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A novel single-stage high-voltage gain DC-DC boost converter for on-board PEV charging system

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ABSTRACT

Currently, the utilization of plug-in electric vehicles is quickly increasing in the vehicle industry owing to reduced costs of transportation, no need for fossil fuels, simple servicing, no fuel expense, and lower environmental effect compared to internal-combustion motor vehicles. In actuality, these motor vehicles function based on available battery energy that are charged by a utility-grid-supplied charging station. In this charging facility, a power converter defined on-board charger is generally used to charge the batteries, which improves the utility grid specifications by reducing the presence of harmonics and power factor regulation. An active two-stage load conditioning approach is commonly employed, however it doubles the conversion stages, requires larger switching components, complicated circuitry, large switching losses, and decreased efficiency, among other issues. To address these issues, a unique single-stage on-board EV charger has been used to regulate utility-grid specifications and seamless management of battery state-of-charge using a load-side DC-DC conditioning method. The major goal of this study is to propose a unique DC-DC boost converter that provides substantial voltage gain, consistent input current, minimal current ripples, and highest efficiency among numerous converters. The effectiveness of the proposed unique single-stage on-board EV charger has been evaluated through MATLAB/Simulink application, and the simulation findings have been presented.

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1. INTRODUCTION

With growing diesel as well as gasoline prices and their significant impact on the global climate, the use of electric vehicles (EVs) in the transport sector is increasing. The fundamental benefits and attractiveness of the EV technology over internal combustion motor (ICM) vehicles are cheaper cost of transportation, lower repair costs, no oil expenditures, and ecological friendliness. Such EVs are divided into three categories: hybrid electric vehicles (HEVs), plug-in electric vehicles (PEVs), and battery-powered electric vehicles (BOEVs). In India, the use of PEVs, which as electric cars, electric motorbikes, and e-auto's is rapidly increasing, leading to over 38 percent of all automotive registrations by the end of 2024 [1], [2].

The PEV includes a motor that is powered by the battery energy, and these battery packs are recharged at utility-grid supplied charging facilities. For powering the battery packs, most EV charging facilities necessitate on-board charger equipped with a non-linear diode-bridge rectifier. This onboard charger distorts harmonic current and degrades the quality of power in grid-connected distribution systems [3]-[8]. The advent of PQ difficulties produces serious problems in the electrical grid, impacting supply terminal voltage, current, and fundamental frequency. Current harmonics and non-unity supply power factor have the leading causes of poor quality in the utility grid [9].

Several load-side conditioning (LSC) on-board charging circuitry techniques are studied and to establish the modern enhancement devices are explored in [10]-[13]. These load-side conditioning techniques are developed as two-stage conversion methodology in an on-board charging unit, which consists of two-stages, such as a DC-DC PFC topology in the 1st stage for controlling the harmonic currents and power-factor correction, and a coupled transformer based dual-active bridge converter in the second stage for controlling the battery state-of-charge (SOC) is explored in [14]. However, these two-stage on-board chargers increase the complexity, size, cost, and switching devices. Figure 1 shows the model of a conventional 2-stage on-board charging circuit.

