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A Novel Topology of Isolated Bidirectional Buck Boost DC-DC Converter

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Abstract
This paper proposes a bidirectional buck- boost isolated DC-DC converter to realize the bidirectional and buck boost voltage conversion. To do so, simulation of a 7.75-kW, full-bridge, bi-directional isolated DC-DC converter using a 12-kHz transformer and battery energy storage system using MATLAB/Simulink is operated. The full bridge converter is widely used for the high power application and high frequency transformer is used for isolation purpose. The DC voltage at the high-voltage side is controlled from 640 to 700 V to low-voltage side battery voltage of fixed 330V. The converter operates as a buck mode while charging the battery, while the DC mains is powering the downstream load converter. On failure of the DC-mains, the converter operates as if a boost converter and the battery regulate the bus voltage and thereby powers the downstream converters. The voltage and current during both charging and discharging the battery is observed and better energy utilization is verified.

Keywords
Buck Converter, Boost Converter, Battery Charging, Bidirectional Converter

1. Introduction

The bidirectional isolated DC-DC converters have attracted attention of researchers due to it's wide range of applications as uninterrupted power supply, electric vehicle charger, energy storage systems, computer systems. It allows bidirectional transfer of power between two DC sources while maintaining voltage polarity at either end unchanged [1, 2].

Various bidirectional DC-DC converters are reported using resonant [3], soft-switching [4, 5, 6] and hard switching PWM [7]. These topologies lead to increase in the ratings of components, conduction losses, switching losses, lack of isolation. Various bi-directional isolated DC-DC converters have been proposed as the interface battery with focus on electric vehicles and grid applications. Most of the presented DC-DC converters have asymmetrical circuit configurations to couple the two dc links having largely different voltages, several tens volts and several hundred volts [8, 9, 10].

Different topologies to design the DC-DC converter are mentioned but most efficient method is by use of the full-bridge pulse width modulation (PWM) topology. A dual full bridge PWM topology is used to increase the power capacity of the bidirectional converter, as the transmission power of bidirectional DC-DC converter is propertional to number of switches stated that the rated voltage and current of switches are same [11]. So, eight switch two-stage DC-DC Full bridge converter is proposed in this paper to achieve the required specification. The main objective is to get a high efficiency, high power density and cheap topology in simple structure. Previously, resistors were used to discharge the battery. So total energy wasted in the form of I^2R losses. In the proposed topology, during the discharge mode of operation the battery power will flow in the reverse direction and it will feed into the supply grid. Bi-directional power flow is obtained by the same power components and provides a simple, efficient isolated boost converter. It is able to conduct both step up and step down voltage and can have multiple output voltage benefitting over linear regulators which can only operate as step down converter [12].

The paper is organized as follows: Section II presents the describes bi-directional DC-DC converter model, Section III discusses the simulation results verifying the proposed topology, and Section IV concludes the paper.

2. Proposed Bi-directional Buck Boost DC-DC converter

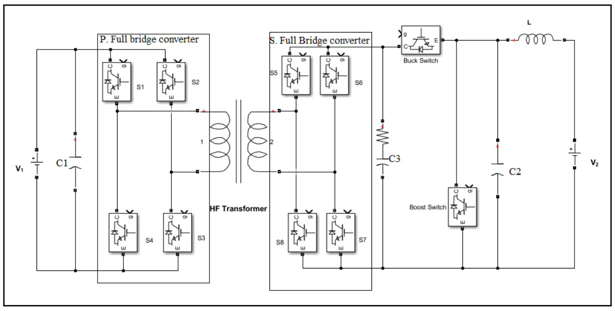

Figure 1: Schematic diagram of the proposed system

Fig. 1. shows the basic schematic circuit diagram to simulate the bi-directional buck boost DC-DC converter. During the charging mode 650 Volts DC is supplied. The constant DC voltage from the capacitor is supplied to full bridge inverter. The switching device to be used is for high voltage medium frequency application, so IGBT is chosen for the purpose. It consists of four major parts. They are:

A. Primary side Full Bridge converter: The first stage is a pulse width modulated full-bridge inverter or a diode rectifier. During charging mode, it works as a phase shifted Full bridge inverter. During discharging mode of operation, it works as full bridge diode rectifier. The switching frequency used in the simulation is 12kHz.

B. High Frequency Transformer: The high frequency transformer provides advantages of high power density, reduced weight, low noise, reduced cost, and better reliability of the system[11]. The high frequency transformer used in the simulation is step down transformer during charging mode and step up transformer during discharging mode and is fed with high frequency square waves. It also provides isolation between two full bridge converter located on either side of the transformer.

