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Design and Implementation of Modified Bidirectional Converter

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***Abstract*— In recent days, the need for highly power efficient methods are required to create an environment that is sustainable and eco-friendly. Therefore, the usage of converters has increased exponentially. DC-DC converter is widely used in electronic devices powered by batteries to regulate the battery voltage to a suitable level. These converters convert the battery voltage to a different level, either higher or lower, depending on the device requirements. For instance, a boost converter can be used to increase the voltage for a device that requires a higher voltage than the battery can provide. Conversely, a buck converter can be used to reduce the voltage for a device that needs a lower voltage than the battery provides. This paper involves designing a new model of the SEPIC converter i.e., modified SEPIC converter that can operate bidirectionally by replacing the output diode of the conventional SEPIC converter with a switch. The converter is designed to increase the power efficiency and to reduce the need for using huge battery packs that is used to reduce the size and cost of the batteries to be used. The designed converter is connected to battery at source end and it performs boosting operation when connected to load and it operates in bucking mode when the battery is to be charged. The efficiency of the designed converter is around 95%.**

***Index Terms*— DC – DC converter, bidirectional converter, SEPIC converter, modified SEPIC converter.**

I. Introduction

Converters can have a positive impact on the environment by promoting integrating renewable energy sources, enhancing energy efficiency, and mitigating greenhouse gas emissions. These devices can be used to create microgrids that operate independently of the main power grid, combining renewable energy sources, energy storage solutions, and converters to build a more resilient and sustainable energy infrastructure. Using converters to regulate power supply can harness renewable energy sources such as solar, wind, or hydro power and optimizing their utilization, reducing greenhouse gas emissions. Moreover, converters can help improve energy efficiency, particularly in industrial settings, by converting high voltage to low voltage, reducing energy waste and improving efficiency. By regulating power supply through converters, energy consumption can be optimized and energy losses minimized, leading to substantial energy conservation and decreased emissions of greenhouse gases. Using of converters can promote sustainable energy infrastructure, reduce greenhouse gas emissions, and improve energy efficiency, making them a crucial component of the worldwide endeavor to tackle climate change and advance sustainable development involves enhancing efficiency through voltage and current conversion to reach the

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device's ideal levels. Converters offer more flexibility as they can be used to convert voltage and current to a variety of different levels and also can be used with different power sources, such as batteries, solar panels, and generators, making them useful in a wide range of applications [10][14]. The existing buck boost converter has two stage processes to reach the required voltage, ultimately consuming a lot of space. It also has a low switching frequency, which leads to a low voltage conversion ratio. In the proposed system we use two MOSFET switches to increase the switching frequency. The converter uses a single boosting process to attain the required voltage, reducing the space occupied by the converter. MOSFET switches have high-switching frequency whose voltage conversion ratio is high. Two switches work in a NOT pulse method.

II. Objective

- The goal of utilizing a modified SEPIC converter in battery-based electrical appliances is to effectively transform the battery voltage to a voltage level that is appropriate for the appliance's operation.
- The modified SEPIC converter can offer a regulated voltage at the output that is separated from the voltage at the input, which is crucial for ensuring the appliance operates at a consistent voltage level despite changes in the battery voltage.
- Compared to other DC-DC converters, the modified SEPIC converter boasts several advantages, such as its ability to handle a broad range of input voltages, making it suitable for use with various battery types and configurations.
- Furthermore, the modified SEPIC converter is highly efficient, a crucial factor in battery-based applications where power consumption is critical.
- In essence, the primary aim of using a modified SEPIC converter in battery-based electrical appliances is to deliver a dependable and efficient power source that caters to the appliance's specific requirements.
- Achieving this objective can help prolong battery life and enhance the performance of battery-based electrical appliances.

