

An Efficient Three-Port Partial Power Converter Based EV On-Board Fast Charger

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Abstract - The aim of this project is to design and build a novel three-port boost AC-DC converter that enables on-board rapid charging for electric vehicles through partial power processing (PPP) at the bidirectional DC-DC stage. In contrast to traditional two-stage chargers including dual-port AC-DC and full-power processing (FPP) DC-DC converters, the three-port converter (TPC) minimizes voltage stress on the switches. This enables the converter to operate at elevated power levels without imposing extra stress on devices, hence decreasing the charging duration. The PPP at the DC-DC stage enhances efficiency by minimizing power conversion stages.

The suggested TPC can produce three voltage output levels, hence minimizing converter switching losses. The suggested TPC with PPC concept significantly reduces power losses, as just a portion of the power is managed by the DC-DC converter switches and components. Consequently, the overall dimensions and expense of the charger can be minimized while attaining markedly higher efficiency in comparison to traditional two-stage chargers with FPP, even in the absence of gentle switching. The efficacy of the suggested charger is verified under various operating situations utilizing a MATLAB/Simulink simulation model for 6.6 kW and a scaled-down laboratory prototype for 1.5 kW.

Key Words: Electric vehicle, fast charging, partial power conversion, three-port converter, two-stage charger.

1.INTRODUCTION

Electric cars (EVs) and EV chargers are anticipated to match the refueling speed of traditional fossil fuel-powered automobiles. To fulfill this expectation, and given that charging speed is the primary impediment to the widespread adoption of electric vehicles, both on-board and off-board chargers must be engineered effectively to accommodate higher charging currents, hence enabling greater power output. Nonetheless, the elevated power rating for on-board architecture necessitates a larger size and greater cost of the AC-DC converter due to the utilization of higher-rated power components [2]. Moreover, at elevated power levels, the losses are considerable, adversely affecting the charger's efficiency. A thorough examination of various AC-DC converter topologies relevant to contemporary electric

vehicle chargers is presented in [2]. Conventional on-board chargers are mostly engineered for sluggish charging, owing to constraints on voltage and current stress on devices. Figure 1(a) illustrates the traditional two-stage charger architecture, comprising a two-port buck-boost converter succeeded by a full power processing (FPP) DC-DC converter [3], [4]. The two-port converter sustains VH at 300 V, facilitating the DC-DC stage for battery charging through constant current-constant voltage regulation. In a 220 V single-phase AC system, the voltage stress in these two-port converters generally ranges from 400 V to 500 V for the AC-DC stage and from 400 V to a maximum of 600 V for the DC-DC stage. This limits the charger's functionality for high power, leading to reduced charging speed at the battery. Furthermore, for a specified power level, switches with higher voltage ratings are necessary for the implementation of a two-port converter. Consequently, the expense and total footprint of the charger are typically substantial, and efficiency still possesses potential for further enhancement. The enhancement of efficiency in on-board chargers is accomplished through three methods: employing single-stage/two-stage high-gain configurations and immobilizing full-power processing (FPP) in the DC-DC stage and employing the principle of partial-power processing at the DC-DC stage.

The enhancement in efficiency with single-stage/two-stage high gain configurations [5], [6], [7] is minimal, and the input voltage range must be constrained due to the high gain architecture. Despite employing soft-switching, the peak efficiency of contemporary EV chargers utilizing FPP DC-DC conversion is observed to be between 93% and 96% [8], [9], [10], [11]. Sharma et al. have introduced several bidirectional two-stage chargers featuring FPP, although their efficiency is constrained to the range of 92–94% and they comprise a greater number of components [12], [13]. A single-stage bidirectional EV charger with FPP is documented in [14], exhibiting the same number of devices and components, however demonstrating only a 1% enhancement in efficiency. Furthermore, the management of all these bidirectional chargers is intricate and necessitates costly controllers, like as ds pace, for execution. Additionally, the FPP DC-DC converter necessitates larger current-rated components on the battery side, owing to its design at rated power, which subsequently constrains overall charger

efficiency, size, and escalates costs. Consequently, to address the constraints of size, cost, and efficiency, a novel fast charger configuration utilizing the principle of partial-power processing (PPP) at the DC-DC stage is proposed, as illustrated in

Fig. 1(b), is presented in this paper plummeting soft-switching.

