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Original Article

Design and Simulation of SEPIC Converter for EV Battery Charger

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Abstract *- This paper presents the design and simulation of a Single-Ended Primary Inductor Converter (SEPIC) converter for EV battery charging applications. The SEPIC converter is a type of DC-DC converter designed to provide a steady output voltage while accommodating a wide range of input voltages. Known for its high efficiency and reliability, the SEPIC converter can regulate the output voltage to be either higher or lower than the input voltage. DC-DC converters are particularly appealing to researchers due to their low output voltage ripple and high efficiency, making them ideal for applications requiring low noise and high power density. Continuous advancements in DC-DC converter performance and reliability are essential to meet modern technology's growing demands. The SEPIC converter, sharing similarities with the buck-boost converter by incorporating both buck and boost functions, offers advantages such as having input and output voltages with the same polarity, high efficiency, and capacitor isolation between the output and the input sides. The simulation of the SEPIC converter in both open-loop and closed-loop configurations is carried out using MATLAB software and presented in this paper.*

Keywords *- Electric Vehicle (EV), Diode Bridge Rectifier (DBR), DC-DC converters, SEPIC converter, Battery charger.*

1. Introduction

EVs and hybrid EV (plug-in type PHEV) technologies are becoming increasingly popular due to their reduced fuel consumption and greenhouse gas emissions [1, 4, 6]. The battery packs finish the charging process using an external device known as a battery charger. The device is not connected to the power network and is responsible for converting energy and controlling and processing electric current to charge the EV battery. Figure1 shows the basic block diagram of a two-stage battery charger [9, 10].

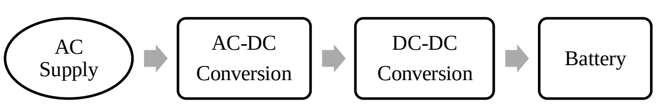

Fig. 1 Basic block diagram of two stage battery charger

The rectification process is finalized by 1st stage (AC to DC) conversion and the 2nd (DC to DC) conversion stage, which is in charge of modifying the voltage level to be appropriate for charging batteries in electric vehicles. Nonetheless, both isolated and non-isolated DC-DC converters are often used in varieties. The topologies of a non-isolated DC-DC converter include Buck, Boost, Buck-Boost, Cuk, and SEPIC. Forward, Fly-back, Half-bridge, Full-bridge, Push-pull, Phase shift full-bridge, and Resonant converters are some of the several types of isolated converters [2, 5, 6, 15, 21].

The DC-DC converter known as Single-Ended Primary Inductor Converter (SEPIC) is explicitly designed to offer a steady output voltage while accepting a variety of input voltage. This unique converter is highly efficient and reliable and can regulate the output voltage should be equal to, higher, or lower than its input voltage. These could mainly depend on the duty cycle of the SEPIC converter. When the duty cycle is 50%, the output voltage is equal to the input voltage, but when the duty cycle is greater than 50% at that time, the output voltage is greater than the input voltage, and it operates as a boost converter and when the duty cycle is less than 50% at that time the output voltage is less than the input voltage, and it operates as a buck converter.

This adaptability makes it an ideal choice for a variety of applications. The SEPIC converters are often used in situations where a stable output voltage is mandatory, such as in battery-powered devices, automotive electronics, and LED lighting systems. Its ability to maintain a consistent voltage output has made it a popular choice in many industries, and it is considered to be a reliable and cost-effective means of converting DC voltage. The SEPIC type of converter shares similarities with the buck-boost converter, as it incorporates both buck and boost converter functions. However, the SEPIC converter offers advantages over the buck-boost converter, such as the output and input voltages possessing the same polarity, high efficiency, and the capacitor's ability to isolate the input and output sides [16-20].

The SEPIC converter offers a stable and positively regulated output voltage for a given input voltage, a crucial requirement for many electronic devices. In contrast, the buck-boost and Cuk converter offer a negatively regulated output voltage. The SEPIC converter is designed with a series coupling capacitor that offers isolation and protects the converter from short Schematics. Moreover, the coupling capacitor's non-inverted output and low equivalent series resistance help reduce ripple and stop heat accumulation. This makes the converter highly reliable and suitable for an extensive range of operations, with electronic devices requiring stable, efficient power supply.

