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DESIGN, MODELLING & ANALYSIS OF NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTER WITH COUPLED INDUCTOR FOR INDUSTRIAL APPLICATION

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Abstract: Bidirectional DC-DC Converter (BDC) play an important role, as an interface circuit between the energy sources and the DC link in variety of industrial applications such as Uninterruptible Power Supply (UPS) units, electric vehicle (EV) and so on. Hence, BDC's are gaining popularity in academic research and industrial applications. The converters manage bidirectional power flow between dc sources and the loads. The excess energy is stored in batteries or super capacitors. The disadvantages of non-isolated BDC's are high voltage stress on the switches, more output ripple, low voltage gain ratio and hard switching operation. In order to overcome these issues, a new non-isolated BDC with coupled inductor was proposed. The advantage of this converter are, high efficiency, low output voltage and current ripple, high voltage gain ratio and also provides soft switching operation. The design, modelling, and simulation of non-isolated bidirectional DC-DC converter with coupled inductor method has been carried out in the present work. The present work included a design guideline for selecting output filter parameters, as well as a thorough overview of different modes of operation and the proposed switching scheme. The PWM technique with suitable PI controller was used to generate gate pulses for the proposed Converter. The performance of the proposed topology was observed by simulation in MATLAB-Simulink software tool. The analysis of closed loop operation using PI Controller was also carried out during the work. The simulation results showed the measurement of output voltage, output current, inductor ripple current for both buck and boost modes of operation of the proposed converter for a resistive load. For the input voltage of 120V DC, the current drawn was 1.98A with a step-down voltage of 48 V DC during buck mode of operation. For the input voltage of 48V DC, the current drawn was 0.834A with a step-up voltage of 120V DC during boost mode of operation. The simulation results showed that the efficiency of converter in boost mode and buck mode were 92.6% and 93.1% respectively. The performance of the converter was analysed and the results were discussed.

Keywords: Bidirectional DC-DC Converter (BDC), Zero Voltage Switching (ZVS), Coupled Inductor, MATLAB-Simulink, Pulse Width Modulation (PWM), PI Controller.

I. INTRODUCTION

Bidirectional DC-DC converters (BDC) play an important role, as an interface circuit between the energy sources and the DC link in variety of industrial applications such as Uninterruptible Power Supply (UPS) units [2], electric vehicle (EV) [3], [4], and so on. The BDCs are classified into two categories: "isolated" and "non-isolated". The isolated type is required, if the output and the input do not share the common ground. It is also used during a high voltage gain is needed. Many of the implementation issues such as increased converter weight, footprint, cost, and Electromagnetic interference (EMI) are caused by the presence of a transformer. Therefore, non-isolated BDCs are desirable, if high voltage gain and galvanic isolation are not required. The simpler structure, simple control mechanism and easy operation are some of the main advantages of non-isolated BDCs in comparison with isolated BDCs [5], [6]. In terms of structure and cost, the traditional bidirectional buck–boost converter is one of the best choices among non-isolated topologies. The traditional bidirectional buck–boost converter topology has some drawbacks, such as high-voltage stress on switches, low voltage gain ratio and hard switching operation [7]. By using soft-switching techniques and high switching frequency to the non-isolated BDCs, the total converter volume and size is reduced. Also, the overall efficiency of the converter is increased and the performance of the converter is improved.

II. NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTER

The non-isolated BDC with coupled-inductor is proposed. This converter topology overcomes the limitations of other non-isolated BDC's and operates in both, buck and boost modes in a smooth way. The suggested converter

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provides an efficient and effective performance, compared to other non-isolated BDC's. The soft switching operation is provided by, auxiliary circuit with ZVS condition. Hence, this topology is best suited for various applications such as, EV charging and discharging, UPS systems, industrial circuits, renewable energy sources, battery storage systems and so on. The proposed non-isolated BDC with coupled-inductor is as shown in the Fig. 1. The suggested converter operates in two modes.
(1) Buck mode: it works as a ZVS Buck converter, during switch Sm1 and diode Dm2 are on.
(2) Boost mode: it works as a ZVS Boost converter, during switch Sm2 and diode Dm1 are on.