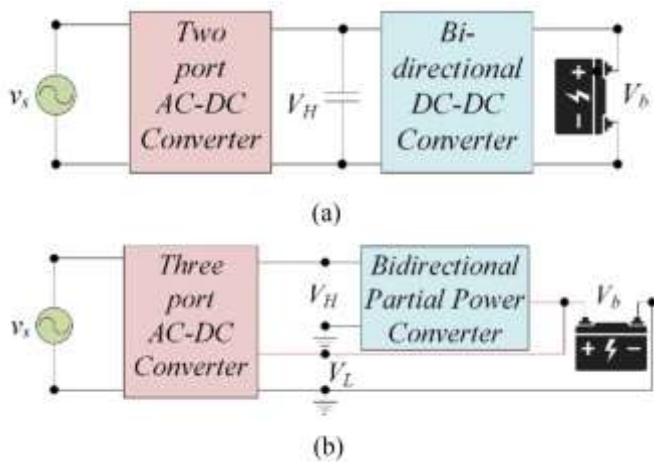


FIG. 1. GENERAL ARCHITECTURE OF. (A) CONVENTIONAL CHARGER WITH FPP TWO-PORT CONVERTER, AND (B) PROPOSED FAST CHARGER WITH THREE-PORT CONVERTER.

Recent literature on PPP converters offers many DC-DC converter methods suitable for EV rapid chargers. Nonetheless, the majority of these topologies need high-frequency transformers and a substantial number of components [15], [16]. According to the SAE J1772 standard [17], for safety reasons, electric vehicles often feature a floating battery ground that is isolated from the power electronic ground, which is linked to the vehicle's chassis. Consequently, the battery and the vehicle's power electronic interface possess distinct grounds. Consequently, the isolation transformer in traditional chargers can be omitted, and an isolated converter is unnecessary at the DC-DC stage. The benefits of the PPP approach in the DC-DC stage regarding size, cost, and efficiency are elaborated upon in [18].

The notion of partial power processing for voltage elevation and reduction is prevalent in photovoltaic (PV) systems [19]. Additionally, other topologies utilizing series-connected PPP converters have been documented in the literature [20] and have also been used for electric vehicle fast charging [21]. The fast-charging concept of PPP relies on minimizing the peak power or current managed by the DC-DC stage, observed during the constant current (CC) charging mode. Conversely, until the converter fulfills the peak charging current requirement during constant current mode, the output voltage of the converter may be less than the battery voltage. Therefore, the converter output voltage can be connected in series with the battery voltage, which embodies the fundamental principle of the PPP concept

employed in this study at the DC-DC stage. The literature on PPP establishes this connection through two distinct methods, resulting in two configurations: type-I and type-II [20], [21]. Type-I setups are classified as step-down and are realized using an IPOS (Input-Parallel Output-Series) connection of the battery, DC-link voltage, and DC-DC converter terminals. The input side features a parallel connection of the DC-DC topology with the DC-link voltage, while the output side incorporates a series connection of a portion of the battery voltage with the DC-DC converter input (or DC-link voltage). The alternative Type-II configuration employs a step-down methodology, realized using an ISOP (Input-Series Output-Parallel) connection of the battery, DC-link voltage, and DC-DC converter terminals [20], [21]. To obtain ISOP, the output of the DC-DC topology is linked in parallel to the battery voltage. The input port of the DC-DC topology is linked in series to a fraction of the battery voltage, as seen in Fig. 1(b). A direct path, or bypass connection, is available to continually charge the battery, allowing a portion of the battery voltage to connect to the DC-DC converter input.

This direct connection enables battery charging through single-stage conversion, circumventing the DC-DC stage for the majority of the charging cycle. Consequently, just a fraction of battery power must be managed by the DC-DC converter, resulting in a substantially decreased rating for the converter, which enhances efficiency and dramatically decreases both size and cost. The integration of a three-port AC-DC converter with the PPP idea at the DC-DC stage can further reduce size, cost, and efficiency challenges, which is the primary objective of this study. Figure 1(b) illustrates the overall architecture of the proposed charger, which includes a three-port boost AC-DC converter, succeeded by a bidirectional buck-boost PPP DC-DC converter.