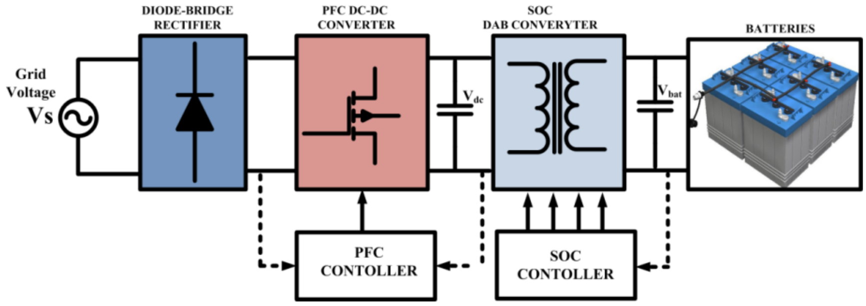

Figure 1. Model of conventional 2-stage on-board charging circuit

A unique single-stage on-board EV charger for PEV systems has been implemented to mitigate the aforementioned problems. It smoothly controls battery state-of-charge and manages utility-grid parameters. With fewer switching devices, a smaller, less expensive, and more compact charging unit, this single-stage on-board PEV charger uses a high-voltage gain DC-DC boost converter for both control functions. In a wide range of energy conversion applications, switch-mode DC-DC converters with high-boost voltage compatibility are utilized at power levels between kilowatts and megawatts and voltage levels between millivolts and kilovolts [15]-[17]. Boost voltage can generally be achieved by using coupled inductors, high-frequency transformers, and multi-winding; however, this necessitates a large number of windings, a complex design, and a high leakage inductance, which results in high voltage stress from voltage spikes at the corresponding switches [18]-[25]. By introducing the novel DC-DC boost converter with few switching components and no requirement for connected inductors, high-frequency transformers, or multi-windings, among other things, the aforementioned drawbacks were readily addressed. For the proposed PEV charging unit, these are the significant benefits of designing, creating, and deploying innovative DC-DC boost converters. This paper proposes innovative on-board EV charging equipment for PEVs that incorporates a single-stage DC-DC boost converter. The effectiveness of the proposed unique single-stage on-board EV charger has been evaluated through MATLAB/Simulink application, and the simulation findings have been presented.

2. PROPOSED METHOD

The greater voltage compliance of switch-mode DC-DC converters are used widely in energy conversion applications at power levels ranging from kilowatts to megawatts and voltage levels ranging from millivolts to kilovolts. Generally speaking, boost voltage can be produced by connected inductors, high-frequency transformers, and multi-winding; however, this requires a large number of windings, a complex design, and a high leakage inductance, which leads to high voltage stress because of voltage spikes at the corresponding switches. By developing an advanced DC-DC boost converter with few switching parts and no need for coupled inductors, high-frequency operated transformers, or multi-windings, among other things, the aforementioned drawbacks were simple to overcome. These are a few of the major advantages of creating, refining, and deploying cutting-edge DC-DC boost converters for suggested PEV on-board chargers.

Figure 2 shows the model of proposed single-stage on-board charger circuit. The proposed higher-voltage gain converter belongs to the category of non-isolated type DC-DC converters; it offers an excellent boosting capacity and can produce sufficient power for charging the PEV battery. The proposed converter is most significant topology and requires only one MOSFET switch S_{a1}, it doesn't require any high-frequency transformers, multi-windings, and coupled inductors to attain high voltage gain. It consists of two inductors named as L_{a1}, L_{a2}, three diode named as D_{a1}, D_{a2} and D_{ao}, three capacitors named as C_{a1}, C_{a2} and C_{ao}, respectively. The model of proposed novel DC-DC boost converter is depicted in Figure 3.