This paper introduces the design and simulation of SEPIC Converter for EV battery chargers. Section II shows an operation of the SEPIC Converter in which two modes are described. Section III shows the design of the SEPIC Converter. Section IV shows that MATLAB simulates the open-loop and closed-loop SEPIC converter with a diode bridge rectifier. Section V shows the conclusion and future work of this paper.

2. Operation of SEPIC Converter

The diagram depicts a fundamental SEPIC, as shown in Figure 2 [3, 7, 11].

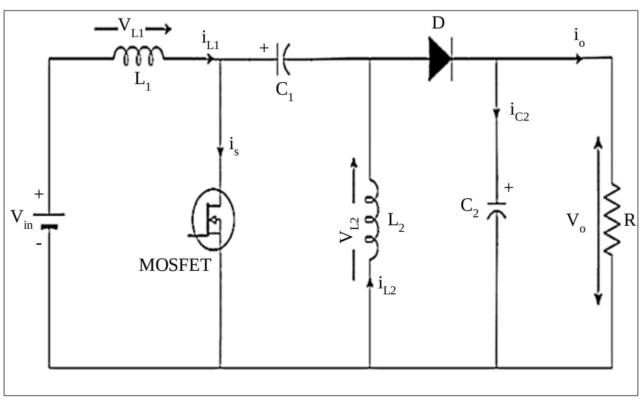

Fig. 2 Circuit diagram of SEPIC converter

It is noteworthy that, similar to Buck-Boost, Zeta, and Cuk converters, the SEPIC converter employs both inductors and capacitors to achieve regulated output. The present schematic involves two inductors, two capacitors, and two static switches. The static switches, semiconductor devices, are composed of a diode and a transistor (typically a MOSFET, IGBT, or BJT). The diode functions as an uncontrolled switch that automatically toggles on and off based on the voltage across it, and the transistor functions as a controlled switch controlled by a gate pulse.

2.1. Mode 1 When Switch is ON

Figure 3 shows a circuit diagram of the SEPIC Converter operated in Mode 1 operation [3, 5, 7]. After applying a gate pulse to the MOSFET, current is allowed to flow from the source to pass through the inductor L1 and then through the MOSFET before returning to the source. This current flow causes the inductor's current (I_{L1}) to rise, which causes the inductor to start charging from the input source.

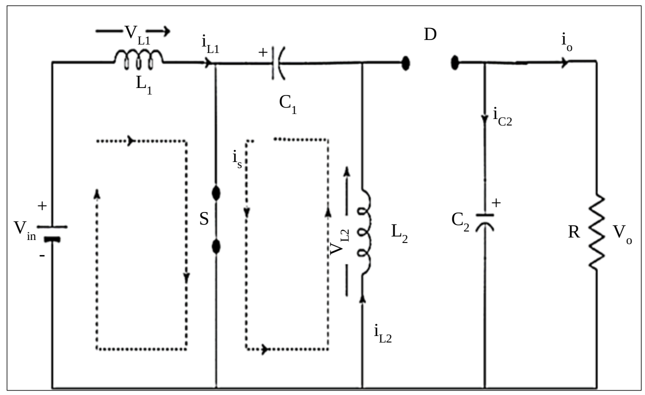

Fig. 3 Circuit diagram of SEPIC converter during mode 1 operation

During the charging phase, the voltage of the inductor L_1 (V_{L1}) will be nearly equal to the source voltage Vin. Furthermore, when the MOSFET is in the ON state, the energy released by the capacitor C_1 is used to charge the inductor L_2. The energy stowed in capacitor C_1 is dissipated to the inductor L_2 via the MOSFET.

2.2. Mode 2 When Switch is OFF

The SEPIC Converter's circuit diagram in Mode 2 operation is displayed in Figure 4 [3, 5, 7].