The soft switching condition of proposed converter is achieved by auxiliary circuit and is comprised of, two auxiliary switches (Sa1, Sa2), two snubber capacitors (Cr1, Cr2), coupled inductors (Lp1, Lp2, Ls) and one diode (D1).

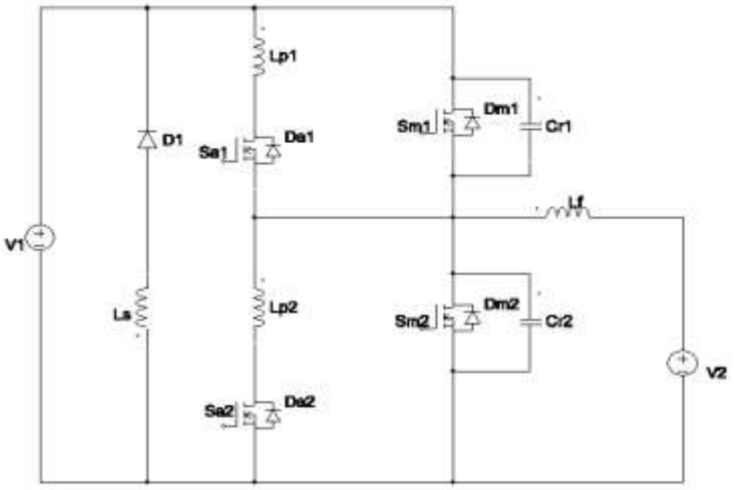
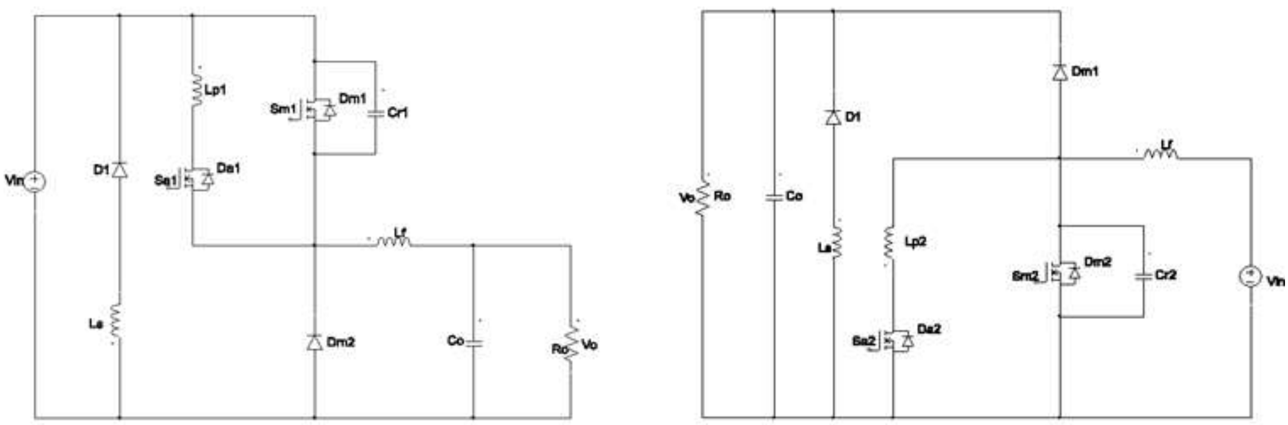


Fig. 1: Schematic Diagram of the proposed non-isolated BDC.

The schematic diagram of circuit of proposed converter in both buck mode and boost mode of operation are shown in Fig. 2 (a) and (b) respectively. In Boost mode operation, Sm2 is the main switch and Sa2 is the auxiliary switch. In addition, Sm1 and Sa1 act as synchronous rectifier (SR) switches. In the Buck mode of operation, Sm1 and Sa1 are the main and auxiliary switches, respectively. In addition, main and auxiliary switches Sm2 and Sa2 act as the SR switches.



(a) (b)

Fig. 2: Schematic Diagram of the proposed converter in (a) buck mode (b) boost mode.