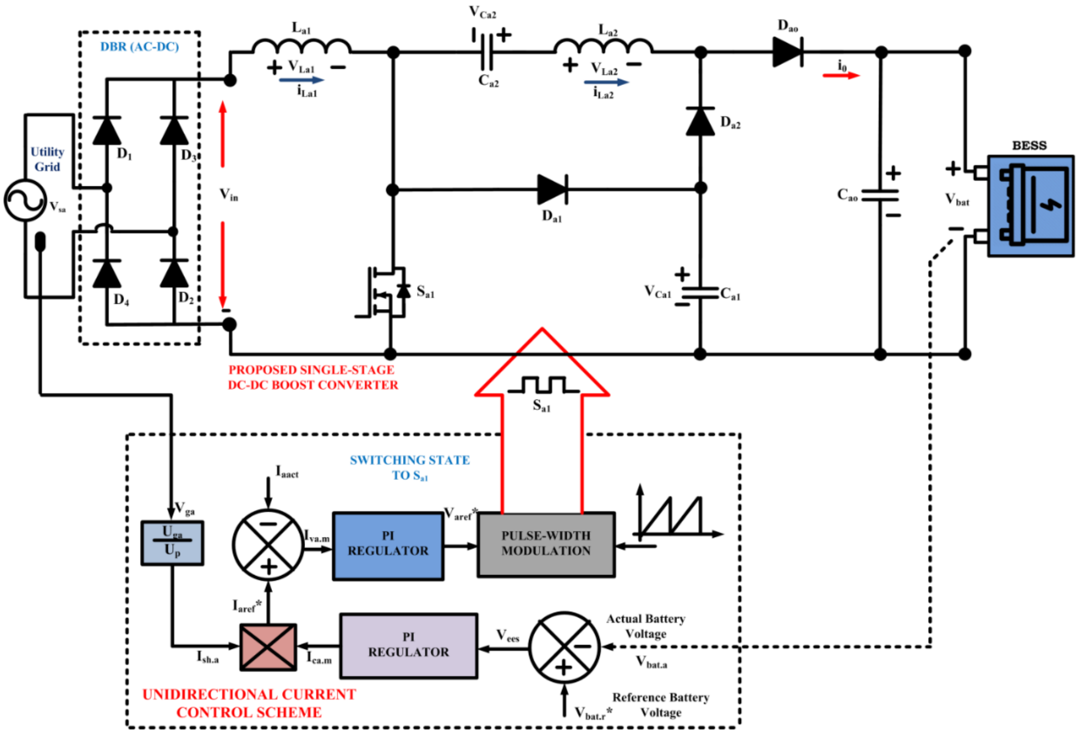

Figure 2. Model of proposed single-stage on-board PEV charging circuit

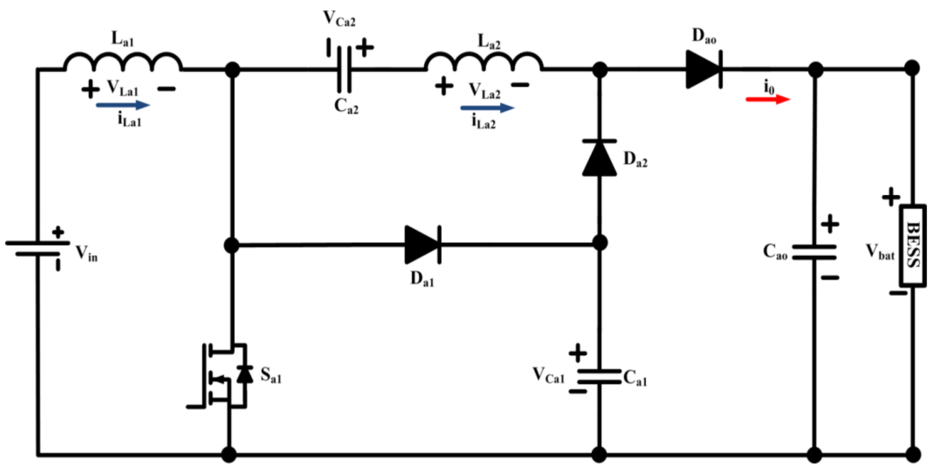

Figure 3. Model of proposed DC-DC boost converter

In summary, the innovative DC-DC boosting converter is driven by a front-end AC to DC DBR with a input voltage of Vin, and it gets boost voltages across the batteries Vbat ports by the simple transitioning action of its numerous components. The proposed converter's high voltage boosting capacity is obtained by the employment of front-end inductors that can operate in either continuous or discontinuous conduction modes (CCM/DCM). In actuality, the role of the converter in CCM is more widely recognized since load dependency on voltage gain, significant current ripples, and lower efficiency are the primary difficulties encountered during DCM operation. The operational modes of the proposed converter are described as follows:

i) Mode 1: When switch S_{a1} is turned-on by using the switching pulses furnished by PWM controller, then the inductor L_{a1} comes to linearly charging powered by input DC voltage V_{in} through switch S_{a1}, and the inductor current i_{La1} rapidly increases. Similarly, the capacitor C_{a2} and inductor L_{a2} comes to charging through switch S_{a1}, Diode D_{a2}, which is powered by capacitor C_{a2} and the inductor current i_{La2} linearly increases. At this instant, the capacitor C_{ao} delivers requisite battery voltage and discharged, due to output diode D_{ao} is in reverse bias. Then the operating mode-1 of DC-DC boost converter is depicted in Figure 4(a).

ii) Mode 2: In this mode, switch S_{a1} is to be turned-OFF by removing the pulse signal furnished by PWM controller, then the inductor L_{a1} goes to discharge and delivers the available energy to battery through capacitor C_{a2}, inductor L_{a2}, and output diode D_{ao}. Similarly, the capacitor C_{a2} and inductor L_{a2} comes to discharging mode and delivers energy to battery through output diode D_{ao}. At this instant, the capacitor C_{ao} comes to charging with requisite battery voltage, due to D_{ao} is in forward bias. The operating mode-2 of novel DC-DC boost converter is depicted in Figure 4(b). The operating modes and typical waveforms of proposed DC-DC on-board EV charger is shown in Figures 4 and 5 respectively. The volt-sec balanced method is generally used for steady-state differential analysis of proposed DC-DC boost converter. In mode 1, the MOSFET switch S_{a1} has been turned-on, the voltage across inductors and the capacitors are calculated as (1)-(4).