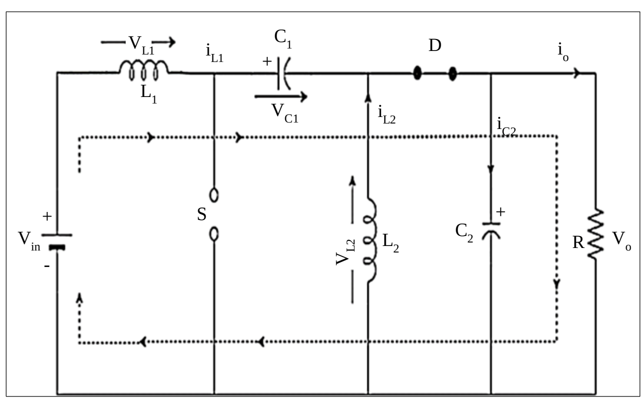

Fig. 4 Circuit diagram of SEPIC converter during mode 2 operation

After the gate pulse is removed, the MOSFET turns OFF. At this point, the inductor L_1 won't permit a sudden change in current, leading to a reversal in the polarity of the inductor as per the Lenz law. As a result, the inductor will start discharging in the reverse direction and supply its energy to the capacitor C_1.

The SEPIC converter can function in two distinct modes: continuous conduction mode and discontinuous conduction mode. The mode of operation depends on whether the current through either of the inductors is made to fall to zero or not. The current flowing through one of the inductors in discontinuous conduction mode decreases to zero throughout a part of the switching cycle, while in continuous conduction mode, the current through both inductors never drops to zero.

3. Design of SEPIC Converter

The SEPIC Converter's design parameters are given below [3, 7, 8, 12, 24].

3.1. Duty Cycle Calculation

The SEPIC Converter's ability to step up or down the voltage is mostly determined by the circuit's parasitic components and duty cycle. For an ideal SEPIC Converter, the output voltage is given by,

$$V_O = \frac{D*V_S}{1-D} \tag{1}$$

However, losses brought on by dependent components, like the diode drop V_D, are not considered. They comprise the equation:

$$V_O + V_D = \frac{D*V_S}{1-D} \tag{2}$$

So, the duty cycle is given by,

$$D = \frac{V_O+V_D}{V_S+V_O+V_D} \tag{3}$$

Where, V_D is the diode voltage drop, V_S is the supply voltage.

3.2. Inductor Selection Calculation

The ripple current that flows through inductors L_1 and L_2 of equal value is provided by,

$$\Delta I_L = I_{in} * Iripple = I_O \frac{V_O*Iripple}{V_S} \tag{4}$$

The value of the inductor is determined by,

$$L_1 = L_2 = L = \frac{V_S*D}{\Delta I_L*f_S} \tag{5}$$

Where D is the duty cycle, *fs* is the switching frequency, Vo is the output voltage, Vs is the supply voltage, and I_{ripple} is the ripple current.

3.3. Capacitor Selection Calculation

The ripple voltage through the capacitor is given by,

$$\Delta V = V_O * V_{ripple} \tag{6}$$

The capacitor value is calculated by,

$$C_1 or\ Co = \frac{I_O*D}{\Delta V*0.5*f_S} \tag{7}$$

Where D is the duty cycle, *fs* is the switching frequency, and V_{ripple} is the ripple voltage.

4. Simulation Results and Discussion

The Simulation analysis of the SEPIC DC-DC converter used for EV battery charging is carried out using the MATLAB Simulink. Table 1 lists the simulation parameters used for the SEPIC converter. The simulation model used in MATLAB with the solver ode23tb. Two simulation studies mainly carried out an open-loop SEPIC converter with a Diode bridge rectifier and a closed-loop SEPIC converter with a Diode bridge rectifier [5, 7].

Table 1. Simulation parameters of SEPIC converter

Parameter	Value
Supply Voltage (Vs)	325V
Output Voltage (Vo)	56V
Output Current (Io)	15A
Switching Frequency (fsw)	50KHz
Output Power (Po)	840W
Ripple Current (Iripple)	10%
Ripple Voltage (Vripple)	10%
Inductor (L)	3848μH
Capacitor (C)	15.85μF
Duty Cycle (D)	14.8%
Load Resistor (R)	3.7Ω

4.1. Open Loop SEPIC Converter with Diode Bridge Rectifier (DBR)

The Open loop SEPIC Converter circuit diagram with the diode bridge rectifier is displayed in Figure 5. The diode bridge rectifier operates as a Front-End Converter that converts alternative current into direct current. The usefulness provides a distinct DC by feeding into the AC to DC power converter. Nevertheless, Power Factor Correction (PFC) techniques can be employed to address the harmonic current that these converters may produce [6]. There are two distinct stages in the design of these converters. In order to achieve the DC voltage, the first stage is rectification. The second stage uses a back-end converter to convert and obtain the isolated DC voltage required to charge an EV's battery (DC-DC converter like SEPIC). In this simulation, a higher frequency of 50KHz is taken, which results in a smaller inductor and capacitor size, which reduces the overall SEPIC converter size.

