A Comprehensive Review of Single-Stage On-Board EV Charging Methodology for PEV System

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Abstract:

The need for a good fuel utilization and further preventing of greenhouse gas emissions is shifting automotive industry to electrified vehicles and, thus, electric vehicle (EV) has come into existence to stabilize the transport sector to a greener side. The on-board charging units are most favored arrangement for Plug-in EVs due to their adaptable nature for house-hold charging which reduces the battery heating. With the large number of EV charging units will become an additional load of single-phase utility-grid and these on-board charging units consists of power-electronic converters to obtain required power to charge the battery. An advanced power-electronic converter plays a significant role in on-board charging unit of plug-in electric vehicle through DC fast charging methodology; it can handle high voltage ranges from milli-volts to mega-volts and milli-watts to mega-watts power. The conventional two-stage converters are employed for charging the battery of electric vehicle which improves the power-factor of utility-grid and control the state-of-charge of battery system. The major problem identified in conventional two-stage converters requires high switching devices, more complex circuitry, high switching losses and low efficiency due to number of operating stages. To overcome, the above-mentioned issues, a single stage conversion methodology has been proposed as the major objective of the work.

Keywords: DC-DC Converters, Electric Vehicle, On-Board Charging System, Power-Factor Correction, Single-Stage System.

I. INTRODUCTION

Electric Vehicle (EV) is comparatively new concept in the transportation sector. Due to several benefits i.e. less environmental pollution, cheaper mode of transportation, EV becomes very much attractive now-a-days. The electrification of the transportation sector is expected to bring several socio-economic and environmental benefits such as reducing fuel prices, ending the reliance on imported oil, and minimizing greenhouse gases (GHGs).

There are several types of EV configurations such as, Plug-in-hybrid electric vehicle (PHEV), Hybrid electric vehicle (HEV) and Battery electric vehicle (BEV), etc. All of the vehicles are using electric motor to run these vehicles with the energy from batteries [1]-[5].

