Wide Conversion Ratio Bidirectional DC-DC Converter for DC Microgrid Applications

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Abstract - *A Bidirectional converter is an essential part of applications where energy storage devices are used. A new transformerless bidirectional buck-boost converter is designed. It has a simple circuit structure, low component count, low voltage stress on the power transistors and a wide voltage gain range. This makes it applicable in the energy storage charge/discharge systems, such as the electric vehicles (EV), microgrids and nanogrids with energy storage units and uninterruptible power supplies. In addition, synchronous rectification between the complementary transistors are used to improve the converter efficiency. In a DC Microgrid system, the excessive energy from renewable energy resources will transfer to the batteries as DC load power demand by the bidirectional DC-DC converter. On the contrary, if the renewable energy resources cannot fully supply the load demand, then the bidirectional DC-DC converter will provide the energy from batteries to DC-load. Supercapacitors are used as source for fast energy transfer in DC Microgrid due to it's ability to store large amount of charge in short period. Steady state analysis of Bidirectional converter is described in detail and simulation result is done in MATLAB/SIMULINK R2017a environment.*

***Key Words*: DC Microgrid, Supercapacitor, Bidirectional converter, Zero Voltage Switching, Energy Storage Unit.**

1. INTRODUCTION

In recent years, due to the shortage of fossil fuels and serious environment problems, much effort has been focused on the development of environmental friendly distributed generation (DG) technologies. In a distributed electric power system, an independent power generation system or large-scale power system in parallel is a trend. Compared to the centralized power system that needs to fulfil different load requirements from different areas, a more reliable and economic DC micro-grid system is better. This requires integration of energy storage units (ESUs) to smoothen the fluctuations in power generation by maintaining the balance between renewable power generation and consumption. In a DC micro-grid system, the excessive energy from renewable energy resources will transfer to the batteries as DC-load power demand by the bidirectional DC-DC converter. On the contrary, if the renewable energy resources cannot fully supply the load demand, then the bidirectional DC-DC converter will provide the energy from batteries to DC-load. Instability in DC microgrid can happen due to various reasons such as dynamic variation of generation and load, changes in system operating conditions, variation in system component values and control parameters. An energy storage unit is employed to compensate the output power fluctuations of renewable energy resources. The renewable sourcesbidirectional converter are connected to the DC bus of the Microgrid via unidirectional power electronic converters, while the ESU is decoupled from the dc bus by a bidirectional dc-dc converter. This bidirectional DC-DC converter allows the ESU to absorb the excessive energy when the power generation exceeds the demand, and release energy when the demand exceeds generation. Additionally, the EV powertrain is another version of microgrids, where the bidirectional dc-dc converter pushes power from the ESU to the dc-link of the three-phase inverter in the motoring mode, and absorbs power from the dc-link back to the ESU in the regenerative braking. The converter consists of minimum number of components and Zero Voltage Switching(ZVS) is attained which reduces switching loss during turn on and turn off. Hence, maximum efficiency is obtained. Here, SCs are used for storing excessive energy from renewable energy resources which can be used when renewable energy resources cannot fully supply load demand.

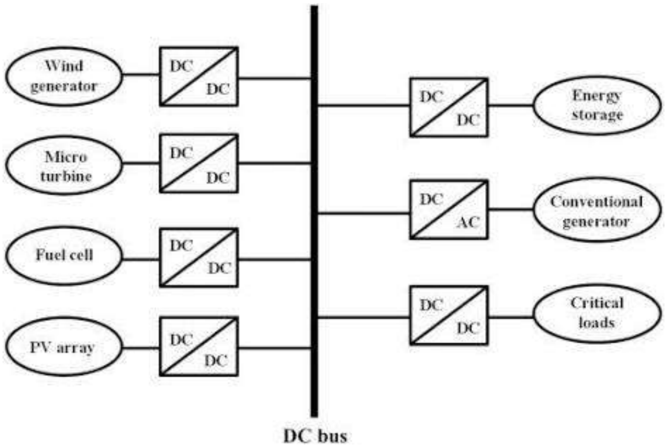


Figure -1: Architecture of DC Microgrid

2. TOPOLOGY OF CONVERTER

2.1 Bidirectional Converter

Instability in DC microgrid can happen due to various reasons such as dynamic variation of generation and load, changes in system operating conditions, variation in system component values and control parameters.This bidirectional dc-dc converter allows the ESU to absorb the excessive energy when the power generation exceeds the demand, and release energy when the demand exceeds generation. Zero voltage switching helps in minimising losses. Another advantage with soft switching is that these waveforms minimise electromagnetic interference(EMI. Its main power stage contains three power switch (S), two inductors (L1 and L2), four capacitors(C_1,C_2,$C_3$and C_4) and one resistive load R. Power switch S is the only part that needs to be controlled. Here, the currents through L_1 and L_2 are defined as iL_1 and iL_2 respectively. The voltages across C_1,C_2,C_3 and C_4 are defined as VC_1,VC_2,VC_3 and VC_4 respectively. The output is connected to the Figure 2 shows a circuit of typical arrangement bidirectional DC-DC converter.