$$V_{La1} = V_{in} \tag{1}$$

$$V_{La2} = V_{Ca2} - V_{Ca1} \tag{2}$$

$$I_{La1}(t) = \frac{V_{in}}{L_{a1}} \tag{3}$$

$$I_{La2}(t) = \frac{V_{Ca2}-V_{Ca1}}{La2} \tag{4}$$

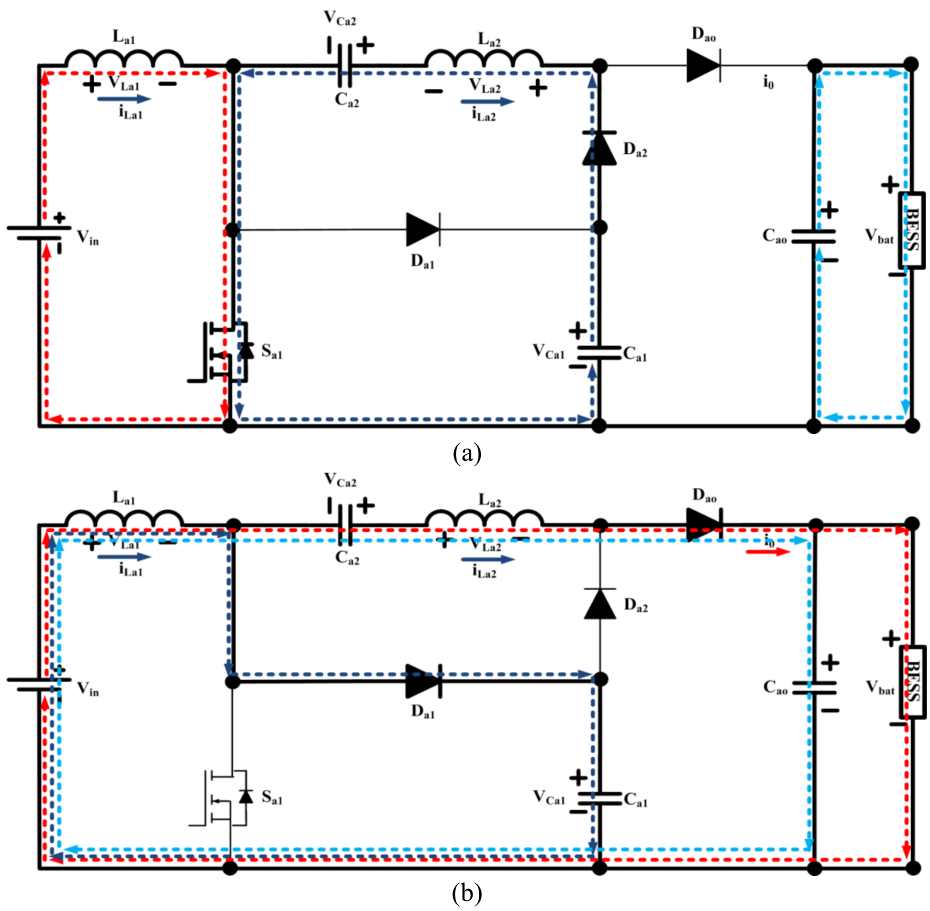

Figure 4. Operating modes of proposed DC-DC boost converter: (a) the operating mode-1 and (b) the operating mode-2