III. Existing System

DC-DC converter is an electronic device that converts DC voltage at the input to a different DC voltage at the output. It is widely used in various electronic devices and systems, including power supplies, battery chargers, motor drives, and LED lighting. DC-DC converter are of three main types, buck converter (step-down), boost converter (step-up), and buck-boost converter[9]. Buck converters lower the voltage at input to a desired voltage at the output by turning the input voltage on and off and storing energy in an inductor. In contrast, boost converter increases voltage at the input to a desired voltage at the output by storing energy in an inductor and releases to output load. Buck-boost converter can step down or step up the voltage at input to produce a desired voltage at output and can operate in four different modes. DC-DC converters have several advantages over traditional linear regulators, including improved efficiency, smaller size, and lower cost [15] [16]. They also offer better power density, higher reliability, and improved transient response.

DC-DC converters find utility in portable electronic gadgets striving for extended battery longevity and in renewable energy setups like solar panels and wind turbines. Isolated DC-DC converters are extensively employed in various applications that require protection against electrical noise, including medical equipment, industrial control systems, and telecommunications. One main challenge of buck-boost converter is its tendency to generate significant output and input current ripple. This can create noise and electromagnetic interference (EMI) issues, and may require additional filtering to smooth out the current waveforms. Another drawback of the buck-boost converter is its intricate control circuitry[16]. Because it is a bidirectional converter, its feedback loop must be designed to handle both step-up and step-down operation, which can make closed-loop control more challenging [2] [3].

This added complexity can increase the overall cost and design effort required for buck-boost converter-based system. In efficiency terms, buck-boost converter may not be the best choice for applications where power efficiency is critical. Compared to unidirectional converters such as buck converter and boost converter, buck-boost converter typically has lower efficiency due to the additional circuitry required for bidirectional operation [4][7]. The buck-boost converter, like other unidirectional converters, does not provide separation between output and input. This may be disadvantageous in certain applications that require isolation for safety or performance reasons [6].

IV. Proposed System

In a modified SEPIC (Single - Ended Primary Inductor Converter) converter that uses a switch instead of a diode, the basic circuit topology remains the same as a regular SEPIC converter. However, instead of using a diode to rectify the output voltage, a switch such as a MOSFET or a BJT is used. The main advantage of using a switch instead of a diode is that it can offer higher efficiency, especially in high - power applications. The voltage drop across a diode can result in significant power losses, which can reduce the overall efficiency of the converter. By using a switch instead of a diode, the power loss can be reduced, leading to higher efficiency. In this modified topology, the switch is controlled using pulse width modulation (PWM) signal, produced by the control circuit of the converter, is employed to switch the device on and off rapidly at a high frequency, typically ranging from several hundred kilohertz to several megahertz. This modulation is used for the purpose of regulating the output voltage[1].

When the switch is turned on, the inductor in the circuit stores energy, when the switch is in the off position, energy is discharged into the output capacitor[12]. By adjusting the duty cycle of the PWM signal, the output voltage can be regulated. One important consideration when using a switch instead of a diode is the issue of reverse recovery time. When a diode turns off, it takes a certain amount of time for the stored charge to dissipate. This is known as the reverse recovery time. If a switch is used instead of a diode, the reverse recovery time is not an issue, but the switch must be carefully selected to ensure that it can handle the voltage and current levels of the application. Not Pulse Method – In this method the MOSFET switches SW1 and SW2 are ON & OFF alternatively based upon the Not Pulse. i.e., when the switch SW1 is ON the switch SW2 is OFF at that particular instant of time and when switch SW2 is ON, switch SW1 is OFF. The On and OFF duration the switches SW1 and SW2 can be controlled by driver circuit which receives the signal from the PIC microcontroller and the switching operation can be varied by modifying the code present in the PIC controller.