The unique characteristic of the suggested charger is that the majority of the power is sent to the battery directly by the three-port converter (TPC), circumventing the DC-DC stage [22]. The suggested TPC provides the benefit of diminished voltage strains on devices (i.e., V_L and $V_H - V_L$) owing to the partial voltage present across the lower and upper ports, respectively. This diminished device voltage stress enables the converter to operate at elevated power levels with the same switches, hence permitting rapid charging at the battery terminal. Consequently, the charging speed is seen to be superior to that of traditional two-port converter-based chargers. Furthermore, switches with lower voltage ratings might be utilized at the TPC stage to minimize the size of the converter. Additionally, the DC-DC stage handles only a portion of the total charging power, which markedly decreases the number of conversion stages relative to the traditional two-stage charger, thereby enhancing charger efficiency. Furthermore, the diminished power

processing has resulted in less current stress on the DC-DC converter switches. This enables the utilization of switches with lower current ratings for the bidirectional converter. Consequently, the total dimensions and expense of the charger are diminished due to increased efficiency.

A comprehensive comparison analysis of the suggested charger with PPP against the current solutions in the literature [5], [6], [7], [8], [9], [10], [11], [12], [13] is presented in Table I. The primary contribution and innovation of this unique TPC-based charger utilizing the PPP idea are outlined below. The proposed charger utilizing the PPP idea enables a higher charging rate compared to the traditional charger with full power processing. The implementation of the PPP idea improves the overall efficiency of the charger, as just a portion of the total power is managed by the DC-DC converter. The voltage stress on the device at the TPC stage and the current stress of the DC-DC converter are markedly low. The suggested TPC offers three output voltage levels, leading to less switching losses and enhanced efficiency.

2. On-Board Charging Station for Electric Vehicles

The automobile sector is one of the most significant in the world economy and in terms of technological innovation. Contemporary technology is progressively utilized in current cars to enhance transportation efficiency, pleasure, and safety. The transportation business has expanded rapidly, providing individuals with increased options for expeditious travel from point A to point B. Nonetheless, the increasing volume of vehicles on roadways has exacerbated pollution levels in urban areas. Transport infrastructure reliant on fossil fuels continuously emits harmful pollutants, such as particulate matter (PM), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and carbon monoxide (CO), which substantially contribute to air pollution. The transportation sector plays a crucial role in climate change and environmental degradation, with road transport being a significant source of CO₂ emissions globally.

Numerous countries are utilizing government incentives and supportive policies to encourage the acquisition of electric vehicles (EVs), aiming to reduce greenhouse gas emissions and enhance air quality. Various initiatives have been implemented to promote the use of eco-friendly transportation systems, including reductions in transport taxes, provision of purchase subsidies, allocation of free parking spots, and access to low-emission traffic zones. Drivers of electric vehicles enjoy numerous advantages compared to those of conventional gasoline-powered cars. Electric vehicles significantly reduce air emissions of harmful gases such as CO₂ and NO₂, as they do not emit these pollutants during operation. Further benefits include reduced maintenance

expenses and quieter functionality, as electric motors possess more mechanical simplicity and fewer moving components. The enhanced reliability of electric vehicles and reduced engine wear, corrosion, and vibration arise from their absence of complex gear systems, cooling mechanisms, and fuel combustion processes, unlike conventional engines.

3. Circuit Configuration, Steady-State Analysis and Design

The suggested charger comprises a three-port boost AC-DC converter at the front end, succeeded by a bidirectional buck-boost DC-DC converter utilizing partial power processing (PPP). As shown in Fig. 2(a), the circuit comprises a three-port AC-DC converter using switches Sw , SwL , diodes $D1$, $D2$ and inductor Li with the DC-link capacitors CH and CL .

The TPC is additionally linked in series with the bidirectional DC-DC converter by switches $Sb1$, $Sb2$, and inductor Lb . In a single-phase 220V system, the bus voltage VH is maintained at 400 V, while the charging port Vb is regulated to deliver 270 V. The bottom port VL primarily conveys charging power to the battery via a bypass connection (red line). The direct transfer of power is predominantly contingent upon the ratio of battery voltage, Vb , to the peak supply voltage, Vp . The DC-DC converter processes just a fraction of the entire charging power, as indicated by the partial power ratio. Nonetheless, the charger can still deliver the complete charging power to the battery, utilizing the new TPC at the front end. The proposed TPC functions in two unique modes: mode-1 ($v_{in} < Vb$) and mode-2 ($v_{in} > Vb$). Figure 3(a)–(d) illustrates the converter's operation across one switching cycle. The detailed description of these two switching states during each mode is provided as follows.

