding Mode Controller. The SMC ensures fast dynamic response, precise voltage regulation, and strong disturbance rejection under varying load and input conditions. Its nonlinear control action enables the system to maintain stability even in the presence of uncertainties and parameter variations, making it highly suitable for real-world EV charging applications.

Overall, the proposed system offers several advantages over traditional charging architectures. By combining a three-port converter with PPP and SMC, the system achieves high efficiency, reduced component stress, and improved dynamic performance. The reduction in processed power through the DC-DC stage leads to lower switching losses and enhanced thermal management, which contributes to increased system reliability and lifespan. Additionally, the elimination of bulky components and reduced converter rating results in a more compact and cost-effective design. The proposed architecture is capable of delivering fast and stable charging while maintaining high power quality and efficiency, making it a promising solution for next-generation EV on-board fast charging systems.

RESULTS AND DISCUSSION

The performance of the proposed three-port partial power processing (PPP) based EV charger integrated with Sliding Mode Control (SMC) is evaluated through detailed simulation under various operating conditions. The system is analyzed for steady-state behavior, input voltage variation, load changes, and transient conditions such as startup and shutdown. The simulation model is implemented with realistic parameters including a single-phase 220 V AC input, regulated DC-link voltage, and controlled battery charging voltage. The obtained results are compared with a conventional system employing a proportional-integral (PI) controller to highlight the improvements achieved through the proposed approach. Key performance metrics such as efficiency, voltage regulation, ripple content, and dynamic response are used for evaluation.

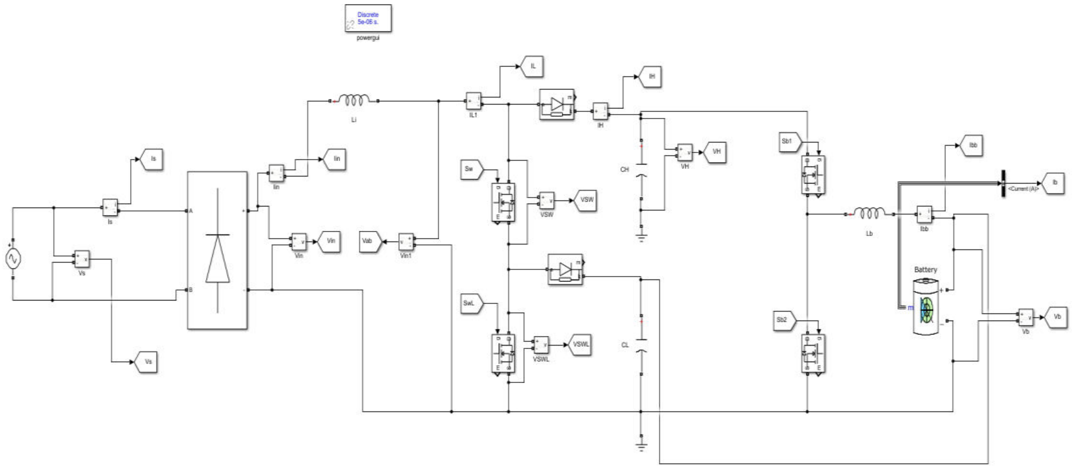


Fig 1. MATLAB/SIMULINK Circuit diagram of the system

Under steady-state conditions, the proposed system demonstrates stable operation with well-regulated output voltage and current. The input current waveform is observed to be nearly sinusoidal and in phase with the input voltage, indicating near unity power factor operation. The three-port converter efficiently transfers most of the input power directly to the battery through the lower port, while only a small fraction is processed through the DC-DC converter. This results in reduced switching losses and improved overall efficiency. The output voltage ripple is significantly minimized compared to the conventional system, indicating superior filtering and control performance. Additionally, the switching waveforms of the converter devices confirm smooth operation with reduced stress on components.

During input voltage variation tests, where the supply voltage is changed from 220 V to 270 V and vice versa, the proposed system exhibits excellent dynamic performance. The Sliding Mode Controller enables rapid adaptation to changing input conditions with minimal overshoot and faster settling time. In contrast, the conventional PI-controlled system shows noticeable oscillations and delayed response before reaching steady state. The ability of the proposed system to maintain stable output voltage under fluctuating input conditions demonstrates its robustness and suitability for real-world grid environments where voltage variations are common.