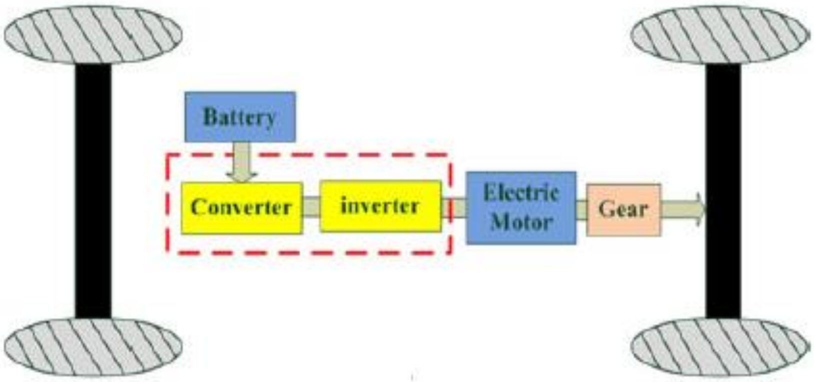


Fig.1 Electric vehicle

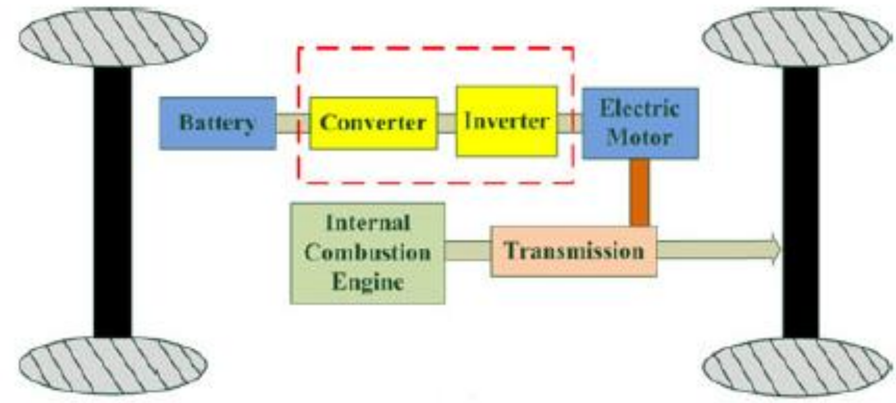


Fig.2 Hybrid Electric Vehicle

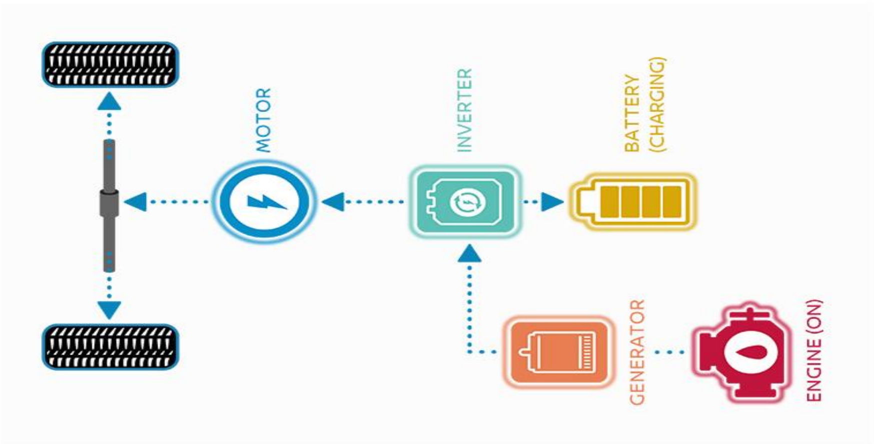


Fig.3 Battery Operated Electric Vehicle

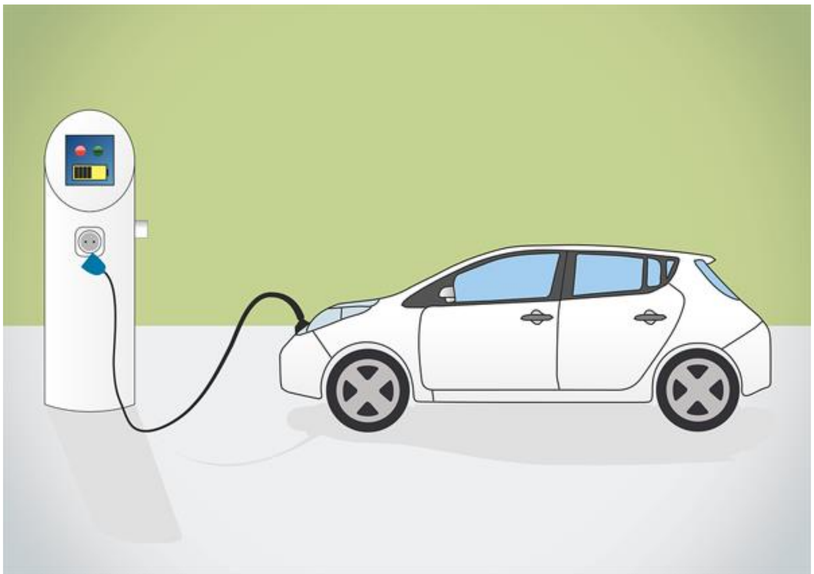


Fig.4 Plug-In Electric Vehicle

The battery energy is used to drive the PEV system through charging stations which are powered by utility-grid and becomes a cause of system loss in power sector due to proliferation of power-quality standards. The charging stations require power-conditioning converters for charging the batteries which produces the current harmonics and affect the power-factor of utility-grid system. This paradigm shift in transportation which currently involves the integration of both plug-in hybrid electric (PHEV) and plug-in battery electric vehicles (PBEV) into existing electric distribution system (EDS) may have negative impacts on power quality (PQ) [6]-[8]. The evolution of high-storage battery units, erratic charging or discharging operations will initiates the new challenges to stable and safe operation of single-phase utility-grids. The on-board charging units are most favored arrangement for PEVs due to their adaptable nature for house-hold charging which reduces the battery heating [9]-[12].

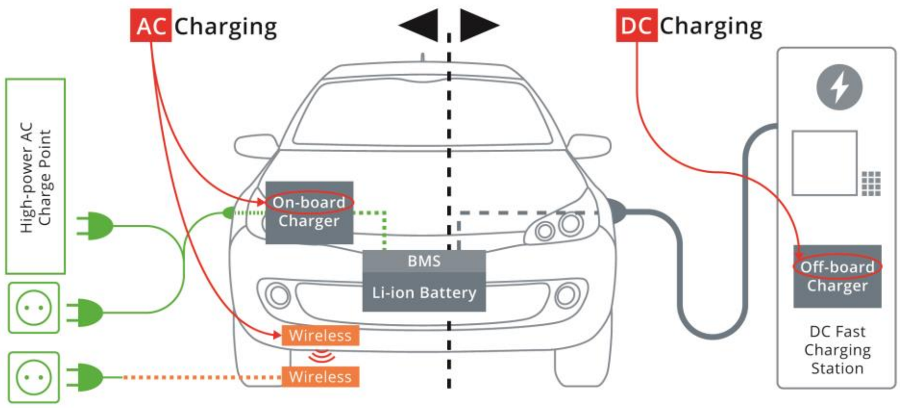


Fig.5 Comparison of On-Board and Off-Board Charging System

With the large number of EV charging units will become an additional load of single-phase utility-grid and these on-board charging units. It consists of high-range power-electronic converters to obtain required power to charge the battery through AC-DC rectifier.

But these front-end AC/DC rectifiers inject the harmonic current distortions into utility-grid which proliferate the entire utility-grid system. Moreover, it reduces the power-factor influences the power-quality of utility-grid and degrade the performance of other loads connected at utility-grid. Therefore, power-quality enhancement devices are used to mitigate the harmonic currents, power-factor correction and enhance the power-quality features. But these are very complex design and huge cost for installing and running of power-quality compensation devices [13]-[15].

To alleviate this issue, load-side compensation technique like PFC on-board charger configurations are available, such as two-stage on-board chargers and single-stage on-board chargers. The two-stage battery charger consists of front-end AC/DC rectifier is connected to utility-grid, one Power-Factor Correction (PFC) converter and high voltage gain DC-DC converter is connected to battery units to charge the EV batteries. In general, these two-stages PFC conversion charger have complex design, consists more switching elements which increases size, cost of entire charger unit. To overcome the above-specified issues, a novel single-stage on-board charger has been proposed without using any high frequency transformers and coupled inductors [16]-[18].

The single-stage DC-DC converters with high step-up voltage competency are extensively preferred in various conversion applications which ranges from milli-volts to thousand-volts and milli-watts to mega-watts power levels. Various high-step-up non-isolated DC-DC converters are basic boost converters, switched-capacitor type, switched-inductor type, SEPIC converter, etc. But the conventional topologies suffer high dv/dt stress, di/dt stress, low efficiency, moderate voltage gain, etc. To alleviate these demerits, a novel high step-up DC-DC boost converter has been employed in single-stage conversion for reduction of current harmonics, obtaining improved power-factor with good output voltage regulation. In this work, a novel single-stage switched-inductor based Boost DC-DC Converter has been proposed for EV-battery charging system with enhanced power-factor, elimination of harmonic current distortions and attaining improved power-quality in utility-grid system.

II. DETAILS OF RESEARCH WORK

The advances of power-electronic technology easing the conversion, conditioning and controlling the electrical energy in one form to another with definite characteristics and also used to drive any type of load. At recent past, it is a very precious resource for used in several domestic and industrial applications, allowed for controlling the motor speed in washing machines, light intensity, temperature rate in oven and so on. In this regard, a DC-DC converter is a power-electronic device that converts unregulated DC input voltage into regulated DC output voltage and provides distinct output voltage-level over the input voltage. It plays a significant role in both domestic and industrial operations like laptops, desktop computers, uninterruptible power-supplies and DC motor speed control, space-crafts, telecommunications, belt conveyors, petro-chemical industries, etc.

In general, the basic type DC-DC converters are categorized as linear type DC-DC converter and switched type DC-DC converters. The linear type DC-DC converters are very common, cheap and easy to use, capable for low-power devices and produces DC output voltage that is very lower than DC input voltage.