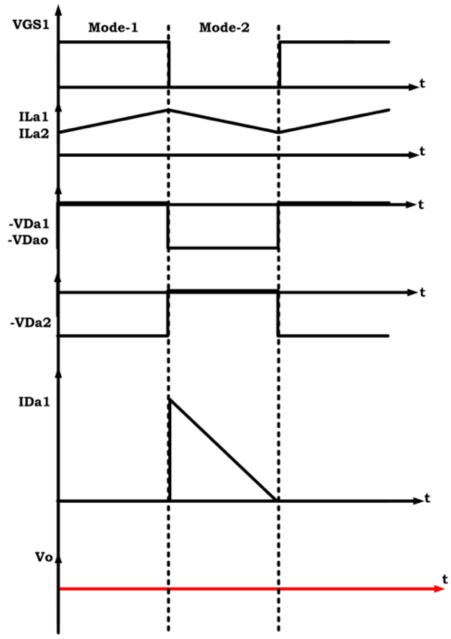

Figure 5. Typical waveforms of proposed novel DC-DC boost converter

In mode 2, the MOSFET switch S_{a1} has been turned-off and then the total induced voltage has been calculated as (5). Based on volt-sec rule, the voltage across inductors are calculated as (6) and (7).

$$V_{in} + V_{La1} + V_{La2} + V_{Ca2} - V_O = 0 \tag{5}$$

$$V_{La1} = \frac{2V_{in} - V_o}{2} \tag{6}$$

$$V_{La2} = \frac{V_{Ca1} - V_o}{2} \tag{7}$$

The final voltage-gain equation has been developed through mathematical analysis, stated as (8).

$$V_{in} \,.\, DT_s + \frac{2V_{in} - V_o}{2}(1-D)T_s + \frac{V_{Ca1} - V_o}{2}(1-D)T_s + \frac{V_{La2} + V_{Ca1}}{2}(1-D)T_s = 0 \tag{8}$$

The (8) can be written as (9).

$$V_o = \frac{2}{(1-D)} V_{in} \tag{9}$$

The voltage gain of proposed novel DC-DC boost converter is represented as (10).

$$VG_{CCM}(boost) = \frac{V_o}{V_{in}} = \frac{2}{(1-D)} \tag{10}$$

The unidirectional control technique provides the current reference signal to switch Sa1 in a unique single-stage on-board charger, allowing for continuous power transmission from the utility-grid to the battery packs of the PEV. First, detect the grid voltage V_{ga} at the nth levels, that is transmitted using maximum amplitude to produce the simplified vector phase current angle Ish.a has been stated in (11).

$$I_{sh.a} = \left| \frac{V_{ga}(n)}{V_{pk}} \right| \tag{11}$$

Similarly, the actual battery voltage ($V_{\text{bat.a}}$) is propagated with reference battery voltage ($V^*_{\text{bat.r}}$) and obtained some error signals (V_{ees}), which are reduced by adopting proportional-integral (PI) controller which produces the magnitude of reference current ($I_{ca.\text{m}}$) is shown in (13).

$$V_{ees}(n) = V_{\text{bat.r}}^{*}(n) - V_{\text{bat.a}}(n) \tag{12}$$

$$I_{ca.\text{m}}(n) = V_{ees}(n-1) + K_p\big(V_{ees}(n) - V_{ees}(n-1)\big) + K_i V_{ees}(n) \tag{13}$$

Then the shape of reference current ($I_{sh.a}$) and the magnitude of reference current ($I_{\text{ca.m}}$) is differentiated to get final current reference signal (I_{aref}^{*}) is expressed in (14).

$$I_{aref}^{*}(n) = I_{sh.a} \times I_{\text{ca.m}}(n) \tag{14}$$

Moreover, the reference signal with nth levels (I_{aref}^{*}) is propagated with actual inductor current (i_{Lact}) which furnishes error sequences ($i_{\text{v.am}}$) which are passed through PI controller for production of reference current is described in (15).

$$i_{\text{v.am}}(n) = V_{aref}^{*}(n) - i_{Lact}(n) \tag{15}$$

$$V_{aref}^{*}(n) = V_{aref}^{*}(n-1) + K_p\big(i_{\text{va.m}}(n) - i_{\text{va.m}}(n-1)\big) + K_i\, i_{\text{va.m}}(n) \tag{16}$$

Therefore, the final reference signal (V_{aref}^{*}) is compared with sawtooth carrier signals for production of suitable switching pulse to switch S_{a1} of DC-DC boost converter. Then, the current is well with in the in-phase proportional throughout of the grid voltage considered as unity power-factor with reduced harmonic current distortions and also regulation of battery voltage up to desired voltage level.