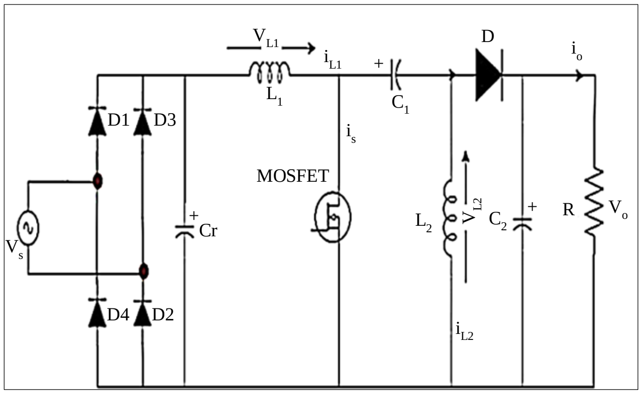

Fig. 5 Circuit diagram of open loop SEPIC converter with DBR

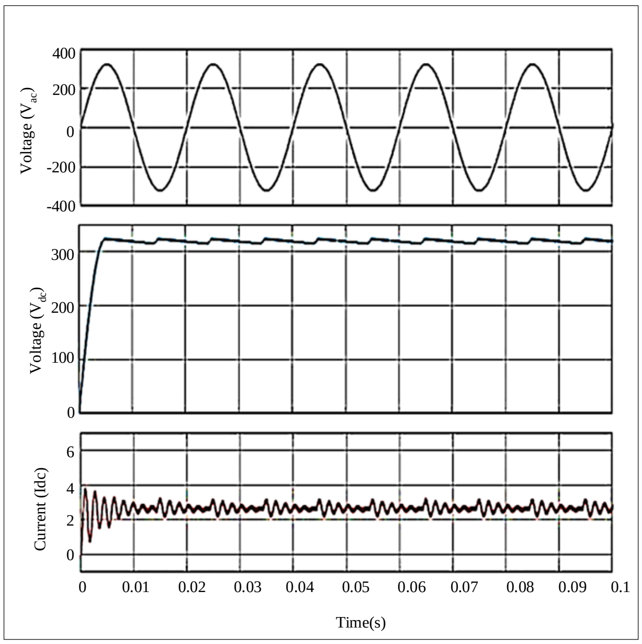

Fig. 6 Simulation results of diode bridge rectifier

The simulation results of the open loop SEPIC Converter with DBR are demonstrated in Figures 6 and 7. Figure 6 indicates the simulation results of the diode bridge rectifier wherein AC supply voltage (Vac), rectifier DC voltage (Vdc) and rectifier DC current (Idc) are presented. Figure 7 indicates the simulation results of an open loop SEPIC Converter, which consists of output DC voltage (Vo), output DC current (Io), and input DC voltage (Vdc).

The value of input DC voltage (Vdc) is 325V, output DC voltage is 55.56V, and output DC current is 15A. In this open loop SEPIC Converter simulation with the change of duty cycle, the value of output DC voltage and output DC current changes. When the duty cycle (D) is more than 50% at that time, the SEPIC converter operates as a boost converter, and if the duty cycle (D) is less than 50% at that time, the SEPIC converter operates as a buck converter.