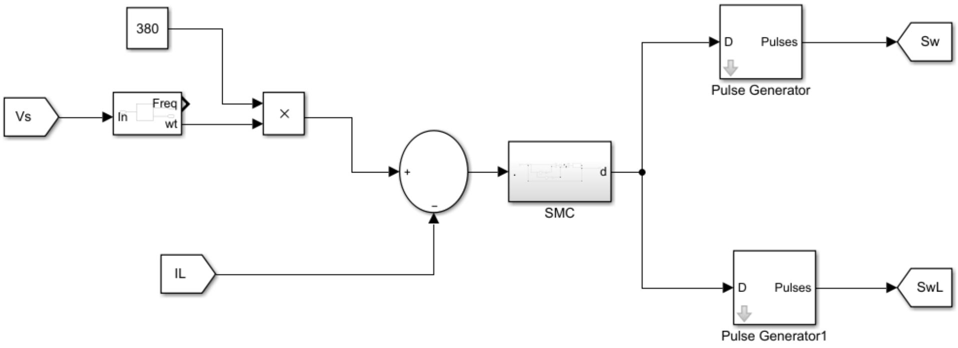


Fig 2. Control system of AC/DC Converter

The response of the system to load variations is also analyzed by changing the battery load from full load to half load conditions. The proposed system maintains consistent output voltage with minimal deviation, showcasing strong load regulation capability. The SMC effectively compensates for sudden changes in load demand by adjusting the control action in real time. Compared to the conventional system, which experiences slight instability and voltage dips, the proposed system ensures smooth and stable operation. This improved load handling capability is particularly important in EV charging applications, where battery conditions and charging requirements may vary dynamically.

Transient performance during startup and shutdown conditions further highlights the advantages of the proposed system. At startup, the system achieves a fast rise in output voltage with minimal overshoot, ensuring a smooth transition to steady-state operation. The SMC plays a crucial role in limiting transient spikes and preventing instability. During shutdown, the system exhibits controlled voltage decay without oscillations, ensuring safe operation and protecting the battery and converter components. In contrast, the conventional system shows slower response and noticeable oscillations during both startup and shutdown, which may affect system reliability over time.