C. Secondary side Full Bridge converter: Similar to the primary side converter, it is also a full bridge converter. It works as a full bridge diode rectifier during charging mode whereas as a phase shifted full bridge inverter during discharge mode. The switching frequency for this converter is 12kHz for this paper.

D. Buck-Boost Converter: The buck boost converter can step-up or step-down DC-DC voltage based on the switching of the corresponding switches.

Charging Mode: In this mode, the buck switch is on. The boost switch is turned off, so it operates as a diode. So the input provides energy to the battery via inductor. When the buck switch turns off, the inductor releases its stored energy through the boost diode, hence transferring stored energy to the battery. For charging mode, the voltage at the terminal is given by:

$$V_{ch} \propto N_1 * D_1 * V_{in} \tag{1}$$

where N1 is the turn ratio of the transformer, D1 is the duty cycle of buck switch and Vin is the source voltage.

Discharging mode: In this mode, the boost switch is on. The buck switch is turned off, so it operates as a diode. The battery supplies energy to the load via buck diode. When the boost switch is on, battery supplies energy to the inductor. When the boost switch is off, the inductor transfers the energy to load via buck diode. During discharging, the voltage at the load is given by:

$$V_{disch} \propto \frac{V_{in}}{(1-D_2) * N_1} \tag{2}$$

where D2 is the duty cycle of boost switch and Vin is the battery voltage. The output of buck IGBT during charging mode contains both A.C. and D.C. components. So in order to smooth the output current of buck IGBT, a LC filter is connected for the filtering purpose.

To maintain a constant voltage at the load during discharging mode, a look-up table to calculate duty cycle for the boost switch is evaluated for different battery voltage. So a variable duty cycle approach is used to maintain constant voltage at the load terminals.

3. Simulation Results

Fig. 2. shows the model of the proposed bidirectional isolated buck boost DC-DC converter. The model

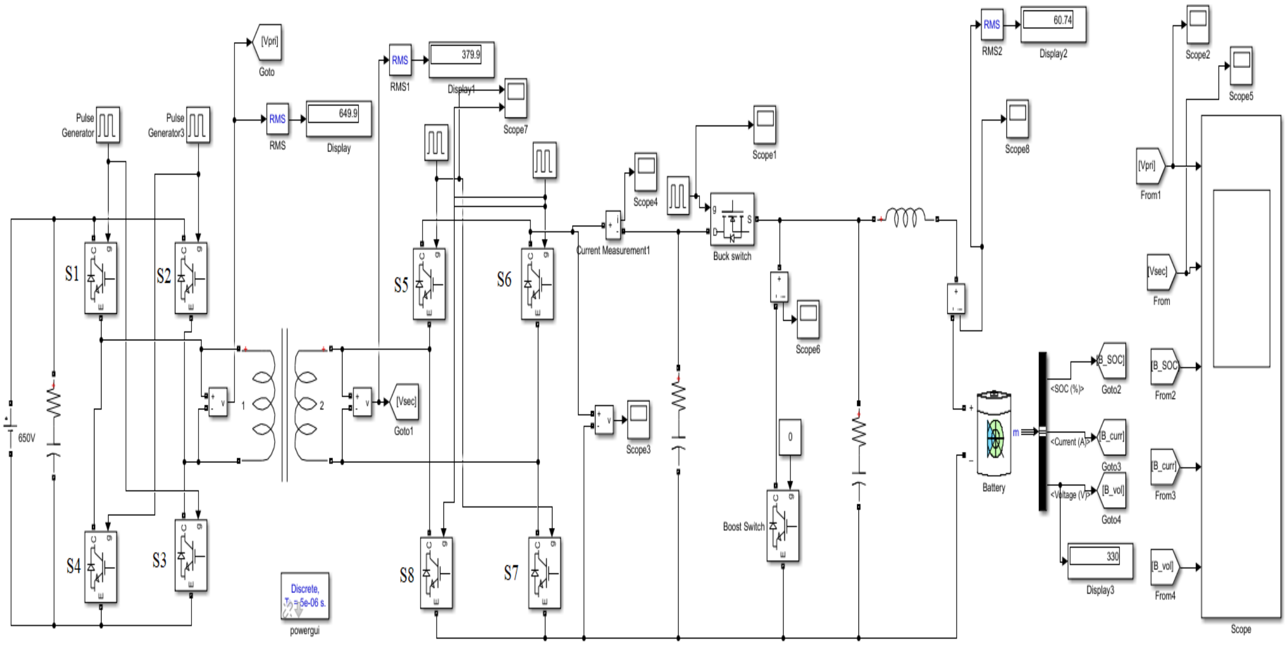

Figure 2: Model System for Bidirectional Buck boost converter

was simulated using MATLAB/Simulink. The circuit parameters for the simulation are tabulated in table 1.