Mode-1 ($v_{in} < Vb$): In this mode, switch Sw remains in the ON position, resulting in diode $D1$ being reverse biased. As illustrated in Fig. 3(a), during the first switching state, the inductor, Li , commences energy storage via Sw and SwL , as both switches are in a conductive condition. The lower capacitor, CL , directly provides the battery charging current through single-stage conversion. The diodes $D1$ and $D2$ are both in the OFF condition. In the second switching condition, switch SwL is deactivated, while switch Sw remains in conduction.

This renders the diode $D2$ forward-biased. As illustrated in Fig. 3(b), the inductor, Li , commences the discharge of stored energy via the diode $D2$ and the capacitor, CL . The majority of the charging power is delivered via the lower port capacitor CL during this moment as well. Consequently, in mode-1, the total charging power is provided directly by the TPC.

Mode-2 ($v_{in} > V_b$): As shown in Fig. 2(b), during mode-2, switch S_{wL} is completely OFF during both the switching states, while, switch S_w is switching ON and OFF, repeatedly.

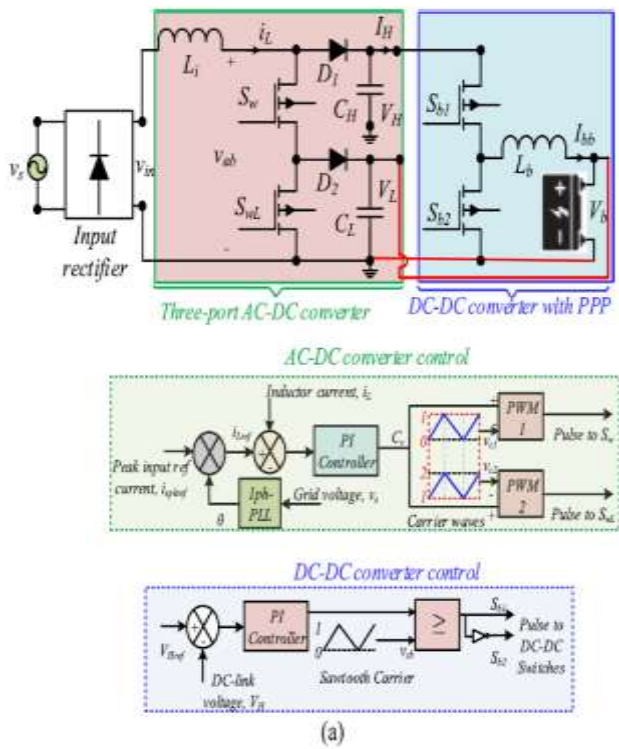


FIG. 2. PROPOSED PPP CONVERTER BASED FAST CHARGER (A) CONFIGURATION AND CONTROL. (B) PULSE GENERATION AND SWITCHING WAVEFORMS.