Coming to non-isolated type DC-DC converter, there is no dielectric isolation between the input and output terminals. It has electric contact between the terminals as regular converter and highly recommended for many applications like electric-vehicles, EV on-board charging systems, air-craft, and traction, so on. The major advantages of non-isolated type DC-DC converters are low cost, size, weight, reduced losses and high efficiency. Some of the prominent non-isolated type DC-DC converters are boost, buck, buck-boost, Cuk, SEPIC and etc. In this way, the DC-DC boost converter is the best suited for proposed battery charging system, it converts low-level DC voltage into high-level DC voltage by using appropriate switching action to maintain output DC voltage to a predefined level. In this chapter, various classical DC-DC boost converters are presented and identify key disadvantages in classical DC-DC boost converters to develop the reliable on-board EV charging system. There are several classical boost DC-DC converters are developed to avail the significant requirements to develop high-voltage gain DC-DC converter for proposed on-board EV charging system.

2.1 REGULAR DC-DC BOOST CONVERTER

The regular DC-DC boost converter acts as intermediate device between input and output terminals for real-time problems, it converts low DC voltage into high DC voltage with constant output voltage at load terminals. It is the class of non-isolated type DC-DC converter comprises of Metal-Oxide Semiconductor Field Effect Transistor (MOSFET) switch, diode, combination of passive devices like inductor and capacitor to minimize the ripple content in output voltage. The input power for regular boost converter come from any one of DC source like solar-PV arrays, DC batteries, rectified AC supply, etc.

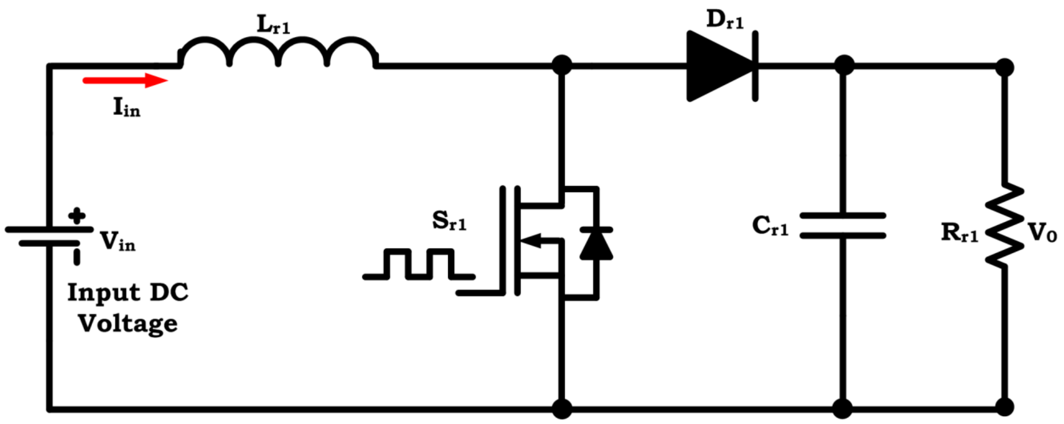


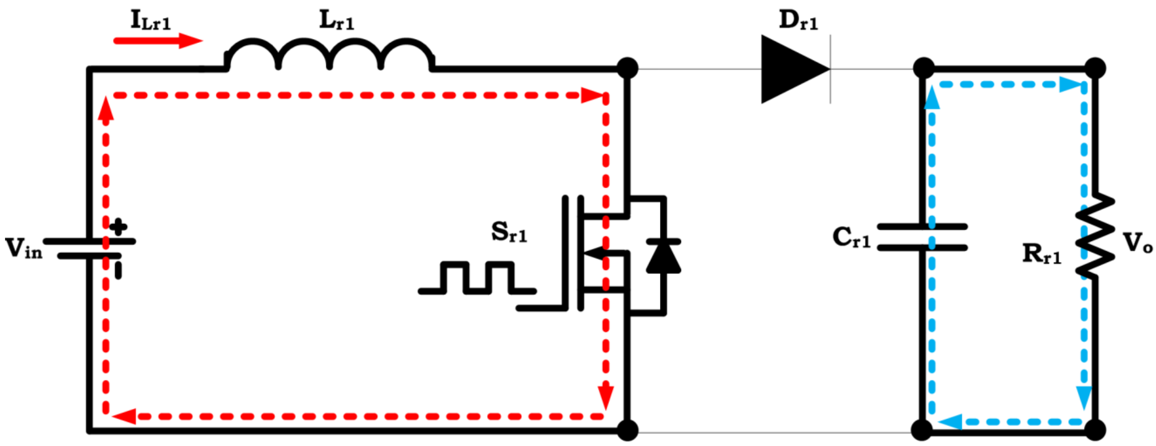
Fig.6 Regular DC-DC Boost Converter

The operating principle of regular DC-DC boost converter is go

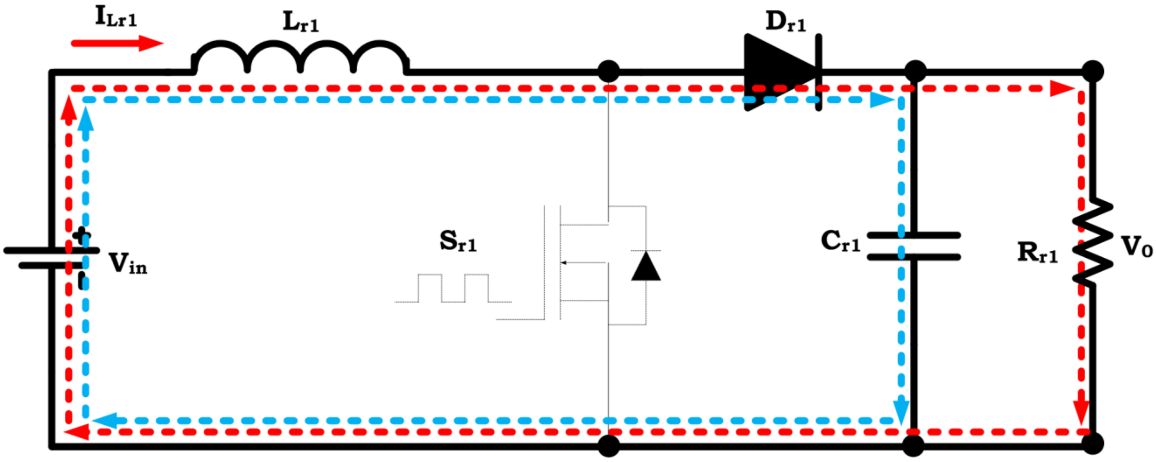
od tendency of boost inductor to confront the changes in the current. In regular boost converter, the voltage at output terminals is always more than the input terminal voltage, the schematic model and operating modes of regular DC-DC boost converter is depicted in Fig.6 and Fig.7.