Table 1: Circuit parameters of the bidirectional converter

Switching Device	IGBT
Input Voltage	640-670 volts DC
Output Voltage	330 volts DC
Switching Frequency	12 kHz
Transformer turn ratio (1:N1)	1:0.5846

Mode 1: Charging mode: The switches S1 and S3 are turned on simultaneously and similarly switches S2 and S4 are turned on simultaneously. In this simulation, Whenever switches S1 and S3 are turned on, switches S2 and S4 are turned off and vice versa. The switches S5 and S7 are turned on simultaneously and similarly switches S6 and S8 are turned on simultaneously. In this simulation, Whenever switches S5 and S7 are turned on, switches S6 and S8 are turned off and vice versa.

The converter operates as a buck mode while charging the battery , while the DC mains supply is powering the downstream load converters. Fig.3. and Fig. 4. shows the primary and secondary side voltage of the transformer respectively. Fig. 5. shows the gate switching pulse for the buck switch. Fig. 6. and Fig. 7. shows the voltage and current injected to the battery. The negative current indicates current being injected into the battery. Fig. 8. shows the current through the inductor.

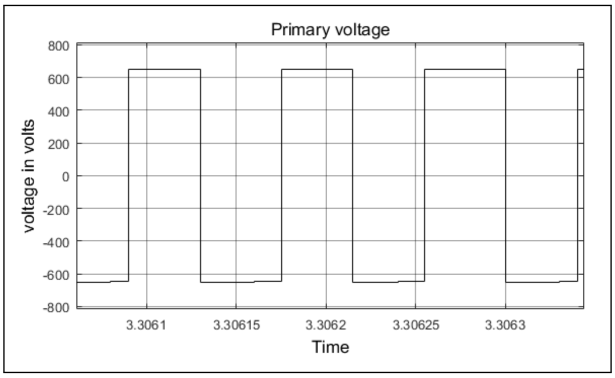

Figure 3: Primary side voltage

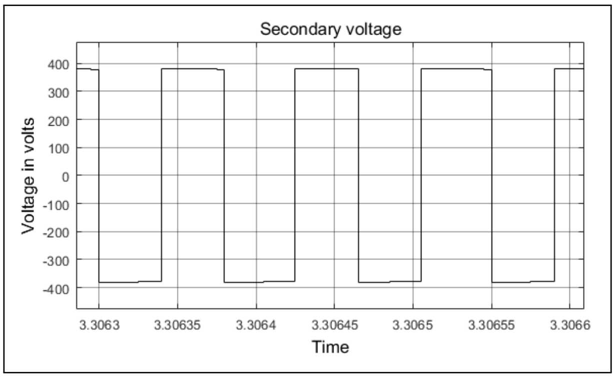

Figure 4: Secondary side voltage

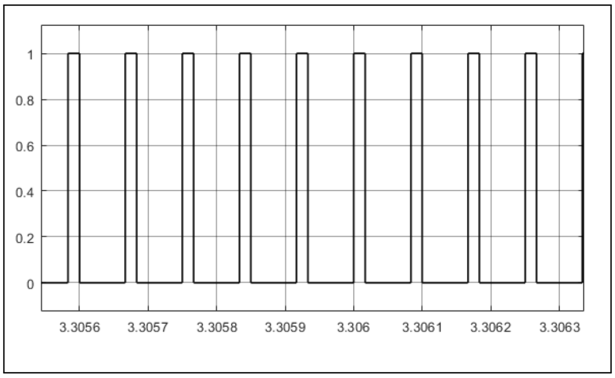