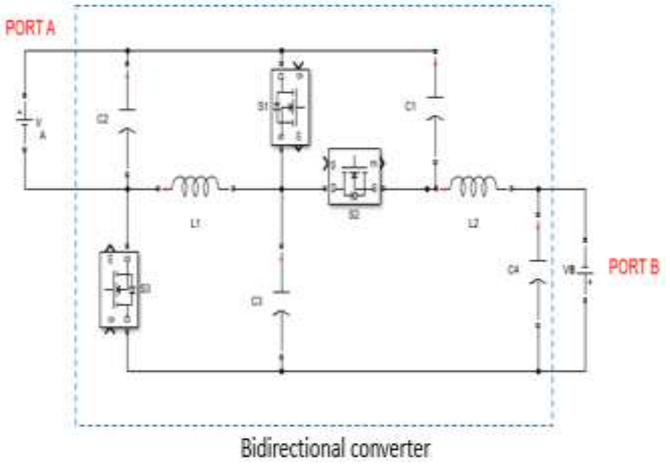


Figure -2: Bidirectional DC-DC Converter

2.2 Boost Mode of Operation

- Mode 1, In this switching state, Q1 is turned on and Q_2 and Q_3 are turned off. The period of this state is D1T, where T is the periodic switching time, and D1 is the duty cycle of Q_1. There is zero-voltage-switching (ZVS) during turn-on and turn-off for Q_2 and Q_3, which enhances the converter efficiency. The capacitors C_1 and C_3 discharges and L1 and L2 charges. Figure 3 shows the equivalent circuit diagram of the converter and current paths for this mode. The theoretical waveforms of the converter in Buck Mode is shown in Figure 5 .

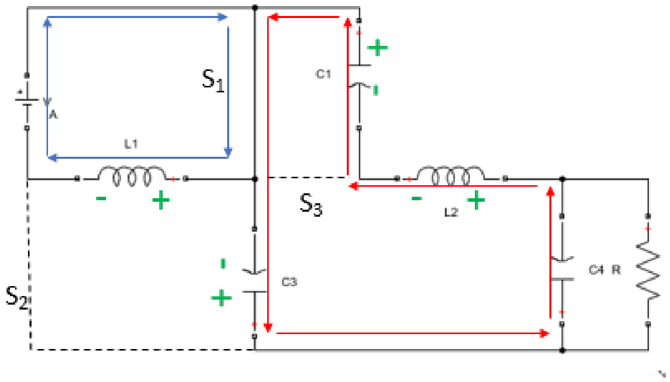


Figure -3: Operating circuit of Mode 1

- Mode 2, In this switching state, Q_1 is turned off, Q_2 and Q_3 conduct current in the reverse direction. The period of this state is D2T = D3T= (1-D1)T, where D2T and D3T are the duty cycle values of Q_2 and Q_3 respectively. The capacitors C_1 and C_3 discharges and L_1 and L_2 charges. In this operation, Q_2 and Q_3 are the main power switches and Q_1 is a synchronous rectifier. Figure 4 shows the equivalent circuit diagram of the converter and current paths for this mode.