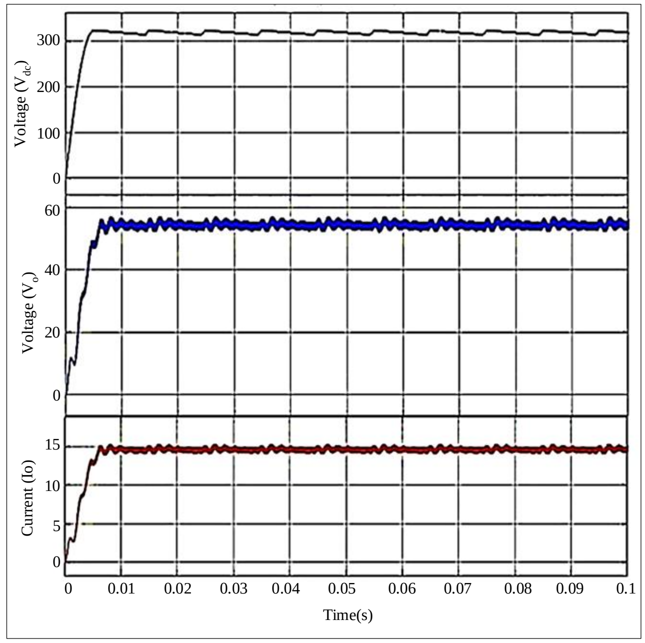

Fig. 7 Simulation results of open loop SEPIC converter

4.2. Closed loop SEPIC Converter with Diode Bridge Rectifier (DBR)

Figure 8 displays the circuit diagram of a closed-loop SEPIC Converter with a diode bridge rectifier. The Proportional-Integral (PI) Controller is a commonly employed feedback controller to regulate the DC-DC converter's output voltage, owing to its simple and practical design [8]. The Proportional-Integral (PI) controller utilizes the error signal as the feedback of the control loop, thereby serving as an effective tool for achieving consistent voltage regulation. Its efficacy is determined by its ability to maintain plant stability at predetermined set points and respond promptly to changes. The proportional constant (Kp) and integral constant (Ki) play significant roles in achieving optimal results in this control system.

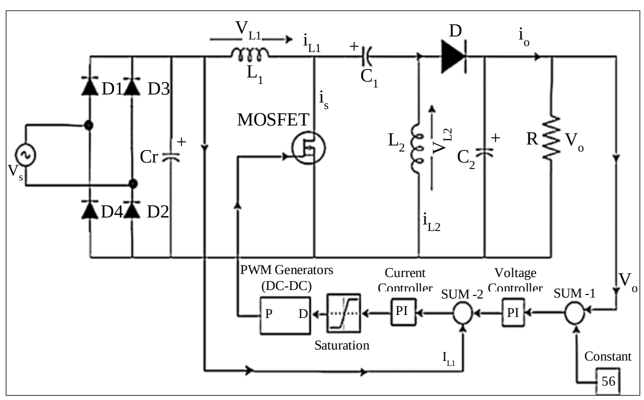

Fig. 8 Circuit diagram of closed loop SEPIC converter with DBR

For effective control, the correct values of these constants need to be set to minimize overshoot errors, obtain faster response times, and increase the stability of the output [23]. The voltage controller gains tune with Kp=0.04428 and Ki=19.63300, and the current controller gains tune with Kp=6.09162 and Ki=0.00024 in this simulation study.

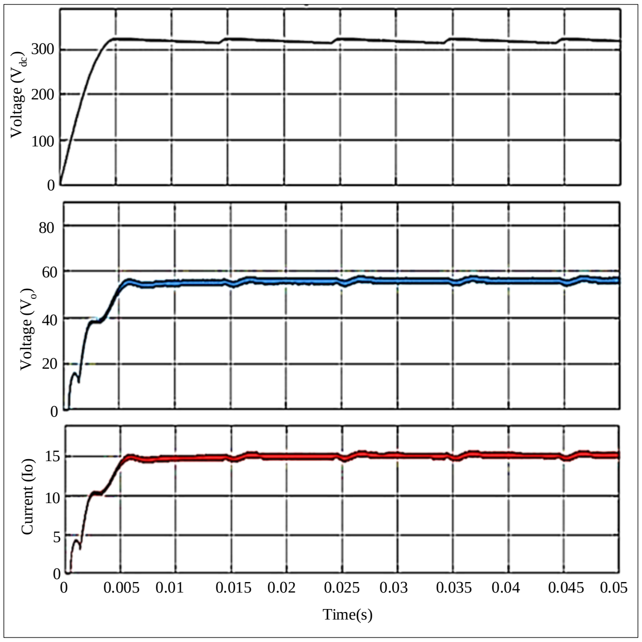

Fig. 9 Simulation results of closed loop SEPIC converter

The closed loop SEPIC Converter's MATLAB simulation results are displayed in Figure 9, which include output DC voltage (Vo), output DC current (Io), and input DC voltage (Vdc). The value of input dc voltage (Vdc) is 325V, output dc voltage (V_O) is 56V and output dc current (I_O) is 15A. Figure 10 indicates the output ripple current and output ripple voltage waveform of SEPIC Converter in which output voltage ripple is 4.5% and output current ripple is 4.6%, which is less compared to buck and cuk converter, which is verified through simulation results shown in Table 2. Vo is output voltage, Io is output current, Vo (ripple) is output voltage ripple, Io (ripple) is output ripple current, and Po is output power.