Figure 5: Buck Switch Gate Pulse

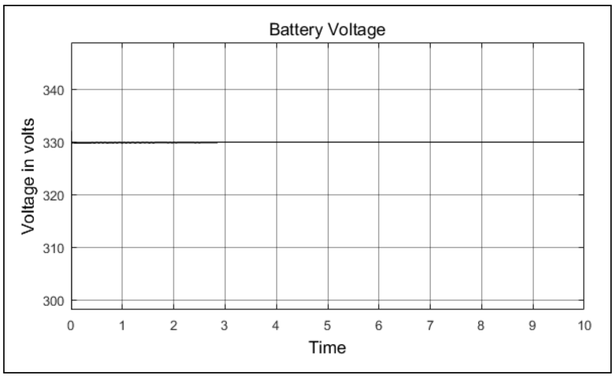

Figure 6: Battery voltage

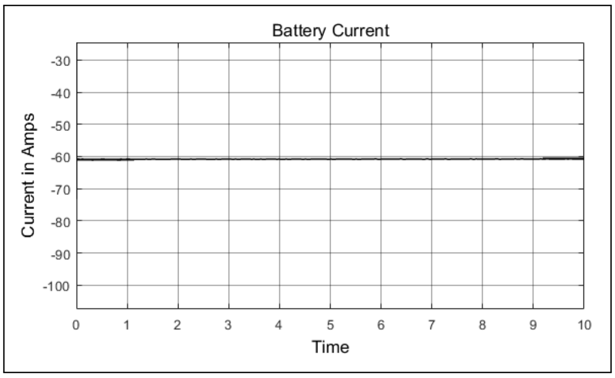

Figure 7: Battery current

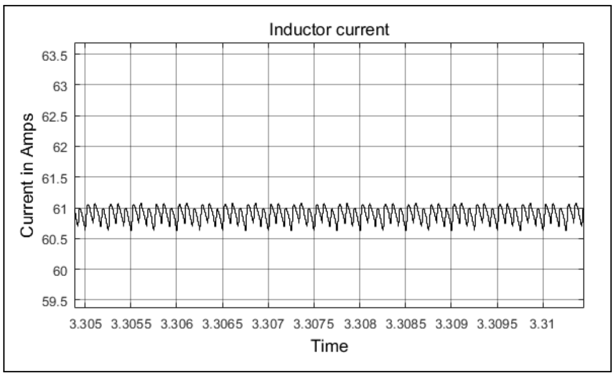

Figure 8: Inductor Current

Mode 2: Dis-charging mode: On failure of the DC-mains, the converter operates as if a boost converter and the battery regulates the bus voltage and thereby powers the downstream converters. The transformer operates as a step up transformer. For the discharging mode, the primary side voltage source was replaced by a resistor of 60 ohm with a capacitor parallel to it. This capacitor acts as a filter, reducing the harmonics in the input load current. Initially, for an input battery voltage of 330 volts, the duty cycle of boost switch was 0.11, but later when the battery voltage reduced to 150V, using the lookup table, the duty cycle was changed to 0.60. Hence the voltage at the load terminals was maintained constant. Fig. 9. shows primary and Fig. 10. and secondary side voltage waveforms of the transformer during discharging. Fig. 11. shows the gate switching pulse for the boost switch. Fig. 12. and Fig. 13. shows the load voltage and load current through the load when the input is 330 volts. Fig. 14. and Fig. 15. shows the load voltage and gate switching pulse of boost switch when the voltage was reduced to 150 volts.