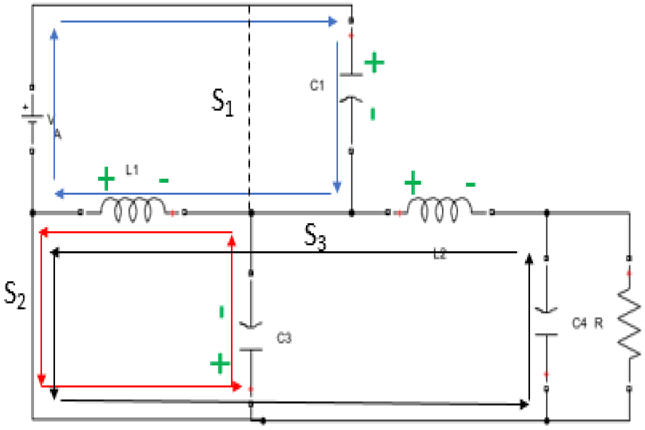


Figure -4: Operating circuit of Mode 2

2.3 Buck Mode of Operation

- Mode 1 In this switching state, Q_1 is turned on and Q_2 and Q_3 are turned off. The period of this stateis D_1T, where T is the periodic switching time and D_1 is the duty cycle of Q_1. There is zero-voltageswitching (ZVS) during turn-on and turn-off for Q_2 and Q_3, which enhances the converter efficiency. The capacitors C_1 and C_3 charges and L_1 and L_2 discharges. Figure 3.4(a) shows the equivalent circuit diagram of the converter and current paths. The theoretical waveforms of the converter in Buck Mode is shown in Figure 3.5.

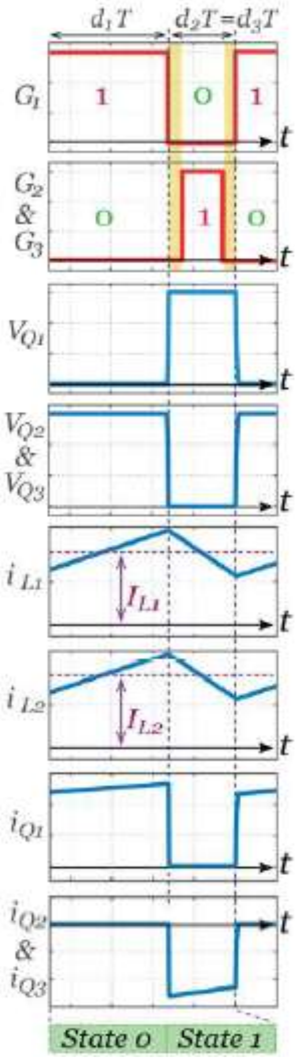


Figure -5: Theoretical Waveform of the Converter in Boost mode

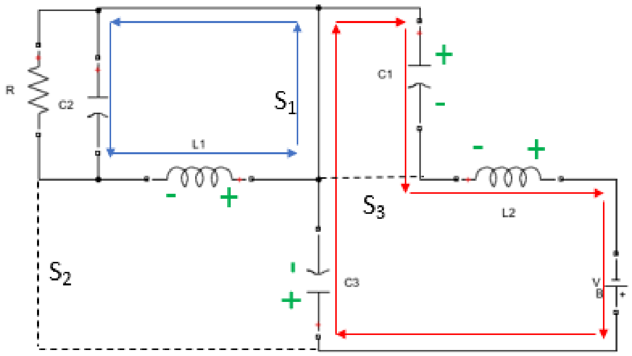


Figure -6: Operating circuit of Mode 1

- Mode 2 In this switching state, Q_1 is turned off, Q_2 and Q_3 conduct current in the reverse direction. The period of this state is $D_2T = D_3T= (1-D_1)T$, where D_2T and D_3T are the duty cycle values of Q_2 and Q_3 respectively. The capacitors C_1 and C_3 charges and L_1 and L_2 discharges. In this operation, Q_2 and Q_3 are the main power switches and Q_1 is a synchronous rectifier. Dead time is employed between the main switches and the synchronous rectifier as shown in Figure 8, to provide ZVS(zero voltage switching) during turn-on and turn-off for Q_1. Figure 7 shows the equivalent circuit diagram of the converter and current paths for this mode.