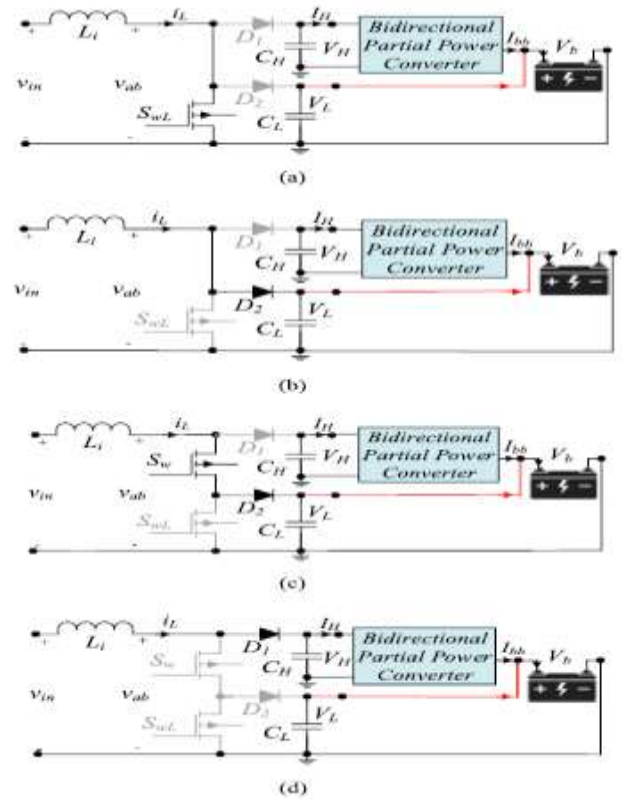


FIG. 3. CONVERTER/CHARGER OPERATION OVER ONE SWITCHING CYCLE DURING (A)–(B) MODE-1. (C)–(D) MODE-2.

In the initial switching condition, seen in Fig. 3(c), S_w is activated while S_{wL} is deactivated. Consequently, diode D_1 remains in the OFF state while diode D_2 is activated. The inductor L_i begins to accumulate energy via the switch S_w and diode D_2 , exhibiting a voltage differential of v_{in} and V_b . The battery receives charging power via the lower capacitor C_L . In the second switching condition, switch S_w is deactivated, but switch S_{wL} is already deactivated. As illustrated in Fig. 3(d), the diode D_1 is now in a conducting state.

The inductor, in conjunction with the input voltage, provides the necessary charging power to the battery through a DC-DC converter utilizing a two-stage power conversion process. Consequently, in mode-2, the charging power is distributed across the upper and lower port capacitors. Nonetheless, this distribution is not uniform for the capacitors, C_H and C_L , but is contingent upon the voltages V_H and V_L . Consequently, even if v_{in} exceeds V_b , during mode-2, the majority of the power is transmitted directly to the battery via TPC. In two modes, the volt-second balance for the boost inductor L establishes the relationship among input voltage v_{in} , V_b , and V_H for mode-1 and mode-2 as follows

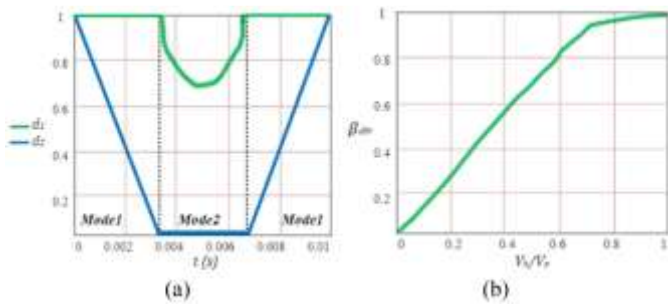


Fig. 4. Graphical change in, (a) duty cycles, d_1 and d_2 , and (b) direct power

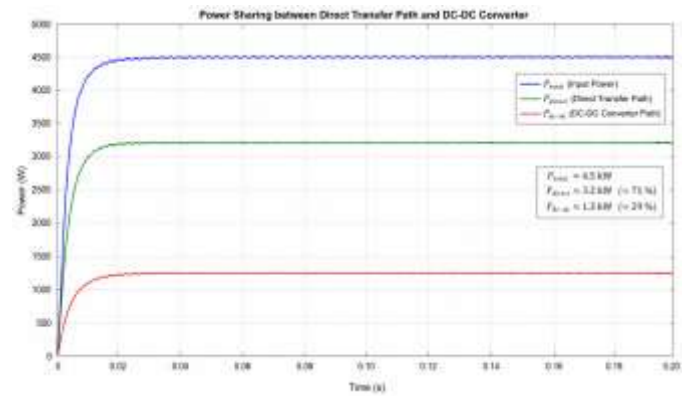


FIG.7. POWER SHARING BETWEEN DIRECT TRANSFER PATH AND DC-DC CONVERTER.

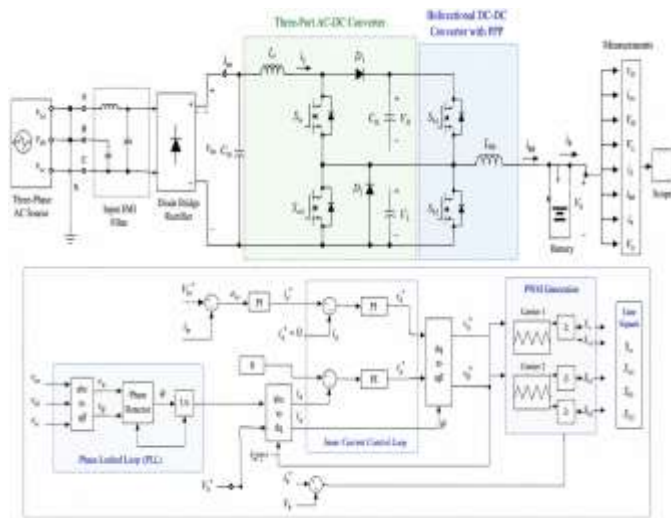


FIG.5. MATLAB/SIMULINK MODEL OF THE PROPOSED THREE-PORT PPP EV CHARGER.