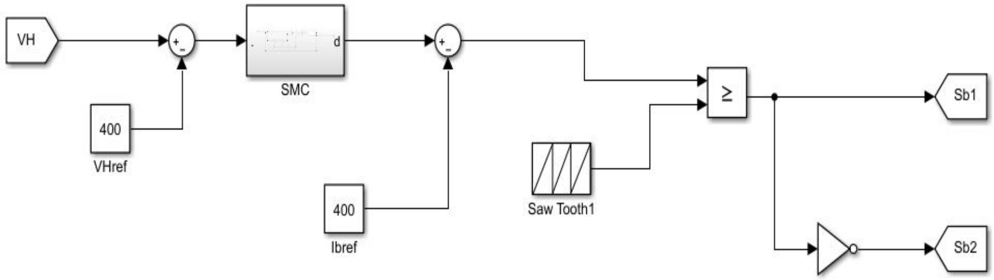


Fig 3. Control system of DC/DC Converter

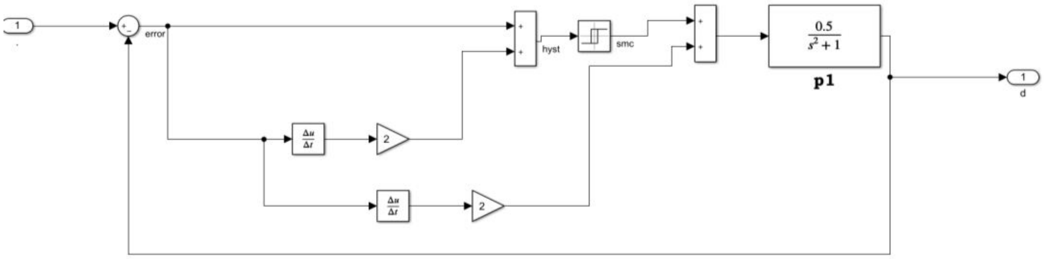
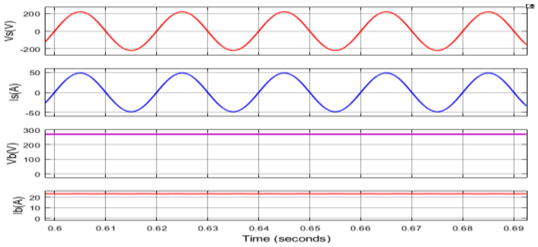
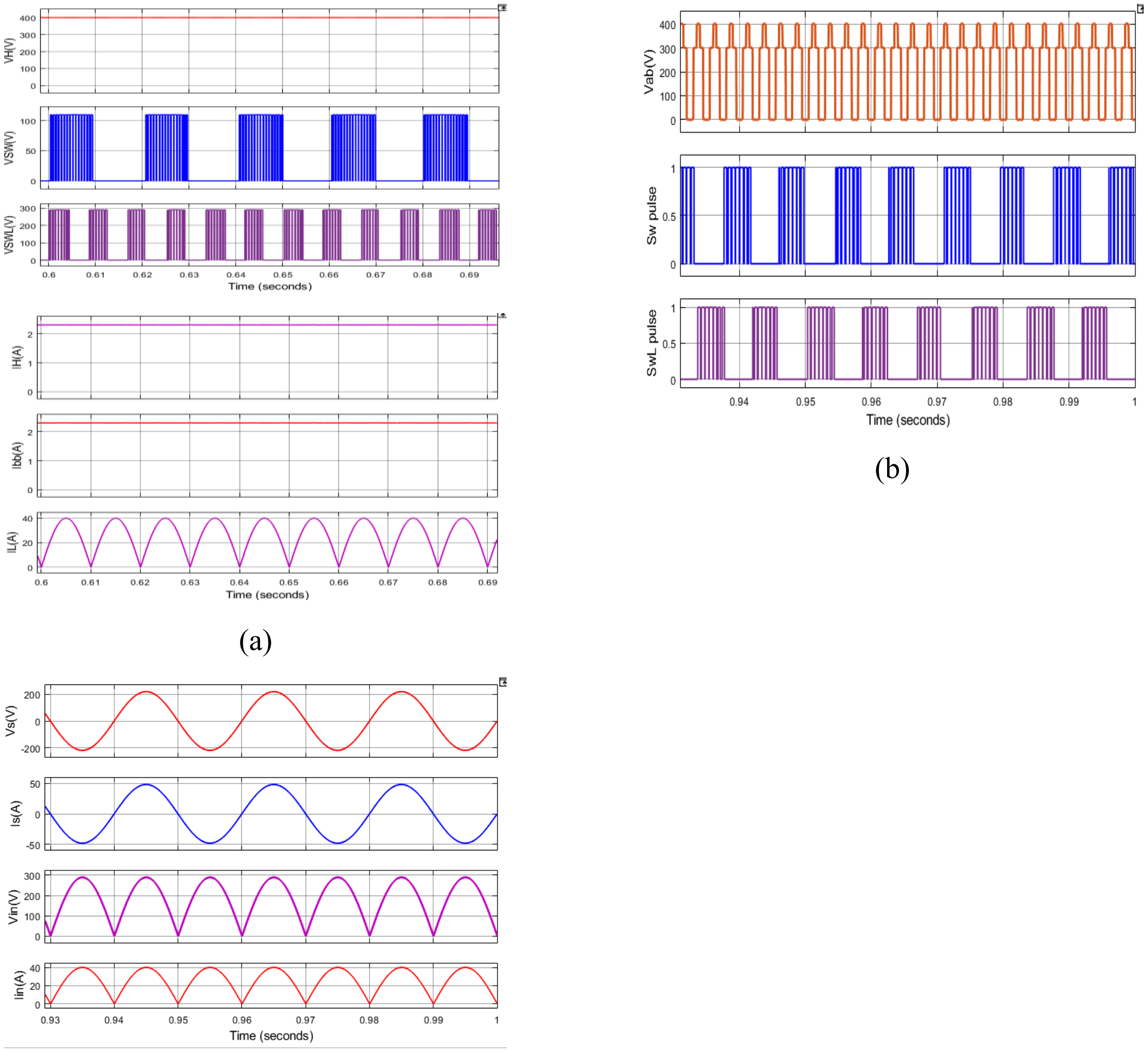