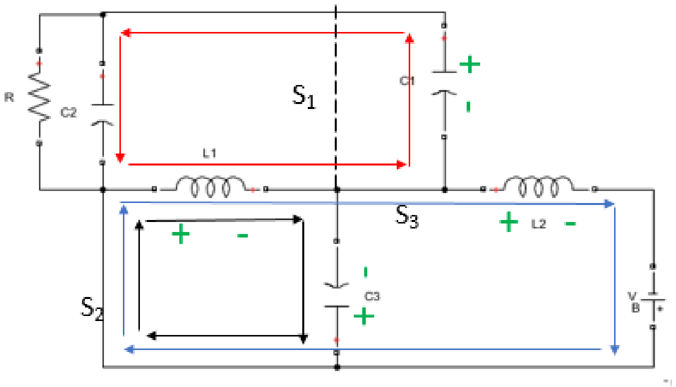


Figure -7: Operating circuit of Mode 2

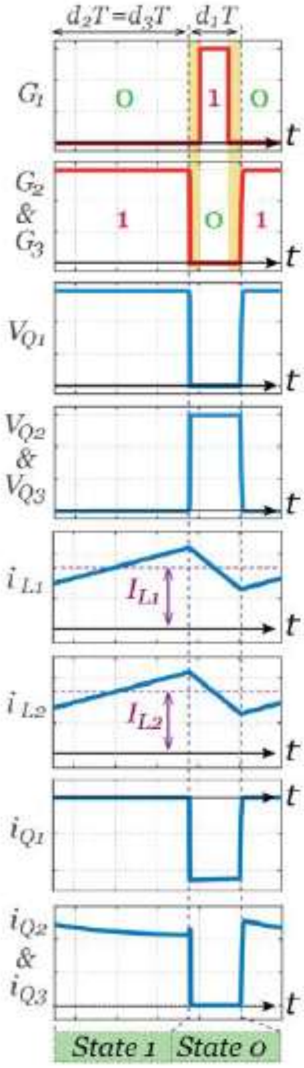


Figure -8: Theoretical Waveform of the Converter in Buck mode

3. DESIGN OF COMPONENTS

The bidirectional Buck and Boost converter is designed at 12V for buck converter and 48V for boost converter. The converter operates at 30kHz and an output power of 100W.

3.1 Output voltage in Buck and Boost Modes

Taking input voltage as 12V and output voltage as 48V for boost converter, the duty ratio is calculated as

$$d_1 = \frac{V_{out}}{2 * V_{in} + V_{out}} = \frac{48}{2 * 12 + 48} = 0.66 \qquad (1)$$

Taking input voltage as 48V and output voltage as 12V for buck converter, the duty ratio is calculated as

$$d_2 = \frac{2 * V_{out}}{V_{in} + 2 * V_{out}} = \frac{2 * 12}{48 + 2 * 12} = 0.33 \qquad (2)$$

3.2 Design Of L_1, L_2, C_1 and C_3

Taking load resistor as 100Ω in boost mode. The voltage across capacitor C_1 is given by

$$V_{C1} = \frac{V_{in}}{1 - d_1} = \frac{12}{1 - 0.66} = 35.29V \qquad (3)$$

The voltage across capacitor C_3 is given by

$$V_{C3} = \frac{V_{in} * d_1}{1 - d_1} = \frac{12 * 0.66}{1 - 0.66} = 23.29V \qquad (4)$$

The current across inductor L_2 is given by

$$I_{L2} = \frac{V_{in} * 2 * d_1}{(1 - d_1) * R_1} = \frac{12 * 2 * 0.66}{(1 - 0.66) * 25} = 1.86A \quad (5)$$

The current across inductor L_1 is given by

$$I_{L1} = \frac{I_{L2} * (1 + d_1)}{(1 - d_1)} = \frac{1.86 * (1 + 0.66)}{(1 - 0.66)} = 9.1A \quad (6)$$

The voltage ripples of capacitor C_1 is given by,

$$\Delta V_{C1} = 1.2\ \%\ of V_{C1} = 1.2\ \%\ of\ 35.29 = 0.42V \quad (7)$$

The value of capacitance C_1 is given by

$$C_1 = \frac{2 * d_1^2 * V_{in}}{\Delta V_{C1} * f_S * (1 - d_1) * R_1} = 97\mu F \qquad (8)$$

The value of capacitor is set at 100 µF.
the voltage ripples of capacitor C_3 is given by

$$\Delta V_{C3} = 1\ \%\ of V_{C3} = 0.25\ \%\ of\ 28 = 0.23V \qquad (9)$$

The value of capacitance C_3 is given

$$C_3 = \frac{2 * d_1^2 * V_{in}}{\Delta V_{C3} * f_S * (1 - d_1) * R_1} = 178\mu F \qquad (10)$$

The value of capacitor is set at 220 µF.
The current ripple of inductors L_1 and L_2 is given

$$\Delta I_{L1} = \Delta I_{L2} = 0.5 * I_{L2} = 0.5 * 1.86 = 0.93A \quad (11)$$

The value of inductor L_1 is given by

$$L_1 = \frac{d_1 * V_{in}}{\Delta I_{L1} * f_S} = \frac{0.66 * 12}{0.93 * 30 * 10^3} = 283\mu H \qquad (12)$$

The value of inductor is set at 300µH.
The value of inductor L_2 is given by

$$L_2 = \frac{d_1 * V_{in}}{\Delta I_{L2} * f_S} = \frac{0.66 * 12}{0.93 * 30 * 10^3} = 283\mu H \qquad (13)$$

The value of inductor is set at 300 µ H.