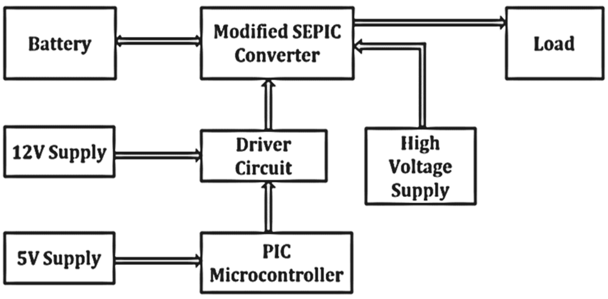

Fig.1 Block Diagram of the Proposed Converter

The above block diagram in Fig.1 is the pictorial representation hardware setup of the SEPIC converter that is modified. It represents connections of components required for operation of the “modified SEPIC converter”. The rechargeable battery is always connected to the terminal near the inductor L1 and it is shown in the Fig.2 and the load is connected to the terminal near the capacitor C2. The PIC microcontroller is powered by an external 5 volt supply.

The PIC microcontroller controls the MOSFET switches present in the modified SEPIC converter. The driver circuit is also externally powered by a 12 volt supply. The driver circuit is used to power the MOSFET switch since PIC microcontroller operates at 5 volts whereas minimum voltage required to activate the gate in MOSFET is 12 volts, so to send the signal to the MOSFET, a driver circuit is required. When the PIC micro - controller sends signal to the driver circuit, MOSFET switch required voltage is supplied by the driver circuit[5]. During the charging of the battery, battery acts as load and load is disabled. From the load side a high voltage source is provides to charge the battery varied by modifying the code present in the PIC controller and the voltage is reduced to the required voltage level to charge the battery.

V. Operation

The SEPIC (Single-Ended Primary-Inductor Converter) topology comprises several key components, including power MOSFET switches, a diode, two inductors (L1, L2), and two capacitors (C1, C2). Initially, this configuration operates as a unidirectional converter. However, it's possible to transform this unidirectional SEPIC converter into a bidirectional version by substituting the unidirectional diode with a bidirectional MOSFET switch, as depicted in Figure 2[11][13].

In the context of continuous conduction mode (CCM), this converter serves as both a buck and a boost converter. The operational sequence involves the low-voltage battery voltage (Vin) being directed to an inductor. During the phase where MOSFET SW_1 is closed and MOSFET SW_2 is open, inductors L1, L2, and capacitor C1 are connected to the power supply. Once these components are charged, MOSFET SW_1 is opened while SW_2 is closed. The MOSFET switches toggle at a notably high frequency, leading to voltage spikes that elevate the voltage to the desired level, a characteristic of the boost conversion process. Importantly, when the battery requires recharging, the high voltage is effectively reduced to match the level of the low-voltage battery, thereby preventing any potential damage.
The converter is powered by a dc supply and it charges the inductor L1. Initially the capacitor C1 is assumed to be fully charged. The MOSFET switch SW_1 is initially ON while the switch SW_2 is OFF simultaneously. The MOSFET switch SW_1 now acts as short circuit and thus the capacitor C1 discharges through that and it charges the inductor L2.

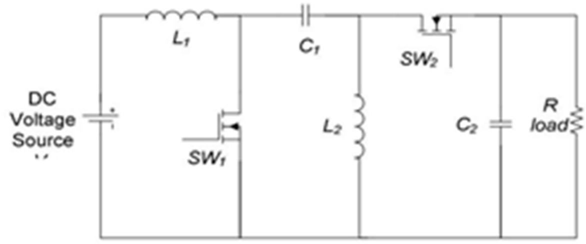

Fig. 2 Circuit Diagram of the Converter that is proposed

Mode - 1 is depiction of state of the MOSFET switches SW_1 and SW_2. In mode - 1 during the boosting process of the Modified SEPIC converter switch SW_1 is ON and the switch SW_2 is OFF.
Now when the MOSFET switch SW_1 is OFF and the MOSFET switch SW_2 is ON as simultaneously due to the NOT pulse control method. From Lenz law it is determined that the inductor opposes the change in current direction and thus changes polarity. Therefore, inductor L1 also follows the same law and now the capacitor C1 is charged, the L2 inductor also opposes the change in current and changes its polarity. By changing the polarity, the current flows through those MOSFET switch SW_2 to the capacitor C2 and charges it. When capacitor C2 charges fully ,the current starts dissipating to load and it can be visualized.