Fig 4. Sliding Mode Controller subsystem

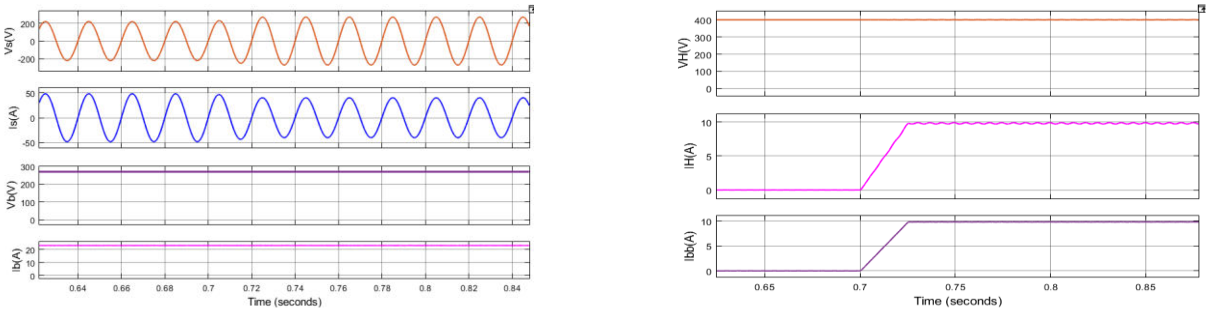




(a)

(b)

Fig 5. Simulated Performance of proposed fast charger during steady state condition, showing waveforms of (a)input and output side quantities with switch voltage, and (b) vin, iin and pole voltage, vab with respect to gate pulses to Sw and SwL.



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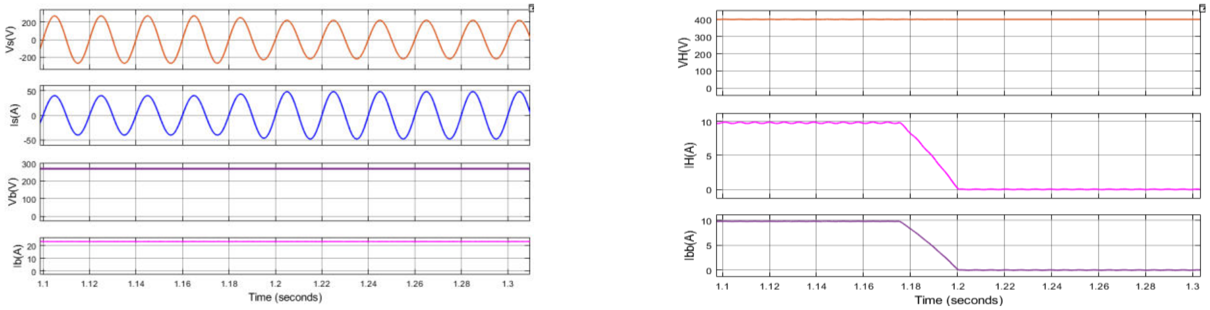
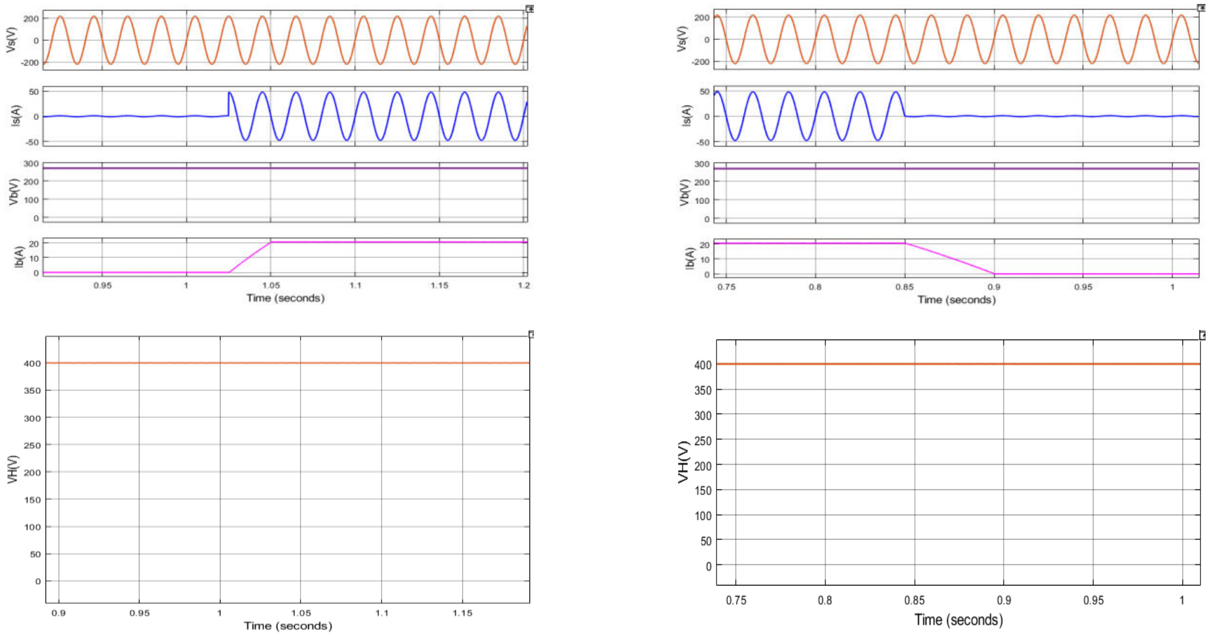