Mode-I: In this mode, the switch S_{r1} is conducted by providing switching pulse through PWM generator, then the current moves towards the boost inductor L_{r1} in a clock-wise direction by applying KCL. The input current I_{in} energizes the boost inductor and produce magnetic field and store required energy in boost inductor.

During this mode, the switch S_{r1} behaves like short-circuit path in parallel with output diode D_{r1} and resistive load R_{r1}, so current doesn't flows to load because diode D_{r1} is in reverse-bias. During this condition, the capacitor C_{r1} delivers energy to load and provides continuous energy flow to load until switch S_{r1} comes to non-conduction mode. The operating mode-I of regular DC-DC boost converter is depicted in Fig.7 (a).



(a) Mode-I



(b) Mode-II

Fig.7 Operating Modes of Regular DC-DC Boost Converter

Mode-II: In this mode, the switch S_{r1} is in non-conduction state by discarding the switching pulse, then the current doesn't move towards the boost inductor L_{r1} because of sudden raise in the impedance of the converter which demands either increase in voltage or decrease in current based on Ohm's law. The input current I_{in} de-energizes the boost inductor L_{r1} and delivers stored energy to resistive load R_{r1} through output diode D_{r1} because diode comes to forward-bias. During this condition, the capacitor C_{r1} maintains load voltage as constant and continuously charging the capacitor until switch S_{r1} comes to conduction mode. The operating mode-II of regular DC-DC boost converter is depicted in Fig.7 (b). The final voltage gain of regular DC-DC boost converter can be rewritten as,

$$VG_{CCM}(boost) = \frac{V_0}{V_{in}} = \frac{1}{1-D} \quad (1)$$

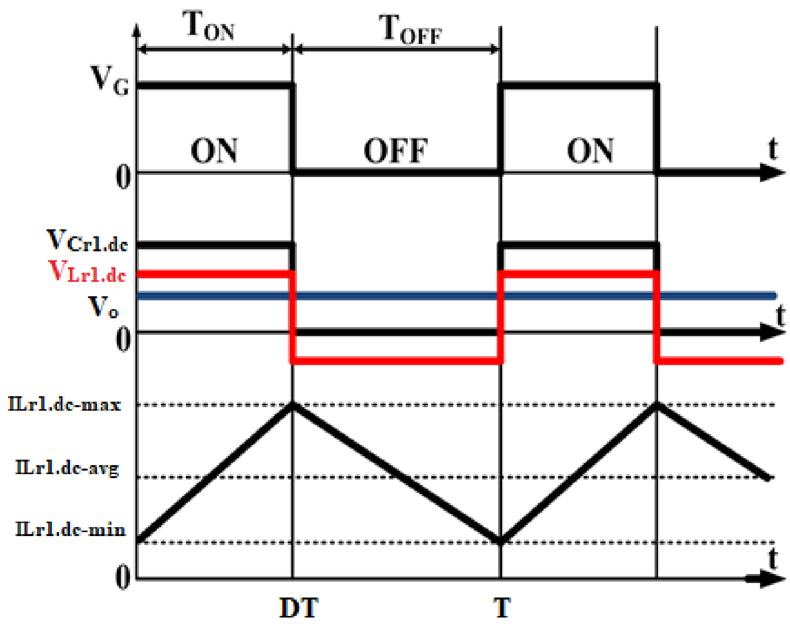


Fig.8 Typical Operating Waveforms of Regular DC-DC Boost Converter

The steady state representation of regular DC-DC boost converter in CCM mode is evaluated and the voltage gain is expressed in Eqn. (1). Here, V_{in} is the DC input voltage, V_0 is DC output voltage at load terminals, D is the duty-cycle of the switch S_{r1} and it ranges from 0 to 1. Usually, D is considered as 0.5 for attaining high-voltage gain and distributing the same switching stress during the operating states. The typical operating wave-forms of regular DC-DC boost converter in steady-state condition are shown in Fig.8.

2.2 ISOLATED TYPE REGULAR DC-DC BOOST CONVERTER

The isolated type regular DC-DC boost converter acts as intermediate type converter, it converts low DC voltage into high DC voltage with constant output voltage at load terminals. It is the class of isolated type DC-DC converter comprises of coupled inductors with equal winding turns in both primary and secondary windings. The isolated regular DC-DC boost converter has significant advantages such as, high voltage gain and very-low average switch current, etc. It consists of three MOSFET switches named as S_{r1}, S_{r2} are controlled by PWM pulses and S_{r3} is acts as synchronous rectifier at load terminals. The schematic model of isolated type regular DC-DC boost converter is depicted in Fig.9. The operating modes are clearly presented as below,

Mode-I (t_0-t_1): During this mode, the switches of S_{r1} and S_{r2} are conducted by providing switching pulses through PWM generator and S_{r3} is in non-conduction state. The input current flows to primary and secondary windings inductors L_{rp} and L_{rs}, these two primary and secondary windings are in parallel connection. The input current I_{in} energizes the both windings of coupled inductors and produce magnetic field and store some energy in windings. During this mode, the switches S_{r1}, S_{r2} behaves like short-circuit path because of parallel, so current doesn't flows to load because switch S_{r3} is in non-conduction state. During this condition, the capacitor C_{r1} delivers energy to resistive load R_{r1} and provides continuous energy flow to load until switches S_{r1}, S_{r2} comes to non-conduction mode. The operating mode-I of isolated type regular DC-DC boost converter is depicted in Fig.10 (a).