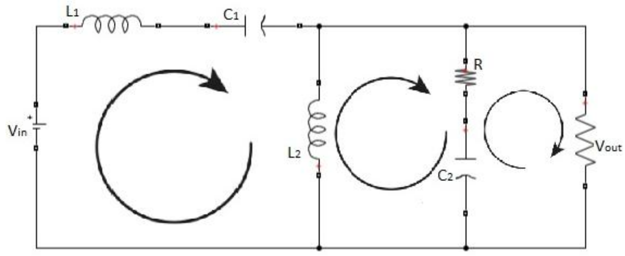

Fig. 3 Mode - II in Boosting Process

Mode - 2 is depiction of state of the MOSFET switches SW_1 and SW_2. In mode - 2 during the boosting process of the Modified SEPIC converter switch SW_2 is ON and the switch SW_1 is OFF. Switching of MOSFET switches at high frequency boosts the voltage to the higher amount. When the MOSFET switches SW_1 and SW_2 are OFF and ON respectively, the current from the inductor L2, capacitors C1 and C2 flows to the load. This process provides the required power to load while increasing the voltage to high level. The flow of current in different loops during the switching process.
During the bucking process in the modified SEPIC converter, load is replaced by a power source and the battery which is to be recharged acts as a load. The battery cannot be directly recharged from high voltage source, so the SEPIC converter that is modified performs the process required by converting the high voltage to required voltage level for safe charging of the rechargeable battery.
Mode - I is depiction of state of the MOSFET switches SW_1 and SW_2. In mode - 1 during the bucking process of the Modified SEPIC converter switch SW_1 is ON and the switch SW_2 is OFF

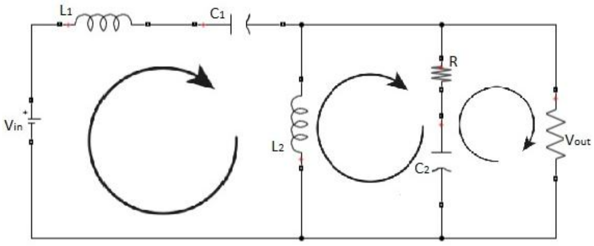

Fig.4 Mode – I in Bucking Process

Initially during the bucking process when the MOSFET switch SW1 is ON and the MOSFET switch SW2 is OFF by the NOT pulse control method. During this. The capacitor C_2 is charged, the capacitor C_1 discharges the current to the inductor L_2 and it stores the energy in it. The inductor L_1 discharges the current to the battery acting as load. Mode - II is depiction of state of the MOSFET switches SW1 and SW2. In mode - 2 during the bucking process of the Modified SEPIC converter switch SW2 is ON and the switch SW1 is OFF. When the MOSFET Switch SW1 and SW2 are OFF and ON respectively, the capacitor C2 discharges the current to capacitor C1. The inductor L2 now discharges and also charges the capacitor C1, inductor L1 discharges the current to the load.

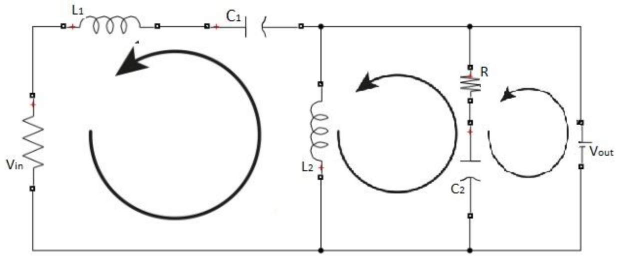

Fig.5 Mode -II in Bucking Process

Now again when the MOSFET switches SW1 and SW2 are ON and OFF respectively, the capacitor C2 works in the same way as the first cycle whereas the inductor L_2 discharges the current to charge the capacitor C1, which opposes the current direction of inductor L1. This reduces the voltage supplied the battery that is in the suitable voltage level to charge the battery. The circuit diagram with the current paths.