4. Results and Discussion

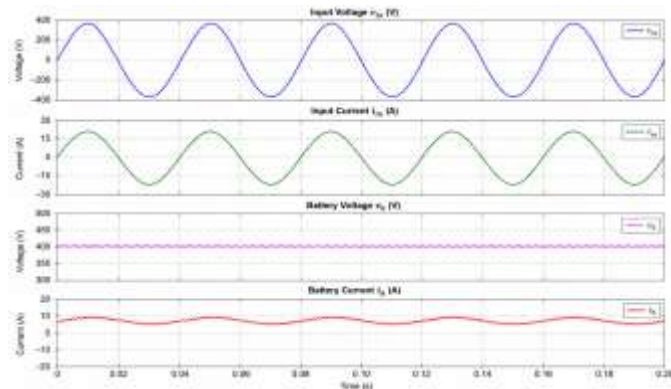


FIG.6. STEADY-STATE WAVEFORMS OF INPUT VOLTAGE, INPUT CURRENT, BATTERY VOLTAGE, AND BATTERY CURRENT.

The suggested charger was assessed under several operating conditions to validate the efficacy of the converter topology and control method. The simulation results indicate stable operation, high efficiency, diminished converter stress, and effective battery charging performance.

1) Approximately 90% of the charging power is directly transmitted to the battery via the bottom port, as indicated by the acquired waveforms. Only 10% of the overall charging power is managed by the bidirectional converter. The significant decrease in processed power, achieved by substantially reducing switching and conduction losses, enhances overall efficiency.

The reduced current flowing through the DC-DC converter signifies the effectiveness of the partial power processing idea. Consequently, passive components and diminutive semiconductor devices may be utilized.

2) The proposed converter inherently generates a three-level pole voltage waveform with voltage levels of 0 V, V_b , and V_H .

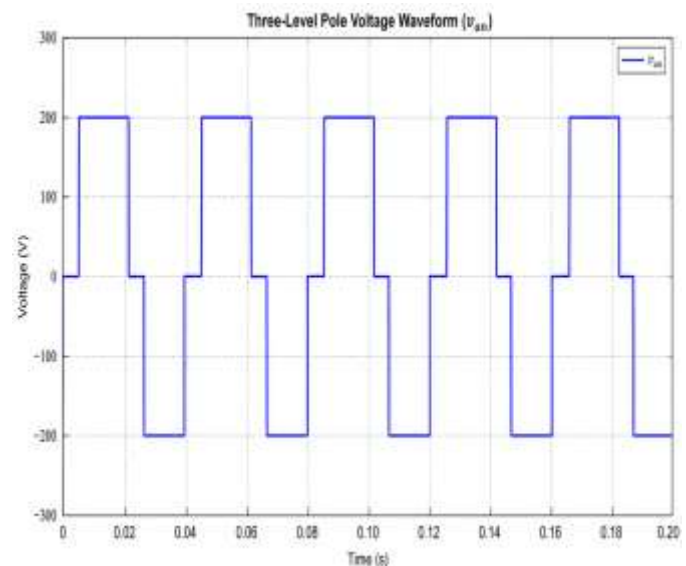


FIG.8. THREE-LEVEL POLE VOLTAGE WAVEFORM GENERATED BY THE CONVERTER.

1) The three-level voltage waveform improves harmonic performance and reduces voltage stress on semiconductor devices. Electromagnetic interference is mitigated and switching losses are reduced due to voltage transitions occurring in fewer increments compared to conventional two-level converters.