3.3 Design Of Output Capacitor

In boost mode, let the peak to peak output voltage ripple is 0.003V. The value of output capacitor is given by

$$C_{out} = \frac{\Delta I_{L2}}{\Delta V_{out} * f_S * 8} = \frac{0.93}{0.003 * 30 * 10^3 * 8} = 1294\mu F \qquad (14)$$

The value of capacitor is set at 2200 µF.
In buck mode, let the peak to peak output voltage ripple is 0.001 V. The value of output capacitor is given by

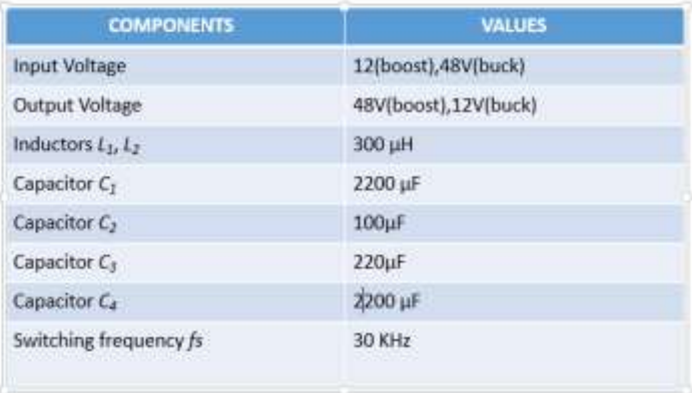
$$C_{out} = \frac{d_2^3 * V_{in}}{4 * f_S * R_B * \Delta V_{out} * (1 - d_2)^2} = 1280\mu F \qquad (15)$$

The value of capacitor is set at 2200 µF.
According to proper design equations the inductors and capacitors designed. By using approximated value of components simulation carried out in MATLAB/SIMULINK R2014a. Prototype is designed in same voltage.

4. SIMULATION RESULTS AND ANALYSIS OF CONVERTER

Simulation parameters for the bidirectional DC-DC converter is given in Table 1. An input voltage Vin of 48V gives an output voltage Vo of 12V in Buck mode and in Boost mode an input voltage Vin of 48V gives an output voltage Vo of 12 V for an output power Po of 100W as shown in figure 9.

Table -1: Simulation Parameters



COMPONENTS	VALUES
Input Voltage	12(boost),48V(buck)
Output Voltage	48V(boost),12V(buck)
Inductors L_1, L_2	300 µH
Capacitor C_1	2200 µF
Capacitor C_2	100µF
Capacitor C_3	220µF
Capacitor C_4	2200 µF
Switching frequency fs	30 KHz

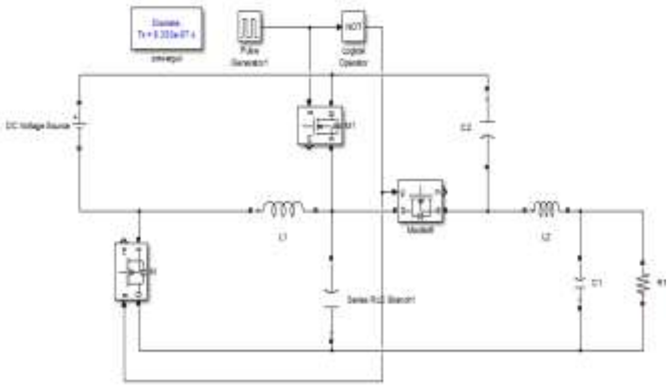


Figure -9: Simulink Model of the bidirectional Converter

4.1 Simulation Results of the Converter in Buck Mode

Figure 10 shows the input voltage and input current of the soft switched BDC in Buck mode of the prototype designed.