VI. Design Considerations

Here are the design formulas for a modified bidirectional SEPIC converter:
The inductance of the inductor L1 and L2 can be determined from the given equation:

$$L = (V_{in\_min} \text{ x } D \text{ x } (1 - D)) / (f_{sw} \text{ x } \Delta IL)$$

In this context, V_{in_min} represents the minimum input voltage, D stands for the duty cycle, f_{sw} indicates the switching frequency, and ΔIL signifies the peak-to-peak inductor current ripple.
Capacitance of the output capacitor C_1 and C_2 is calculated with the equation:

$$C = (1 - D) \text{ x } (V_{out} \text{ x } \Delta IL) / (f_{sw} \text{ x } \Delta V_c)$$

Where the output voltage is V_{out}, ΔV_c is the allowable output voltage ripple, and ΔIL is the peak to peak inductor current ripple.
The output voltage can be controlled by adjusting the duty cycle D as follows:

$$D = (Vout - Vin\_min) / (Vin\_max - Vin\_min)$$

Where V_{in_max} is the maximum input voltage.
The efficiency of the converter can be determined by the following equation: $\eta = (Pout / Pin) * 100\%$
P_{out} represents the power at the output, while P_{in} signifies the power at the input.
The input power can be calculated as: $Pi_n = V_{in} * I_{in}$
Where V_{in} represents the input voltage, and I_{in} denotes the input current.
The output power can be calculated as: $P_{out} = V_{out} * I_{out}$
Here, V_{out} represents the resultant voltage, and I_{out} stands for the resulting current.

TABLE I: PARAMETERS DURING BOOSTING

Circuit Parameters	Rating
Input Voltage V_{in} during boosting	14V
Switching Frequency (f_{sw})	100 kHz
Output Voltage V_{out} during boosting	89V
Inductors L_1 L_2	 10 mH 10 mH
Capacitors C_1 C_2	 2000 µF 1000 µF
Resistive Load Ro	100Ω

VII. SIMULATION AND PERFORMANCE ANALYSIS

The output response of Modified SEPIC during the boosting process is illustrated in Fig.2 are as follows. The input voltage, Vs, is specified as 12 - 14 volts, and the supply current is 5.9A. The converter produced an 89.05v output voltage and a 0.89A output current. The voltage conversion ratio for the boosting process is 6.35. The converter has an efficiency rate of 95%.

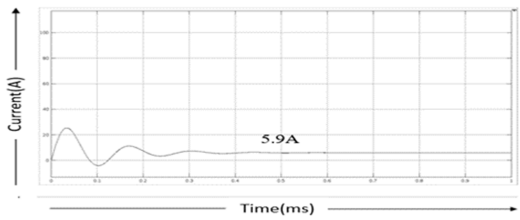

Fig.6 Input Current during Boosting Process

The waveform of the input current supplied to modified SEPIC converter during the boosting process was shown in the fig.6. The horizontal axis is labeled in milliseconds (ms) to denote time, while the vertical axis is used to depict current in amperes (A).

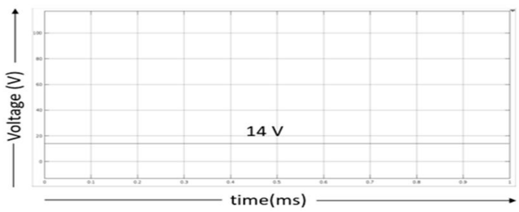

Fig.7 Input Voltage during Boosting Process

The waveform of the input voltage supplied to modified SEPIC converter during the boosting process was given in the fig.7. The horizontal axis is labeled in milliseconds (ms) to denote time, while the vertical axis is used to depict voltage in volts (V).

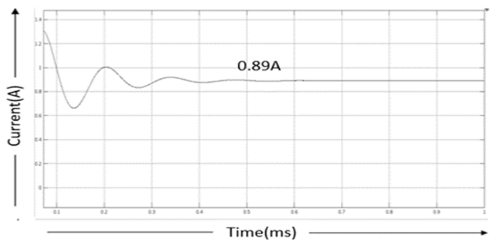

Fig.8 Output Current during Boosting Process

The waveform of the output current that is supplied to modified SEPIC converter from the battery during the boosting process is shown in the fig.8. The horizontal axis is labeled in milliseconds (ms) to denote time, while the vertical axis is used to depict current in amperes (A).