III.BLOCK DIAGRAM

The functional block diagram of proposed non-isolated BDC is shown in Fig. 3. The block diagram consists of DC input power source, proposed non-isolated BDC, PWM Generator and Controller.

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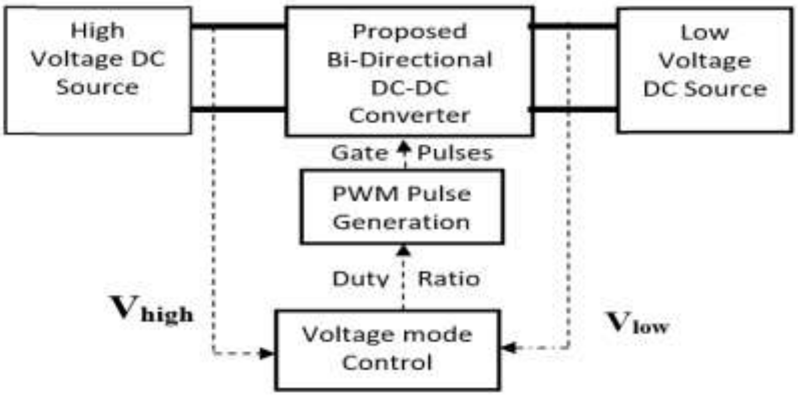

Fig. 3: Block diagram of the proposed non-isolated BDC.

The proposed converter is made to operate in both buck and boost modes. The voltage mode control provides the regulation of load voltages over both buck and boost modes. The duty ratio generated from the controller is provided to PWM pulse generation unit in order to provide corresponding pulses to the proposed BDC.

IV. DESIGN AND SPECIFICATIONS

There are various components used in the design and implementation of converter. The components used in the design of the proposed non-isolated BDC are shown. The main components used for the design of the circuit are as follows.

- Main switch: Sm1, Sm2
- Auxiliary switch: Sa1, Sa2
- Auxiliary Diode: D1
- Coupled Inductors:Lp1, Lp2/Ls
- Turn Ratio: n
- Filter Inductor: Lf
- Snubber Capacitor: Cr1, Cr2
- Filter Capacitor: Cf

A. Specification details of the converter in Buck mode and Boost mode

The proposed non-isolated BDC detailed specifications are tabulated and shown in the tabular column. The following specification details are designed for two converter operations: buck mode and boost mode. The circuit is designed for the following parameters. The specification for both modes of operation is shown in Table 1.

Table 1: Specification details of the converter

Parameter	Boost mode	Buck mode
Input Voltage	120V	48V
Output Voltage	48V	120V
Power rating	100W	100W
Duty cycle	60%	60%
Switching frequency	100kHz	100kHz

B. Design of Filter Parameters

The LC Filter parameters for the converter are calculated as shown.

- For Buck mode

The value of filter inductor Lf during buck mode of operation is calculated using,

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$$L_f = \frac{(1-D_{min})*V_o}{f_s*\Delta I_L} \quad (1)$$

$L_f \geq$ 288uH

L_f = 300uH is selected.

$$\Delta I_L = 20\% * I_{Lf} \quad (2)$$

Dmin is the minimum duty cycle of the converter for operation in buck mode.
The value of filter capacitor Cf during buck mode of operation is calculated using,

$$C_f = \frac{\Delta I_L}{8 f_s*\Delta V_C} \quad (3)$$

$C_f \geq$ 63uF

C_f = 68uF is selected.

$$\Delta V_C = 2 * \Delta V_o \quad (4)$$

Typically, ΔV_o is considered as ±0.2V in the designing.
The load resistor RL for operation in buck mode is calculated as,

$$R_L = \frac{Vo}{Io} \quad (5)$$

R_L = 23.04 Ω

The designed parameter values for buck mode of operation are shown in Table 2.

Table 2: Designed values for buck mode

Parameter	Values
Filter Inductor Lf	300µH
Filter Capacitor Cf	68µF
Load Resistor RL	23 Ω

- For Boost mode

The value of filter inductor Lf during boost mode of operation is calculated using,

$$L_f = \frac{D*V_{in}}{f_s*\Delta I_L} \quad (6)$$

$L_f \geq$ 316.8uH

L_f = 330uH is selected.