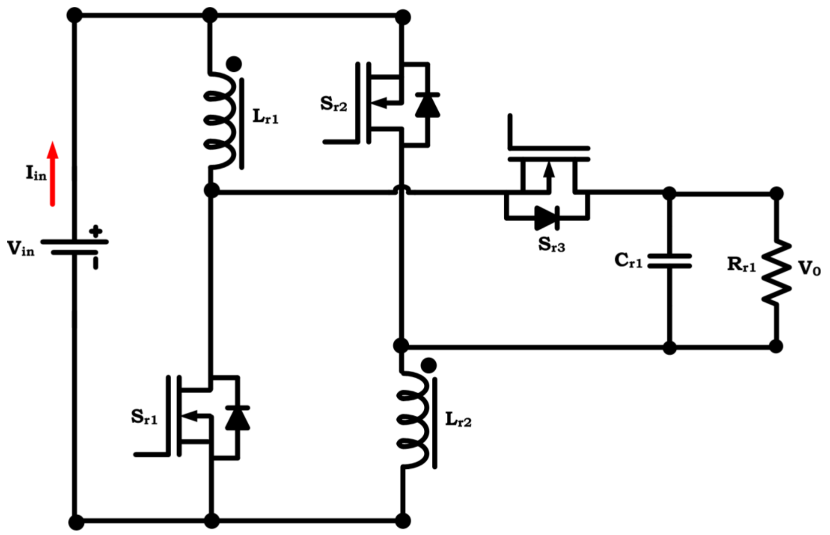
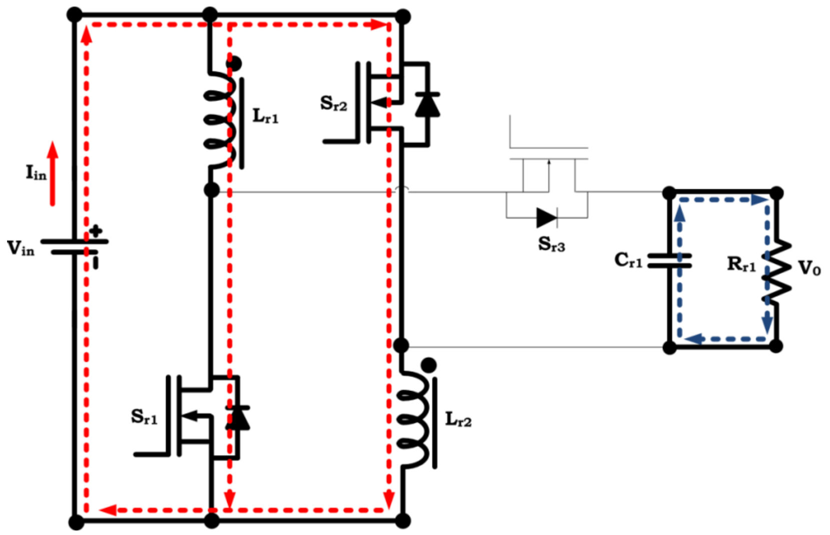
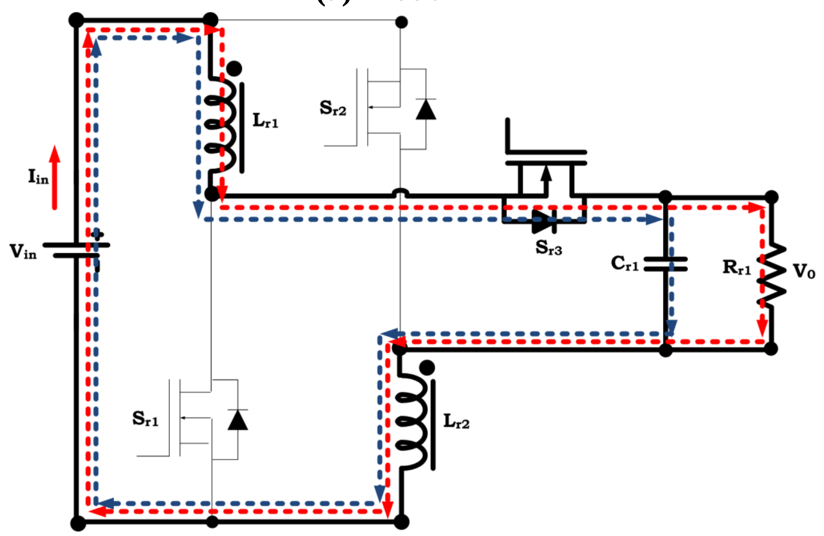


Fig.9 Schematic Model of Isolated Type Regular DC-DC Boost Converter



(a) Mode-I



(b) Mode-II

Fig.10 Operating Modes of Isolated Type Regular DC-DC Boost Converter

Mode-II (t_1-t_2): During this mode, the switches of S_{r1} and S_{r2} are into non-conduction by discarding switching pulses and S_{r3} comes to conduction state by providing switching pulses. The input current doesn't flows to primary and secondary windings inductors L_{rp} and L_{rs} because of open-circuit. In this state these two coupled windings are in series connection and deliver energy to load capacitor C_{r1} and provide continuous energy to resistive load R_{r1} and maintain load voltage V_o as constant until switches S_{r1}, S_{r2} comes to conduction state. The operating mode-II of isolated type regular DC-DC boost converter is depicted in Fig.10 (b). The typical operating waveforms of isolated type regular DC-DC boost converter are depicted in Fig.11.