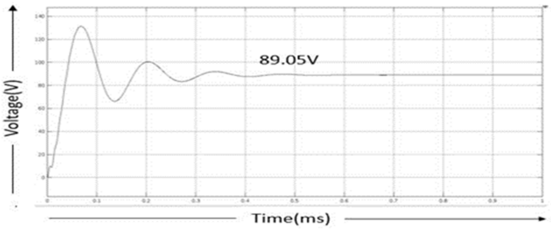

Fig.9 Output Voltage during Boosting Process

The waveform of the output voltage supplied to modified SEPIC converter during the boosting process is given in the fig.9. The horizontal axis is labeled in milliseconds (ms) to denote time, while the vertical axis is used to depict voltage in volts (V).

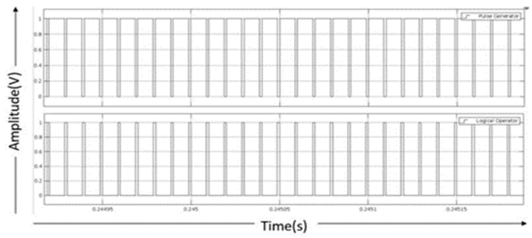

Fig.10 NOT Pulse

Fig. 10 illustrates the waveform of the NOT pulse governing the operation of the two MOSFET switches in both the boosting and bucking processes. On the horizontal axis, time is measured in seconds, while the vertical axis portrays voltage.

VIII. HARDWARE SPECIFICATION

A DC - to - DC bidirectional converter is an electronic circuit that allows power to flow bi directionally between two DC sources, such as a battery and a power grid. The converter consists of several components, as shown in Fig. 11.

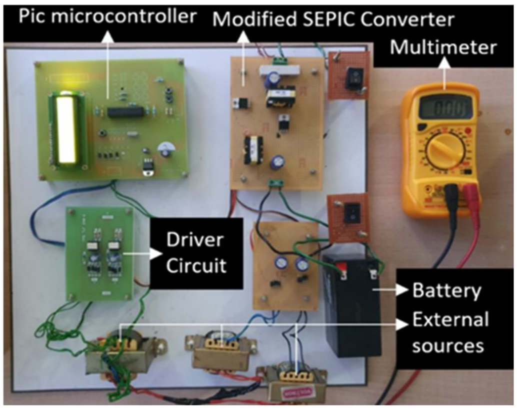

Fig.11 Hardware Setup

1. *Switches*: Both switches SW1 - SW2 were IRF840, a standard n channel MOSFET switches.
2. *Inductor*: Standard inductor L1 and L2 of through type of rating 10mH
3. Capacitors: Capacitors C1 is ceramic capacitor with 2000 µF and C2 is electrolytic capacitor with rating of 1000µF.
4. *Driver circuit*: The custom circuit contains TPL350 driver power by isolated power supplies to drive them based on PIC Controller to drive the MOSFETs.

5. *Controller*: The dsPIC30F2010 is a 16-bit DSC with a 30 MHz clock speed and various features, including timers, PWM modules, CAN 2.0B module etc. designed for high-speed signal processing. It is used to send control signals to the MOSFET through driver circuit to enable switching operation in the converter.

IX. CONCLUSION

A modified SEPIC converter has been successfully implemented and tested, which is capable of delivering a stable output voltage over a wide range of input voltages. MATLAB Simulink has been used to simulate and design the converter circuit, and its hardware prototype was constructed and subjected to testing with a range of input voltage levels. The experimental results demonstrated that the converter was able to produce an output voltage that was higher than the existing system. The converter's small size and reliability make it suitable for use in a variety of applications, such as battery charging, autonomous battery-operated vehicles, drones, and other electronic devices. This bidirectional SEPIC converter has achieved its project objectives and offers an excellent alternative for renewable energy applications.

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