The value of filter capacitor Cf during boost mode of operation is calculated using,

$$C_f = \frac{I_{o,max}*D_{max}}{f_s*\Delta V_o} \quad (7)$$

$C_f \geq$ 3.125uF

C_f = 3.3uF is selected.

Dmax is the maximum duty cycle of the converter in boost mode of operation.
The load resistor RL for operation in boost mode is calculated using,

$$R_L = \frac{Vo}{Io} \quad (8)$$

R_L = 144 Ω

The designed parameter values for boost mode of operation are shown in Table 3.

Table 3: Designed values for boost mode

Parameter	Values
Filter Inductor Lf	330µH
Filter Capacitor Cf	3.3µF
Load Resistor RL	144Ω

V. MODELLING AND ANALYSIS

The selected converter topology is simulated using MATLAB-Simulink® environment. Simulink® is a block diagram environment for multiple domain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems..

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The simulation circuit of the proposed non-isolated BDC in boost mode of operation is as shown in the Fig. 4. The input voltage to the boost converter circuit is, 48V DC for the switching frequency of 100 kHz, to obtain a constant output voltage of 120V DC.

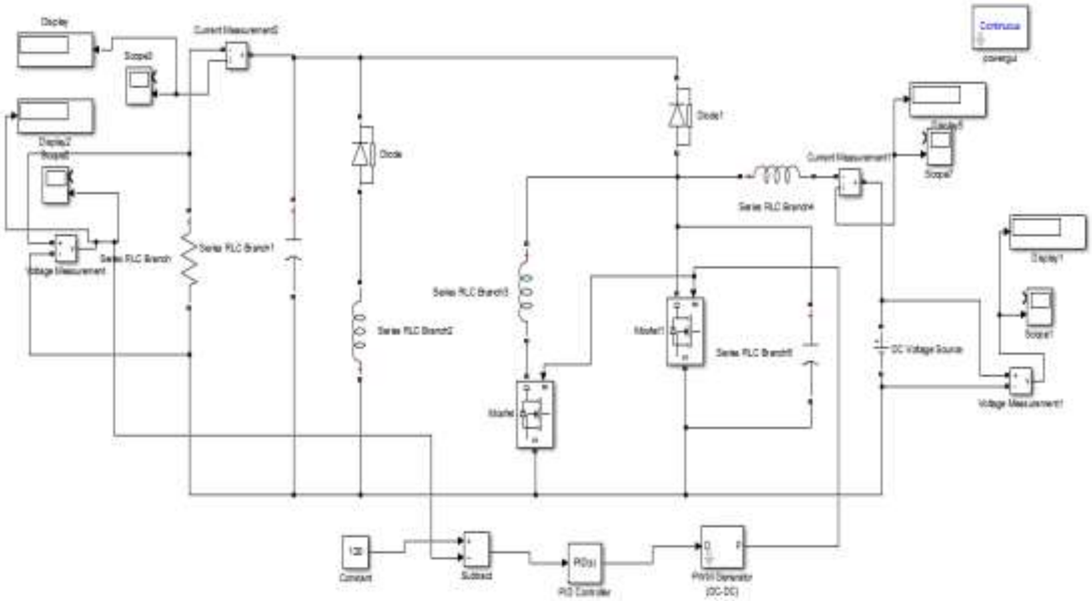

Fig. 4: Model of proposed converter in boost mode.

The model of non-isolated BDC for buck mode of operation is illustrated in Fig 5. Closed loop controller includes comparator, triangular waveform to generate PWM pulses. Closed loop is chosen for proposed converter to regulate and stabilize the constant output voltage.