3. RESULTS AND DISCUSSION

3.1. Performance of novel DC-DC boost converter topology

This work proposes innovative on-board EV charging equipment for PEVs that incorporates a single-stage DC-DC boost converter. The effectiveness of the proposed unique single-stage on-board EV charger has been evaluated through MATLAB/Simulink application, and the simulation findings have been presented. The simulation data are presented in Table 1. Figure 6 shows the simulated results of novel DC-DC boost converter topology. In this case, the performance and switching operation of novel DC-DC boost converter topology has been verified under constant input DC source. This converter is powered by input DC voltage V_{in} of 110 V to drive the DC output voltage or battery voltage which is maintained as constant with a value of 500 V as shown in Figure 6(a). The novel DC-DC converter is functioned with a duty cycle of D-0.6 with a switching frequency of 20 kHz and it generates the nearly 5 times output gain voltage over the input DC voltage, have good boost compatibility over the classical converters. The switching pulses of respective switch of S_{a1} are depicted in Figure 6(b). The inductors L_{a1}, L_{a2} are charged in mode 1 and stores current linearly and carrying the continuous inductor currents with an average measured values of 50 A and 15 A as shown in Figure 6(c). The voltage across switch S_{a1} is measured with a value of 310 V and the switch current of 18A; these values are lower than the novel DC-DC output voltage and current values which illustrate the low dv/dt switch stress as shown in Figures 6(d) and 6(e). The voltage across diodes D_{a1}, D_{a2} and D_{ao} are measured with a value of -300 V, -198 V and -198 V, respectively and also current in the diodes D_{a1}, D_{a2} and D_{ao} are measured with a value of 15 A, 5 A and 8 A respectively. These are non-zero up to the switch Sa_1 has been turned-on as shown in Figures 6(f) and 6(g), so the proposed novel DC-DC boost converter is working in CCM mode.

Table 1. Simulation data

S.No	Simulation parameter	Values
1	Input DC voltage	V_{in}-110 V
2	Battery output voltage & power	V_{batt}-500 V, P_{bat}-13 kW
3	Inductors values	L_{a1}-570 µH, L_{a2}-270 µH
4	DC capacitors	C_{a1}-0.4 µF C_{a2}-1000 µF, C_{ao}-220 µF
5	Switching frequency	F_s-20 kHz

3.2. Performance of novel DC-DC boost converter topology under on-board PEV charging system

Figure 7 shows the simulated results of novel DC-DC boost converter topology under on-board PEV charging system. In this case, battery is connected at output side of novel DC-DC boost converter for charging process which is powered by single-phase AC grid with a grid voltage of 110 V, 50 Hz frequency and the grid current is measured with a value of 20 A as shown in Figures 7(a) and 7(b). The proposed single-stage novel

DC-DC boost converter acts as load-side conditioner for mitigation of harmonics in grid current and also improving the grid power-factor to kept grid specifications as sinusoidal, balanced nature.

Then the current is well with in the in-phase proportional throughout of the grid voltage considered as unity power-factor as shown in Figure 7(c). The THD spectrum of grid current is measured with a value of 1.44% which is well complying with IEEE-514/2014 standards as shown in Figure 7(d). Finally, the novel DC-DC boost converter acts as single-stage on-board EV charger and charging the battery with a rated voltage of 500 V and the battery current of 22 A with respect to state-of-charge of battery is measured as 95% as shown in Figure 7(e). This state-of charge comes to nearly 100% to attain fully charging of PEV battery which supports stable power-flow to drive the PEV battery. The graphical view and comparison of THD and grid side power-factor in conventional 2-stage charging system and novel single-stage proposed charging system is depicted in Table 2.