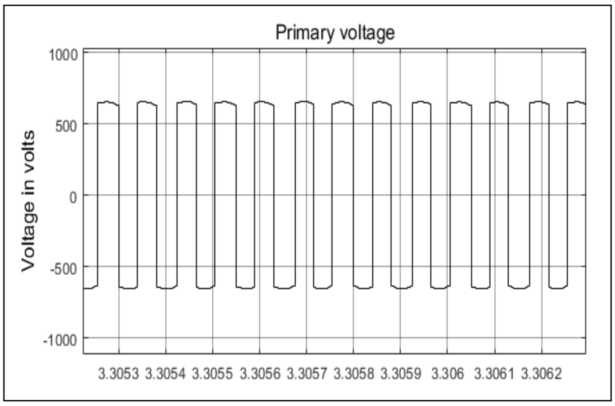

Figure 9: Primary side voltage waveforms; input 330 volts

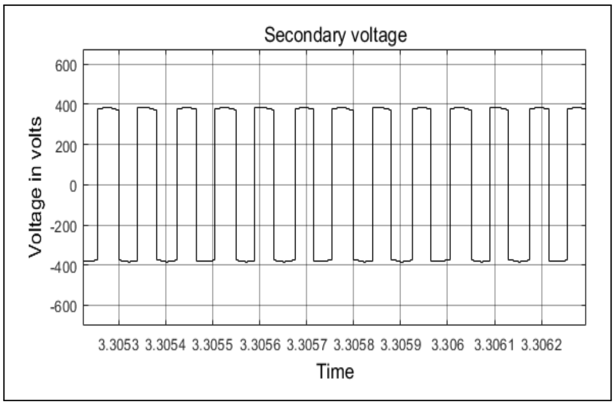

Figure 10: Secondary side voltage waveforms; input 330 volts

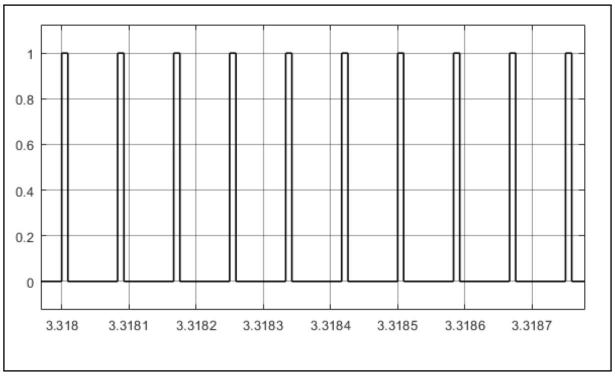

Figure 11: Boost switch gate pulse; input 330 volts

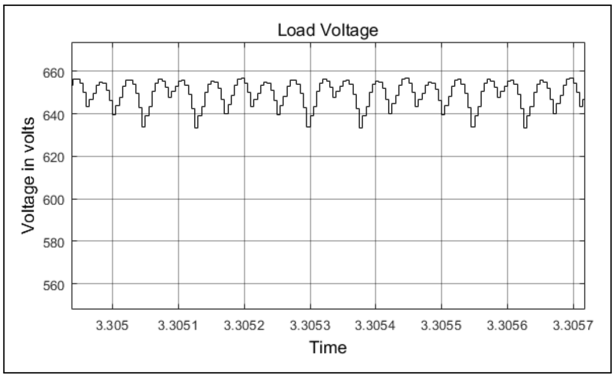

Figure 12: Load voltage; input 330 volts

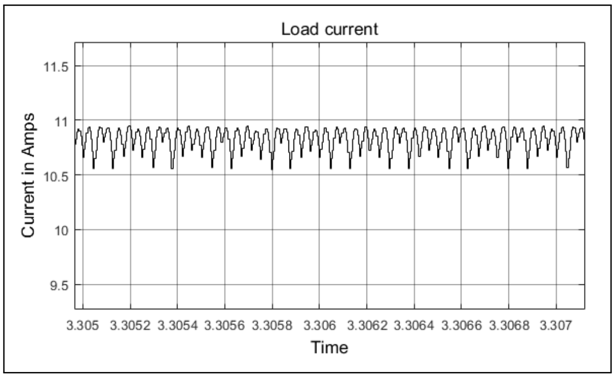

Figure 13: Load current; input 330 volts

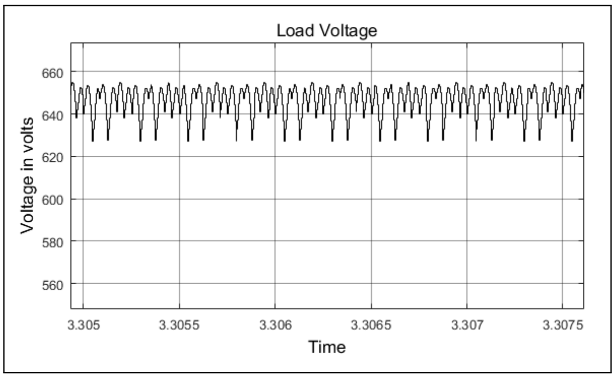

Figure 14: Load voltage; input 150 volts

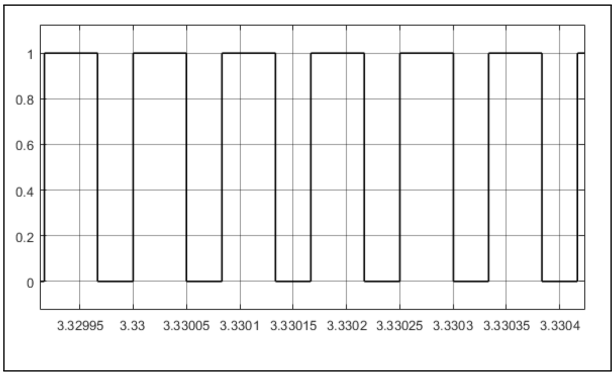

Figure 15: Boost switch gate pulse; input 150 volts

4. Conclusion

In this paper, a bidirectional buck boost DC- DC converter topology with bi-directional power flow control and conversion capability and with electrical isolation between the two sides through a transformer are evaluated for both battery charging and discharging applications. Using duty cycle as a variable, the load voltage was made constant irrespective of the battery voltage. Hence, the overall system saves battery energy by supplying energy back to the grid rather than wasting it as heat.

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