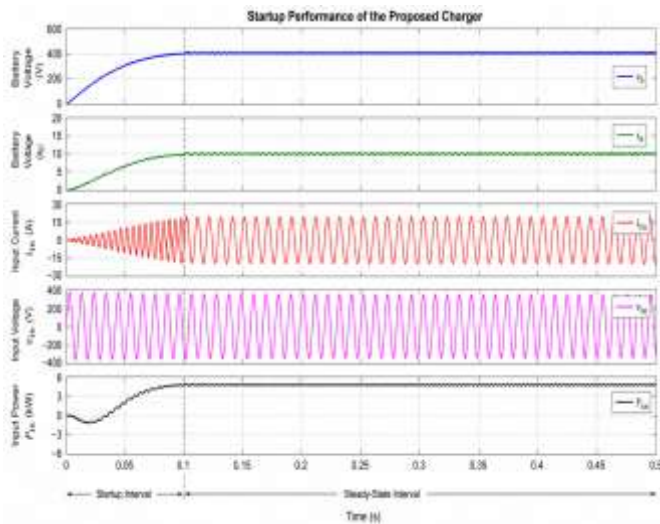


FIG.9.STARTUP PERFORMANCE OF THE PROPOSED CHARGER.

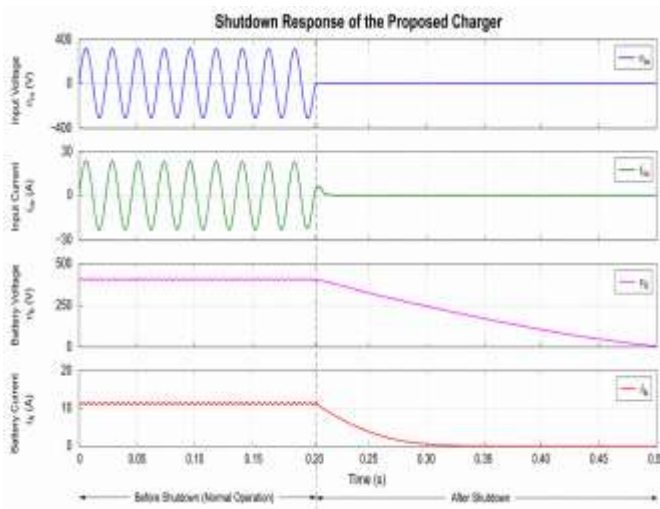


FIG.10.SHUTDOWN RESPONSE OF THE PROPOSED CHARGER

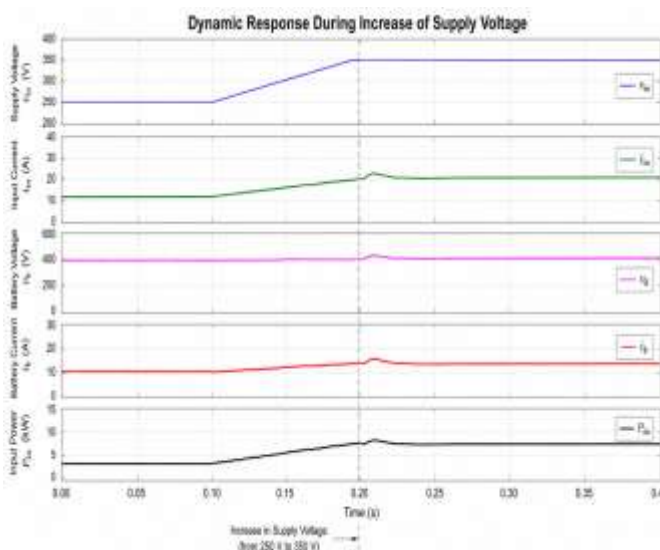


FIG.11.DYNAMIC RESPONSE DURING SUPPLY VOLTAGE INCREASE.