(b)

Fig 6. Simulated Performance of proposed fast charger during change in vs (a) from 220 V−270 V, and (b) from 270 V−220 V.



(a) (b)

Fig 7. Simulated performance of proposed fast charger during (a) startup condition, and (b) shut-down condition.

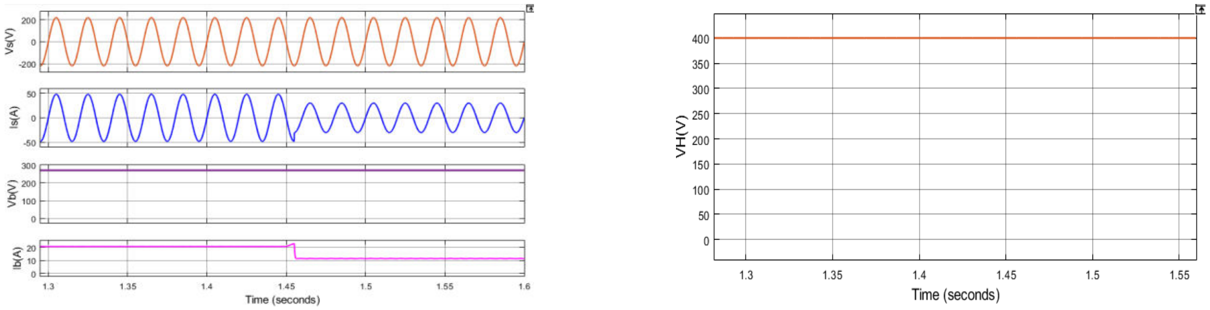


Fig. 8 Simulated performance of proposed fast charger during change in load i.e., Ib changes from full load to half load.

Overall, the results clearly demonstrate the superiority of the proposed PPP-based three-port converter with Sliding Mode Control over traditional charging systems. The system achieves a peak efficiency of approximately 96.13%, which is significantly higher than conventional systems that typically operate around 93–94%. The reduction in processed power through the DC-DC stage lowers switching losses and thermal stress, contributing to enhanced efficiency and reliability. Furthermore, improved voltage regulation, reduced ripple, faster dynamic response, and robust performance under varying conditions validate the effectiveness of the proposed approach. These findings confirm that the proposed system is a highly efficient, stable, and practical solution for next-generation EV on-board fast charging applications.

CONCLUSION

The proposed three-port partial power processing (PPP) based on-board EV charger integrated with Sliding Mode Control (SMC) demonstrates a significant advancement in electric vehicle charging technology. By enabling direct power transfer from the grid to the battery, the system minimizes the power processed through the DC-DC converter, thereby reducing switching losses, component stress, and overall system size. The incorporation of the SMC enhances system robustness, ensuring fast dynamic response, accurate voltage regulation, and strong disturbance rejection under varying input and load conditions. Simulation results confirm that the proposed system outperforms conventional PI-controlled chargers in terms of efficiency, stability, and transient performance. The ability to maintain near unity power factor, reduced output voltage ripple, and consistent operation during line and load variations highlights its practical applicability. Furthermore, the achieved peak efficiency of approximately 96.13% validates the effectiveness of the PPP architecture in improving energy conversion efficiency. The compact design and reduced thermal stress contribute to improved reliability and longer system lifespan. Overall, the integration of advanced converter topology with nonlinear control provides a cost-effective, efficient, and scalable solution for modern EV charging requirements, making it highly suitable for next-generation on-board fast charging applications.

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