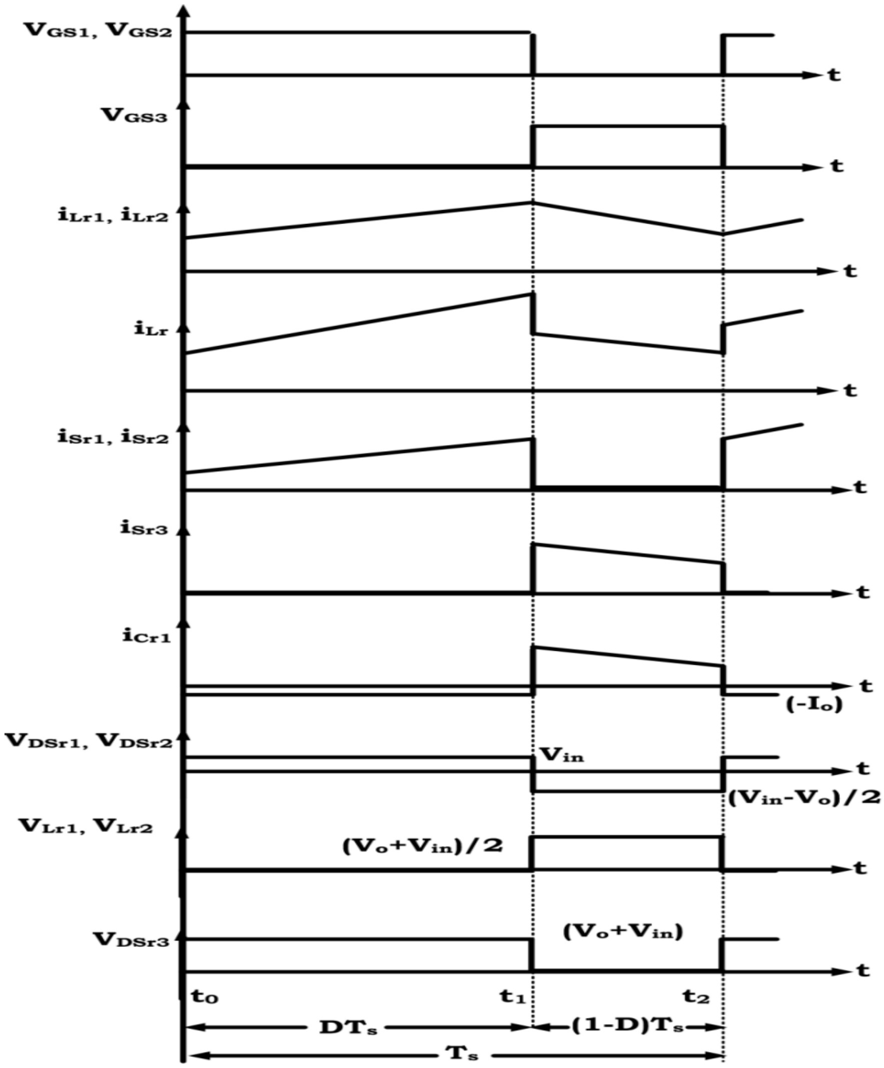


Fig.11 Typical Operating Waveforms of Isolated Type Regular DC-DC Boost Converter

The equivalent voltage gain factor is defined as,

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

2.3 SEPIC DC-DC CONVERTER

The Single Ended Primary Inductor Converter (SEPIC) converter acts as DC-DC boost, buck, buck-boost converter which maintains constant output voltage at load terminals. It is the class of non-isolated type DC-DC converter, transforms low DC voltage into high

DC voltage or vice versa. It consists of MOSFET switch S_{r1}, two inductors L_{r1}, L_{r2}, two capacitors C_{r1}, C_{r2}, one diode D_0 and resistive load R_{r1}, respectively. It allows the output load voltage to be greater than, less than and equal to that of input voltage which is controlled by duty-ratio D. It functions like a classical buck-boost converter and has non-inverted output voltage and drops zero voltage at output terminal. The schematic model of basic SEPIC converter is depicted in Fig.12. The operating modes of SEPIC converter is described as below,

Mode-I (t_0-t_1): During this mode, the MOSFET switch S_{r1} is conducted by giving the switching pulse through PWM generator. The input current flows through inductor L_{r1} and being stores energy and the other inductor L_{r2} is being charged from the capacitor C_{r1}. During this mode, the input current flows continuously through inductor and stores the energy, the switch S_{r1} behaves like short-circuit path. So current doesn't flows to resistive load R_{r1} because the diode D_o is in reverse-bias. Then, the capacitor C_{r2} delivers energy to load and provides continuous energy flow to load until switch S_{r1} comes to non-conduction mode. The operating mode-I of SEPIC converter is depicted in Fig.13 (a).

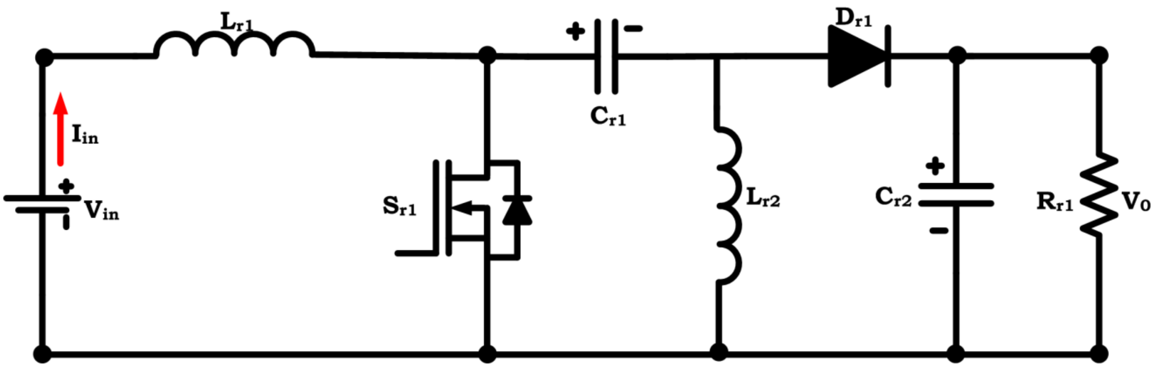
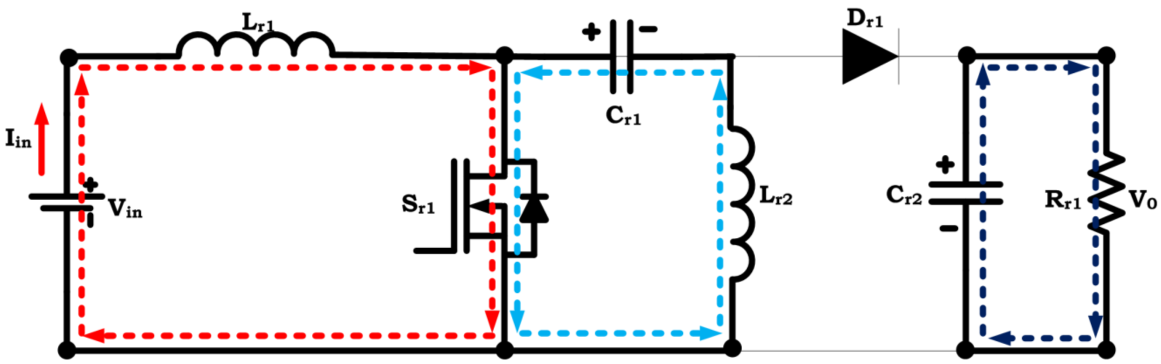
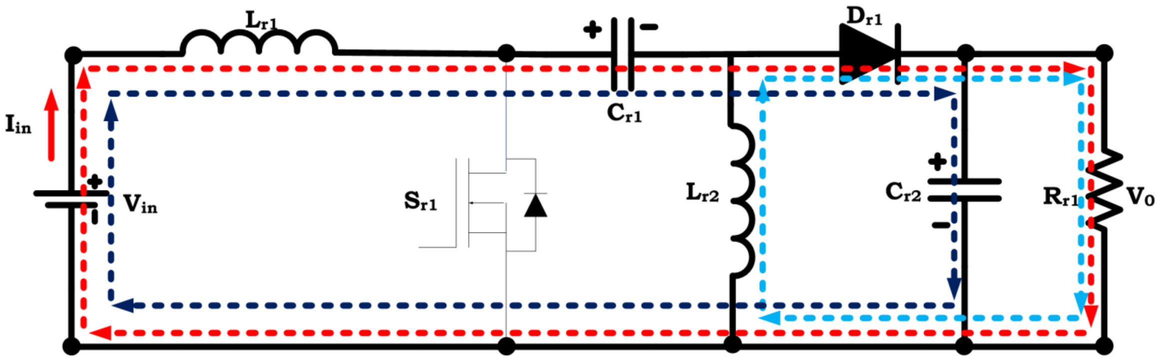