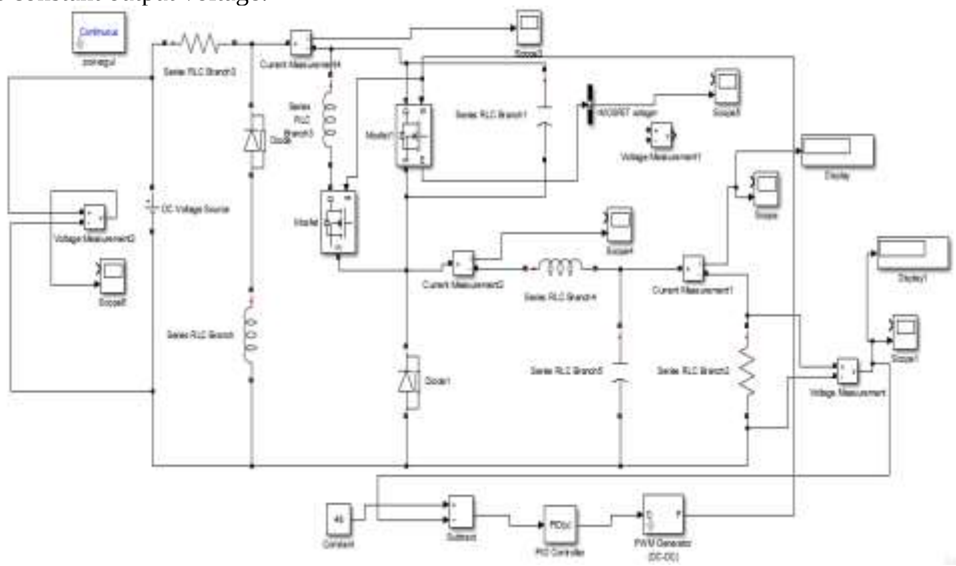

Fig 5: Model of proposed converter in buck mode.

The closed loop simulation model of the proposed non-isolated BDC with buck voltage at input and boost voltage at output is as shown in the Fig. 6. In the Fig. 6, a 12 V DC Voltage is provided at the input side and 108 V DC Voltage is fed at the output side. Thus, there is a bidirectional flow of power between the input to the load and vice-versa.

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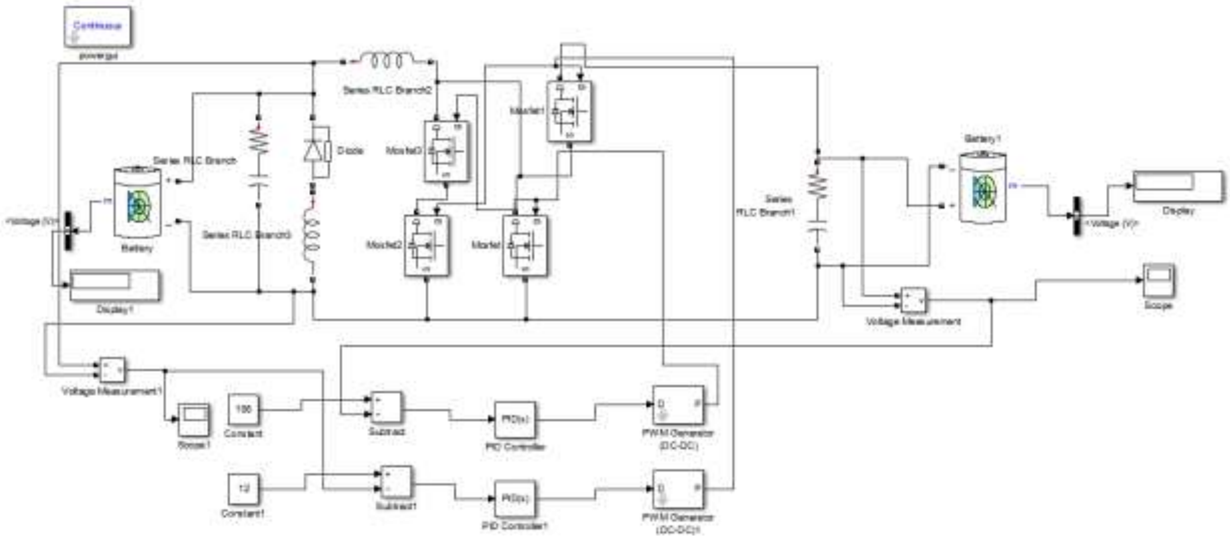

Fig. 6: Model of Bidirectional Buck-Boost dc-dc converter.