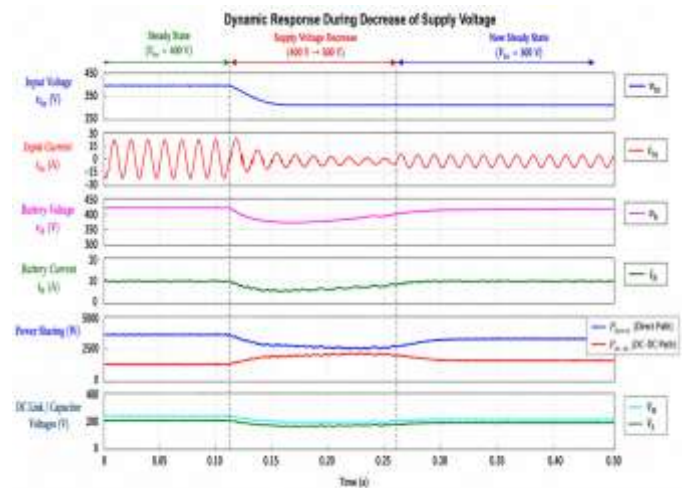


FIG.12.STARTUP PERFORMANCE OF THE PROPOSED CHARGER

Dynamic response during supply voltage the simulation analysis revealed that roughly 90% of the charging power is directly transmitted to the battery, with only 10% handled via the DC–DC converter. This distinctive characteristic allows charger efficiency to surpass 99%, markedly exceeding those of traditional full-power-processing charger configurations. Moreover, the three-port architecture diminishes voltage stress and produces a three-level output voltage, leading to reduced switching losses and enhanced converter dependability.

The proposed charger offers an efficient, compact, and scalable alternative for advanced electric vehicle charging systems.

1) The proposed design's scalability is a further notable advantage. The architecture can support higher charging power levels without necessitating an increase in the DC-DC converter rating. This capability makes the charger particularly attractive for future high-power electric vehicle charging applications.

2) This study presents a Three-Port Partial Power Processing converter designed for high-efficiency on-board rapid charging of electric vehicles. The proposed architecture integrates a bidirectional DC-DC converter employing the partial power processing method with a three-port AC-DC converter. The converter significantly reduces the power processed by the DC–DC stage by allowing most of the charging power to be transmitted directly to the battery.

3) A comprehensive mathematical model, operational concept, design methodology, and control strategy were developed and analyzed. Both steady-state and transient operational conditions, including startup, shutdown, load variation, and supply voltage perturbations, were simulated utilizing MATLAB/Simulink. The results validated exceptional dynamic responsiveness, unity power factor operation, stable performance, and effective battery charge regulation.

4) According to the simulation study, around 90% of the charging power is transmitted directly to the battery, with merely 10% passing through the DC–DC converter. This particular feature enables charger efficiency over 99%, significantly surpassing conventional full-power-processing charger topologies. The three-port architecture generates a three-level output voltage, reduces voltage stress, diminishes switching losses, and enhances converter reliability.

5) Ultimately, the proposed charger presents a highly efficient, compact, and scalable solution for advanced electric car charging systems.

5. CONCLUSIONS

Simulation results show that the contribution of the DC-DC converter is just 10% of the total charging power and over 90% of the power is given directly to the battery. This unique feature allows charger efficiency to approach 99% which is far greater than traditional full power processing charger configurations. The three-port design also minimises voltage stress and produces a three-level output voltage which decreases switching losses and improves converter dependability. The proposed charger provides a scalable, small and efficient alternative to the current electric vehicle charging systems.

1) Another important advantage of the proposed approach is its scalability. The architecture enables a higher charging power level to be used without requiring a change to the DC-DC converter rating. The charger's high-power capability to charge electric cars makes it very attractive for such purposes in the future.

2) Three-Port Partial Power Processing converter is proposed for efficient on-board rapid charging of electric vehicles. The suggested design is composed of a three-port AC-DC converter and a bidirectional DC-DC converter based on the partial power processing approach. By diverting most of the charging current directly to the battery, the converter significantly reduces the power that must go through the DC-DC step.

3) Developed and tested comprehensive mathematical model, control approach, design methodology and operational concept. Using MATLAB/Simulink we were able to model both steady state and transient operating conditions such as power on/off cycles, load changes and disturbances in the supply voltage.

The results exhibited excellent dynamic responsiveness, stable performance, effective regulation of battery charge and unity power factor operation.

4) The simulation study shows that only 10% of the charging power is provided to the DC-DC converter and

other 90% is directly provided to the battery. This feature in particular can enable the charger to achieve an efficiency level beyond 99%, which is significantly better than the efficiency of standard full-power-processing charger topologies. The three-port design has the advantage of a three-level output voltage, lower voltage stress, less switching losses, and enhanced reliability of the converter.

5) Therefore, the proposed charger is a good choice for modern electric car charging systems because of its scalability, small size and high efficiency.

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