Table 2. Comparison based on simulation results between SEPIC, cuk, and buck converter

Sr. No	Converter Topology	Parameter				
		Vo (V)	Io (A)	Vo (ripple) (%)	Io (ripple) (%)	Po (W)
1	**Buck**	54.9	14.8	5	4.7	815.8
2	**Cuk**	52.3	14.1	6.3	7	737.4
3	**Sepic**	55.3	15	4.5	4.6	829.5

The variation in supply voltage for an open loop SEPIC Converter is shown in Table 3, in which, by variation in supply voltage, there are changes in the value of output voltage and current. The variation in supply voltage for closed loop SEPIC Converter is presented in Table 4. The output voltage and output current are almost remaining same in closed loop SEPIC Converter by the variation in supply voltage.

Table 3. Supply voltage variation for open loop SEPIC converter

Supply Voltage (Vs)	Output Voltage (Vo)	Output Current (Io)
325V	54.29V	14.67A
200V	33.14V	8.95A
100V	15.97V	4.31A

Table 4. Supply voltage variation for closed loop SEPIC converter

Supply Voltage (Vs)	Output Voltage (Vo)	Output Current (Io)
325V	56.15V	15.16A
200V	55.87V	15.1A
100V	54.67V	14.78A

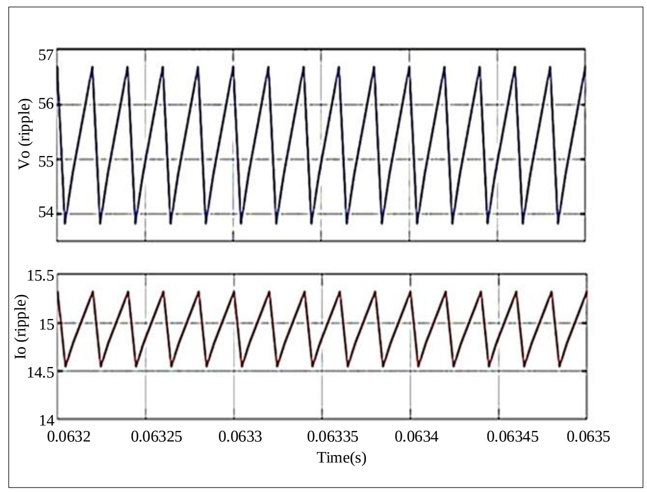

Fig. 10 Output voltage ripple (Vo (ripple)) and output current ripple (Io (ripple)) waveform of SEPIC converter

After evaluating simulation results and supply voltage variation for both open loop and closed loop SEPIC Converter, we get more accurate results in closed loop SEPIC Converter. In a closed loop, the SEPIC Converter maintained an output voltage of approximately 56V and an output current of 15A throughout the load. The simulation results accomplished a high efficiency of 93.63% and much less output voltage and output current ripple, which is 4.5% and 4.6%, respectively.

5. Conclusion and Future Work

The Single-Ended Primary Inductor Converter (SEPIC) converter indicates the capability to work with an input voltage that is either higher or lower than the regulated output voltage. Simulations for both open-loop and closed-loop SEPIC converters were performed. Analysis of the simulation results revealed that the SEPIC converter exhibited minimal output voltage fluctuations and output current fluctuations, maintained a non-inverted output voltage polarity, and had higher efficiency. In the simulation analysis and comparison of SEPIC with the Buck and Cuk converter, the SEPIC converter had less output voltage and output current ripple, which is 4.5% and 4.6%, respectively. The closed-loop SEPIC converter successfully maintained an output voltage of approximately 56V and an output current of 15A across the load, with the capability to control the DC output voltage by adjusting the duty cycle (D).

Future work will focus on the simulation of an isolated SEPIC converter, which will ensure users are safe from electric shocks and other related hazards and the high-frequency transformer's turns ratio can be used to achieve a wider voltage gain range, making the converter suitable for usage with a broader range of loads and the implementation of SEPIC converter hardware for electric vehicle battery charger.

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