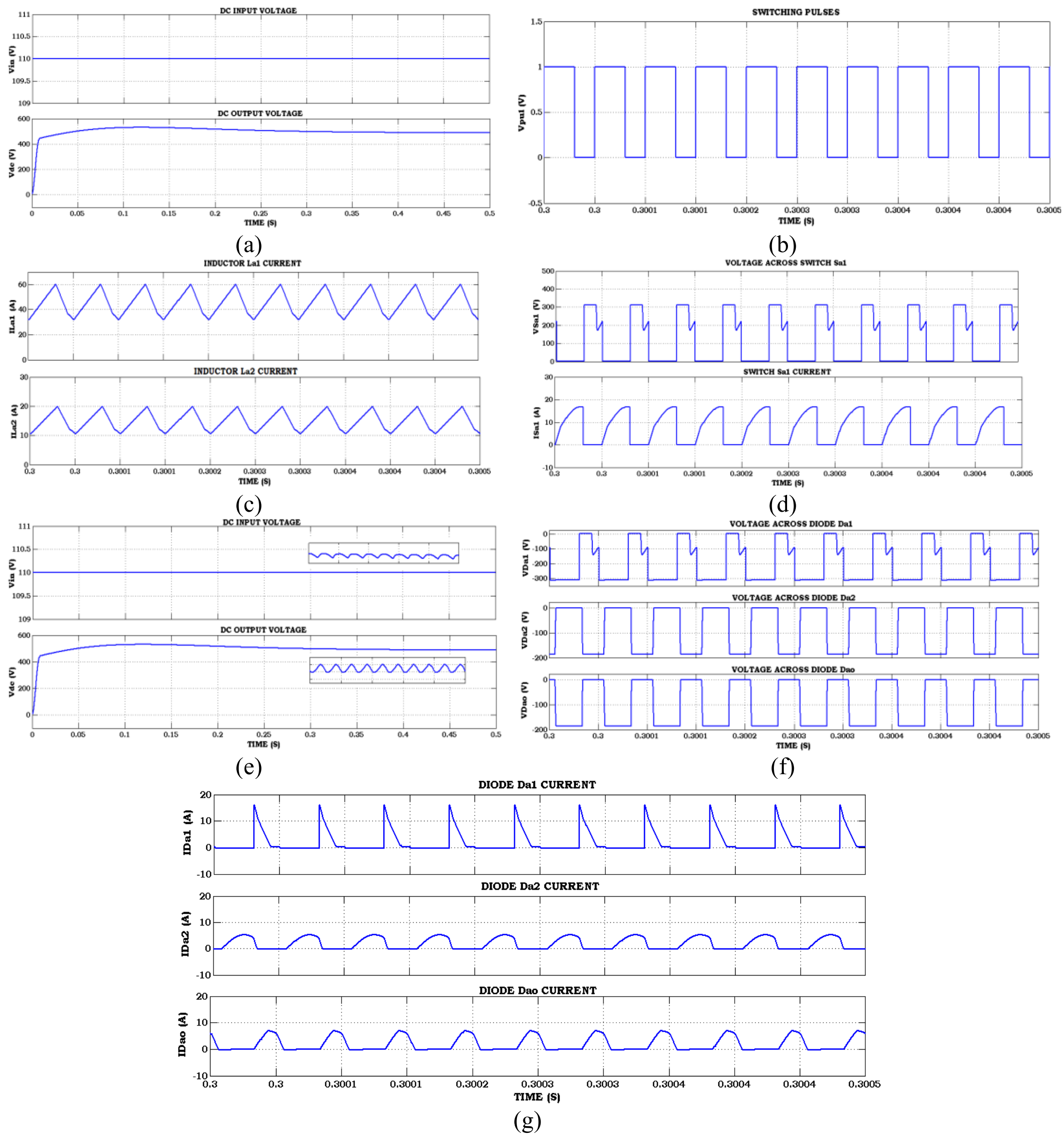

Figure 6. Simulation results of novel DC-DC boost converter topology:
(a) DC input and output voltages; (b) switching pulses of switch S_{a1}; (c) inductor currents L_{a1} and L_{a2}; (d) voltage and current of switch S_{a1}; (e) voltage across capacitors C_{a1} and C_{a2}; (f) voltage across diodes D_{a1}, D_{a2}, and D_{a3}; and (g) diode D_{a1}, D_{a2}, and D_{a3} currents