Fig.12 Schematic Model of Basic SEPIC Converter

Mode-II (t_1-t_2): During this mode, the MOSFET switch S_{r1} is non-conducted by discarding the switching pulse. The input current flows through inductor L_{r1} and being discharge energy to charge the capacitor C_{r1} and the other inductor L_{r2} is being discharged to charge the capacitor C_{r2}. During this mode, the inductor current flows continuously through capacitors and delivers energy to load because the diode D_o is in forward-bias. Then, both the capacitor C_{r1} and C_{r2} stores energy through load and provides continuous energy flow until switch S_{r1} comes to conduction mode. The operating mode-II of SEPIC converter is depicted in Fig.13 (b).



(a) Mode-I



(b) Mode-II

Fig.13 Operating Modes of Basic SEPIC Converter

The voltage-gain equation is expressed as,

$$VG_{CCM}(boost) = \frac{V_o}{V_{in}} = \frac{D}{1-D} \quad (3)$$

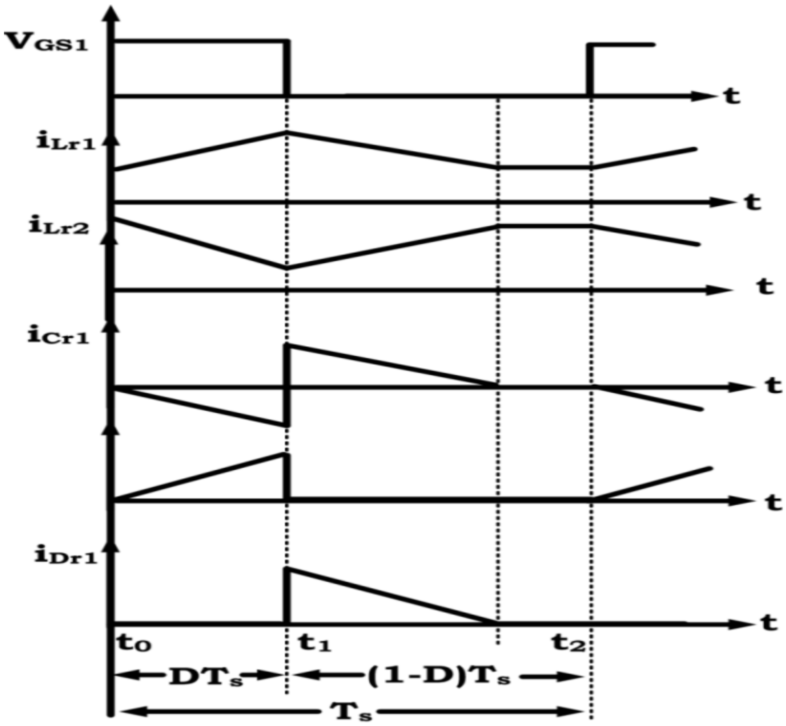


Fig.14 Typical Operating Waveforms of Basic SEPIC Converter

2.4 SWITCHED INDUCTOR TYPE SEPIC DC-DC BOOST CONVERTER

The switched inductor type SEPIC converter acts as DC-DC boost, converter which maintains constant output voltage at load terminals. It is the class of non-isolated type DC-DC converter, transforms low DC voltage into high DC voltage. It consists of MOSFET switch S_{r1}, one switching inductor module, one main inductor L_{r3}, two capacitors C_{r1}, C_{r2}, one diode D_0 and resistive load R_{r1}, respectively. The schematic model of switched inductor type SEPIC converter is depicted in Fig.15.

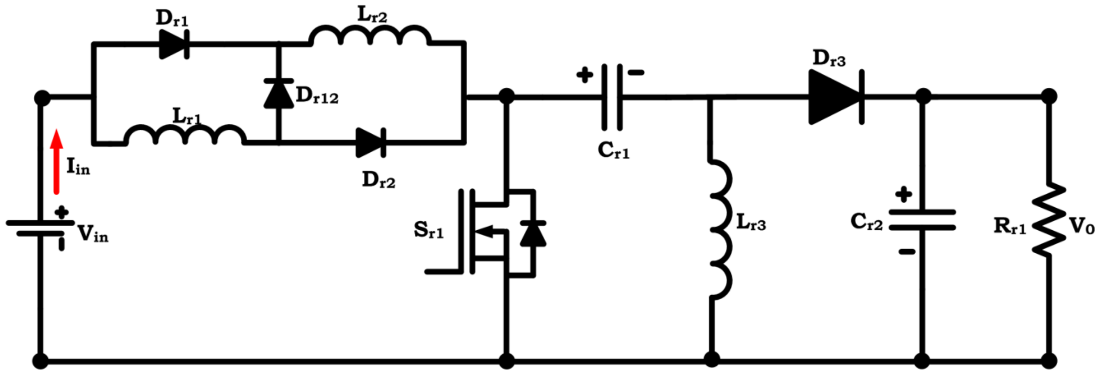
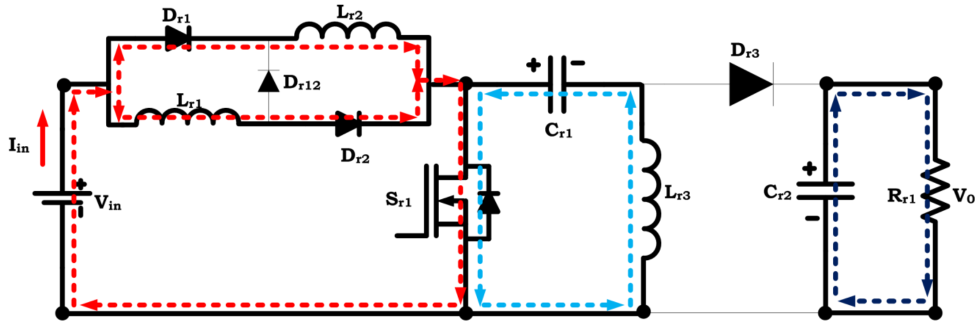