VI. SIMULATION RESULTS

The simulation results of converter for boost mode and buck mode of the BDC circuit are shown. The results of overall efficiency and performance of the converter is analysed.

A. Boost mode Simulation Results

The simulation results of closed loop converter in boost mode operation are shown. The input voltage is 48V DC and input current is 2.25A is obtained in boost mode operation of the converter. The output voltage and output current waveform for operation in boost mode is as shown in the Fig. 7 (a). For an input voltage of 48 V DC, the output voltage obtained was around 120 V DC. For an input current of 2.25A, the output current obtained was around 0.834 A. The output voltage ripple was found to be 1.33% and there was a 1.11% of ripple in the output current.

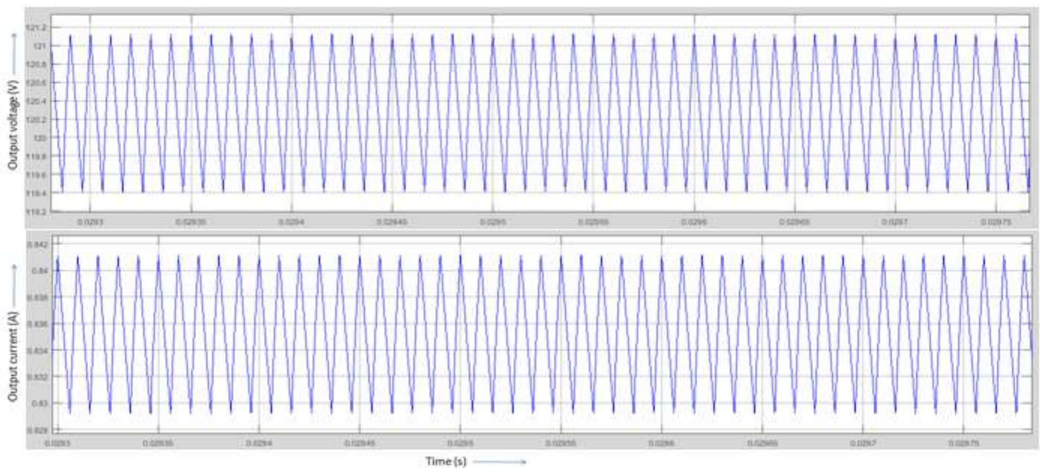

Fig. 7 (a): Output Voltage and Output Current waveform in boost mode.

B. Buck mode Simulation results

The simulation results of closed loop converter in buck mode operation are shown. The input voltage is, 120V DC and an input current of 4.8A is obtained in buck mode operation of the converter. The output voltage and output current waveform for operation in boost mode is as shown in the Fig. 7 (b). For an input voltage of 120 V DC, the output voltage obtained was around 48V DC. For an input current of 0.85A, the output current obtained was around 1.98A. The output voltage ripple and the output current ripple for buck mode, was found to be 1.5% and 0.5% respectively.

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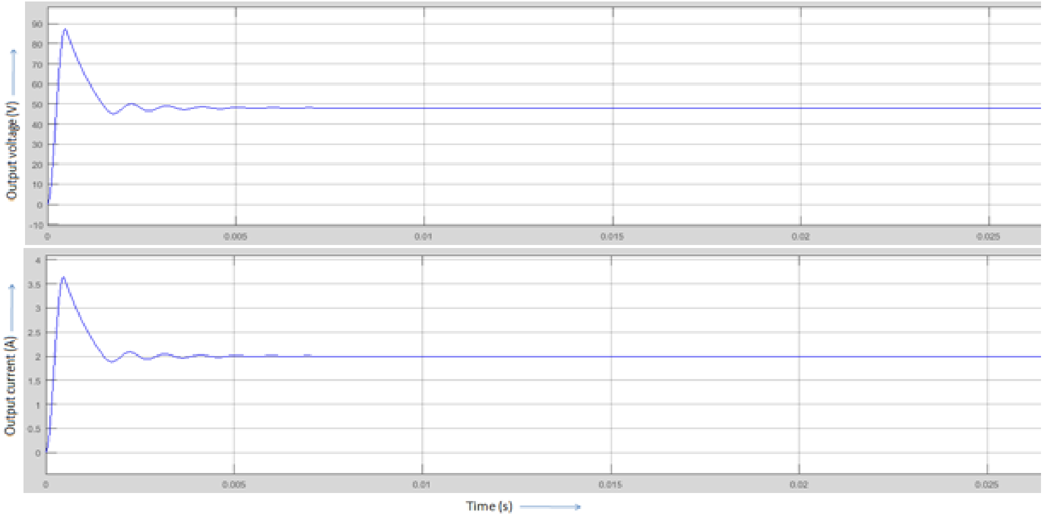