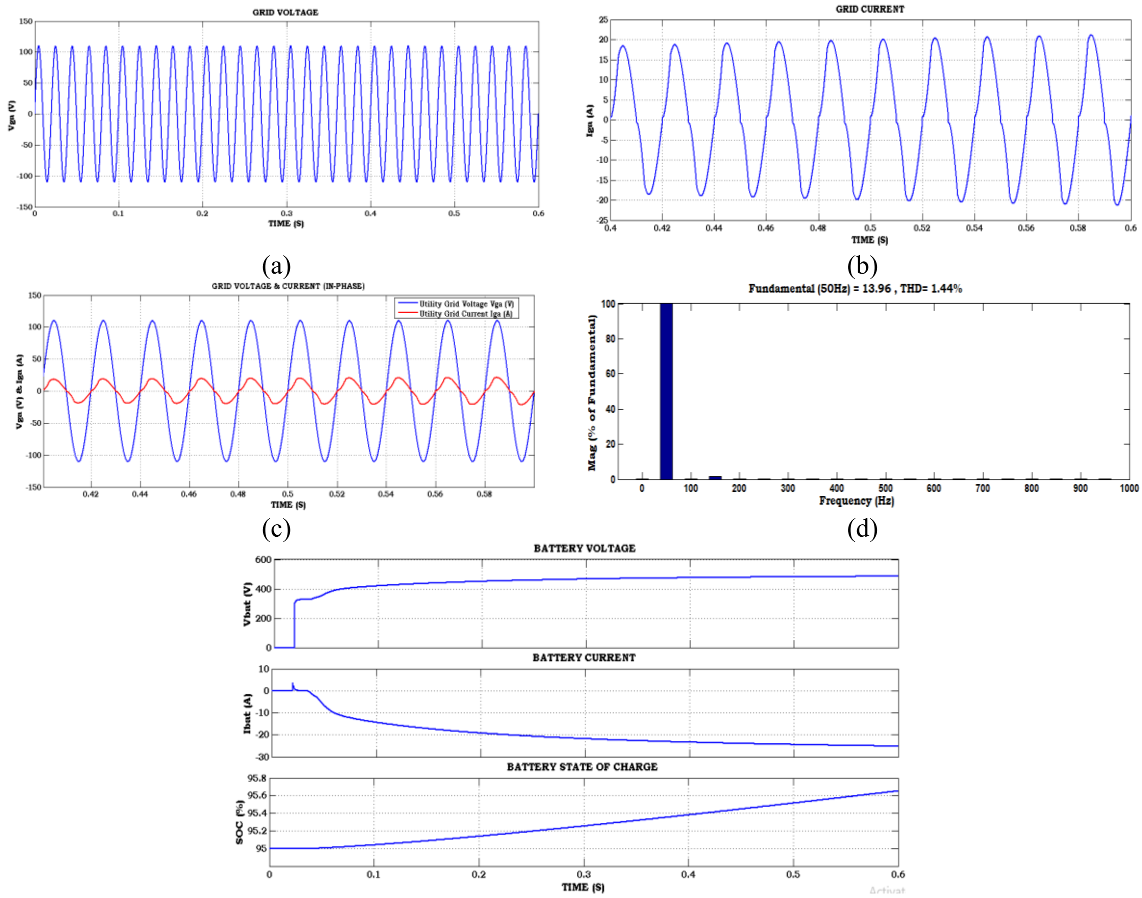

Figure 7. Simulation results of novel DC-DC boost converter topology under on-board PEV charging system: (a) grid voltage, (b) grid current, (c) grid voltage and current (in-phase), (d) THD spectrum of grid current, and (e) battery voltage, current, and state of charge

Table 2. Comparison of THD and power factor in conventional two-stage charging system and proposed single-stage charging system

Charging system configuration	THD (%)	Power-factor
Design of conventional two-stage charging system [18]	2.98%	0.958
Proposed single-stage charging system	1.44%	0.999

4. CONCLUSION

The present work assesses the performance and operation of a novel DC-DC converter that operates at a duty cycle of D-0.6 and a switching frequency of 20 kHz. It produces an output gain voltage that is almost five times greater than the input DC voltage and has good boost compatibility compared to classical boost converters. A single-stage on-board PEV charging system has been used to validate the performance and operation of a unique DC-DC boost converter for PEV battery charging. To charge the PEV battery, the suggested DC-DC converter has a high-power density and boosting capabilities. In order to achieve high voltage gain, the proposed converter requires just one MOSFET switch and no high-frequency transformers, linked inductors, or multi-windings. It is the most important topology. The main benefits of the suggested single-stage charging scheme is its small size, low cost, and compact charging unit. It also smoothly controls battery state-of-charge by utilizing fewer switching devices and manages utility-grid factors like power factor correction and harmonic elimination.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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S. Sasikumar		✓		✓		✓	✓	✓		✓	✓	✓	✓	
B. Suresh Babu	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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