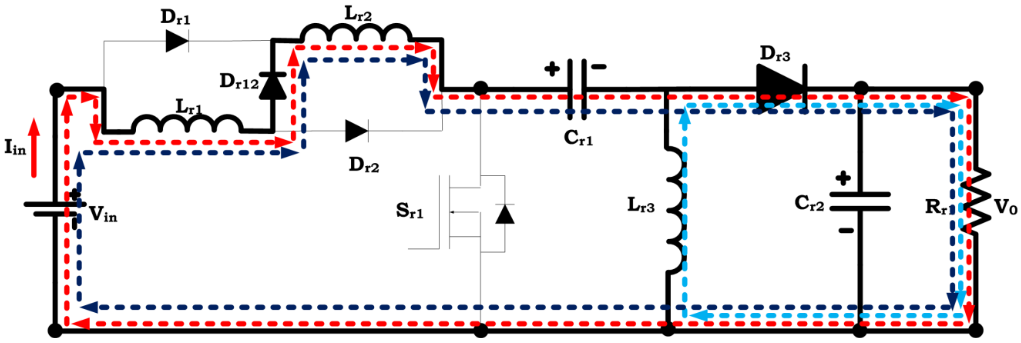
Fig.15 Schematic Model of Switched Inductor Type SEPIC Converter

For achieving high voltage gain, the switched inductor cell has been included and it consists of two inductors L_{r1}, L_{r2} and three diodes D_{r1}, D_{r2} and D_{r12}, respectively. It allows the output load voltage to be greater than to that of input voltage which is controlled by duty-ratio D. It functions like a classical SEPIC converter and has non-inverted output voltage and drops zero voltage at output terminal. The operating modes of switched inductor type SEPIC converter is described as below,

Mode-I: During this mode, the MOSFET switch S_{r1} is conducted by giving the switching pulse through PWM generator. The input current flows through inductor L_{r1} and L_{r2} being stores energy parallel through diodes D_{r1}, D_{r2} and the other inductor L_{r3} is being charged from the capacitor C_{r1}. During this mode, the input current flows continuously through inductors and stores the energy, the switch S_{r1} behaves like short-circuit path. So current doesn't flows to resistive load R_{r1} because the diode D_o is in reverse-bias. Then, the capacitor C_{r2} delivers energy to load and provides continuous energy flow to load until switch S_{r1} comes to non-conduction mode. The operating mode-I of switched inductor type hybrid SEPIC converter is depicted in Fig.16 (a).



(a) Mode-I



(b) Mode-II

Fig.16 Operating Mode-II of Switched Inductor Type Hybrid SEPIC Converter

Mode-II: During this mode, the MOSFET switch S_{r1} is non-conducted by discarding the switching pulse. The input current flows through inductor L_{r1} and L_{r2} being discharge energy series through diodes D_{r12} and the other inductor L_{r3} is being delivered energy to charge the capacitor C_{r1}. During this mode, the input current flows continuously through inductors and discharges the energy because the diode D_o is in forward-bias. Then, both the capacitor C_{r1} and C_{r2} stores energy through load and provides continuous energy flow until switch S_{r1} comes to conduction mode. The operating mode-II of switched inductor type hybrid SEPIC converter is depicted in Fig.16 (b).

The voltage-gain equation is expressed as,

$$VG_{CCM}(boost) = \frac{V_o}{V_{in}} = \frac{D\,(1+D)}{D_1} \quad (4)$$

Table.1. Comaprison of Various DC-DC Boost Converters

Converter Type	Formula of Voltage Gain	Voltage Gain (%)	No of Switches	No of Diodes	No of Inductors	No of Capacitors
Regular DC-DC Boost Converter	$\frac{V_0}{V_{in}} = \frac{1}{1-D}$	2	1	1	1	1
Isolated type Regular DC-DC Boost Converter	$\frac{V_o}{V_{in}} = \frac{1+D}{1-D}$	3	3	–	2	1
Basic SEPIC converter	$\frac{V_o}{V_{in}} = \frac{D}{1-D}$	3	1	1	2	2
Switched Inductor Type SEPIC Converter	$\frac{V_o}{V_{in}} = \frac{D\,(1+}{D_1}$	5	1	4	2	2

The output voltage gain and number of switching components of various classical DC-DC boost converters are illustrated in Table.1.

III. CONCLUSION

In this work, the switching operation and analysis of various classical DC-DC boost converters for getting high-voltage gain with the requirement of moderate switching elements. It gives the comprehensive summary of various voltage-boosting converters by means of major characteristics such as voltage-gain, cost, reliability, complexity, more switching elements, etc. The selection of specific converter relies on above-specified terms, each converter have its own distinct features and suitable applications.

The significant demerits of classical DC-DC boost converters such as, high dv/dt and di/dt stress, more switching loss, low efficiency, need have coupled inductors, etc. To overcome the above mentioned demerits a novel high voltage gain DC-DC boost converter has been proposed in future with the help of low switching elements and non-requirement of any coupled inductors and high-frequency transformers. Moreover, the proposed single-stage high-voltage gain DC-DC boost converter produces the high- step-up gain output voltage at battery terminals without using any two-stage conversion stages which helps to maintain the simple onboard charger, low cost, high power density, low switch stress, high efficiency and reliable performance.

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