Fig. 7 (b): Output Voltage and Output Current waveform in buck mode.

C. Buck-Boost mode Simulation results

The buck voltage fed at the input side was 12 V DC and the boost voltage at the output side was 108V DC. Hence, the power flow is controlled from the load side to source side and vice-versa. Therefore, there is bidirectional flow of power between the input and output. The voltage waveforms for buck and boost mode is shown in Fig. 7 (c).

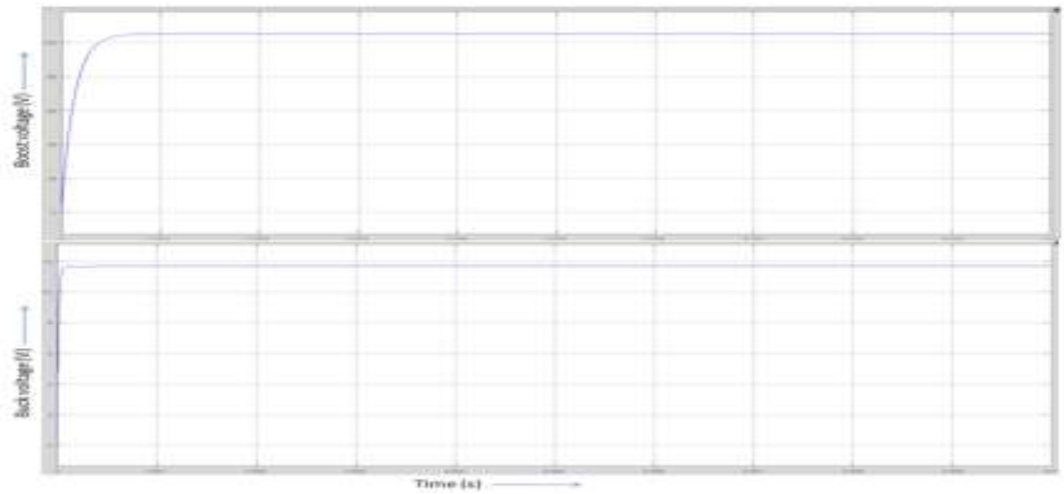

Fig. 7 (c): Buck voltage and Boost voltage waveforms of proposed non-isolated BDC.

The efficiency of the converter in boost mode of operation is calculated and is found to be 92.6%. The efficiency of the converter in buck mode of operation is calculated and is found to be 93.1%.

VII. CONCLUSION

A new non-isolated BDC with coupled inductor method was proposed. The suggested topology has simple structure, easy operation and control. The proposed converter was designed according to the design specifications and the values were obtained. The circuits were simulated using the MATLAB-Simulink software tool. The simulation was carried out for buck and boost modes of operation. A suitable PI controller was implemented for the smooth operation of the circuits. The following conclusions were drawn from the simulation experiments.

- The simulation results were obtained for both buck and boost modes and the output waveforms were shown.
- The output voltage and output current ripple for buck mode and boost mode were low and found to less than 1.5%.
- The efficiency for both buck mode and boost mode were calculated and found to be 93.1% and 92.6% respectively.
- The performance analysis of the converter was found to be satisfied for the required specifications of industrial applications.

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