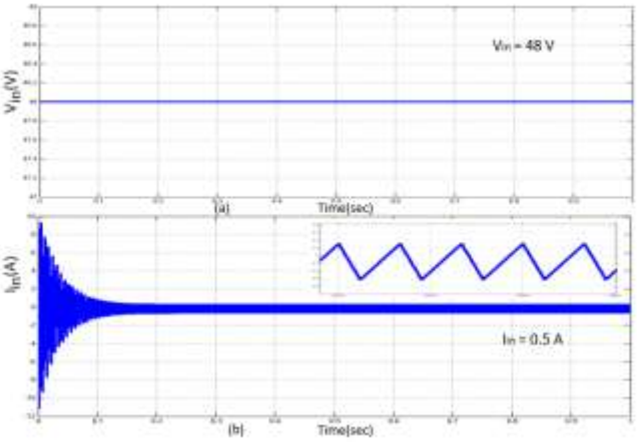


Figure -10: (a)Input Voltage (b) Input Current of Prototype in Buck mode

Figure 11 shows the output voltage and output current of the soft switched BDC in buck mode of the prototype designed. The output voltage is reduced to 12V.

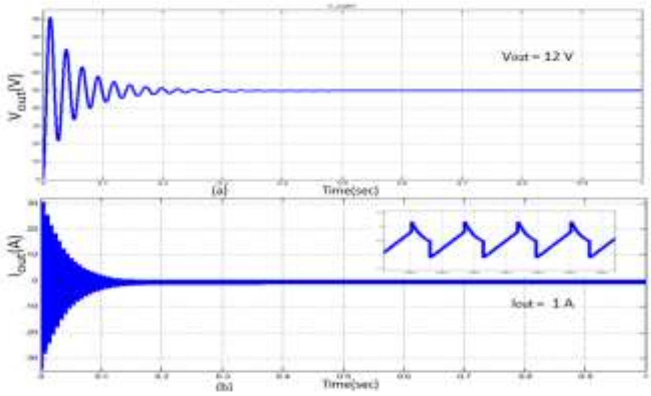


Figure -10: (a) Output Voltage (b) Output Current of Prototype in buck mode

4.2 Simulation Results of the Converter in Boost Mode

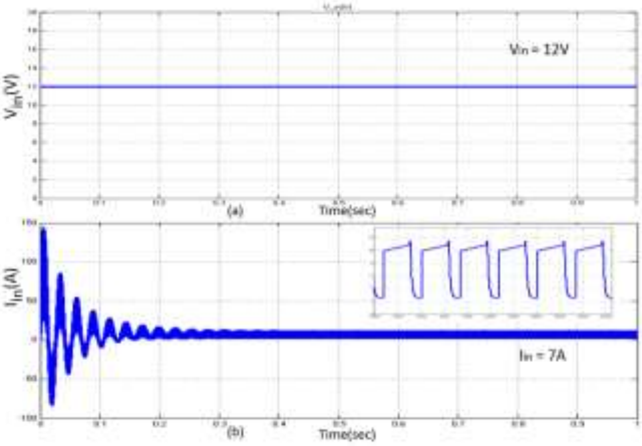


Figure -12: (a)Input Voltage (b) Input Current of Prototype in Boost mode

Figure 12 shows the input voltage and input current of the soft switched BDC in Boost mode of the prototype designed.

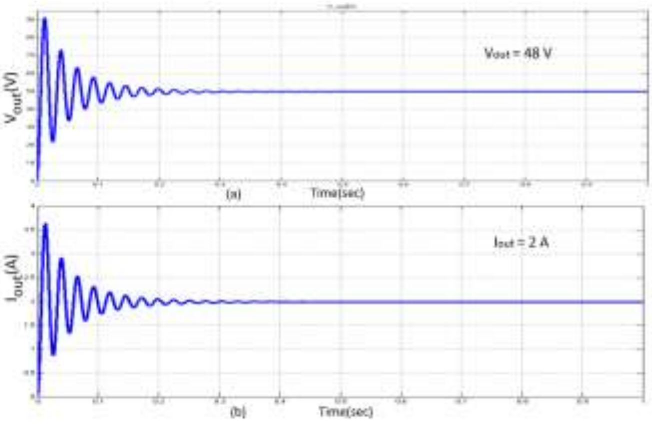


Figure -13: (a)Output Voltage (b) Output Current of Prototype in Boost mode

Figure 13 shows the output voltage and output current of the soft switched BDC in Boost mode of the prototype designed. The output voltage is increased or boosted to a value of about 48V.

4.3 Efficiency Vs Output Power

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. The efficiency is the fraction of the input power delivered to the load. A typical curves for the variation of efficiency as a function of output power is shown in Fig. 15 and 16. The converter efficiency is around 90% for 28.8W output power for R load in boost mode. The converter efficiency is around 85% for 9.6W output power for buck mode. The efficiency is around 89% for 28.8W output power for Rl load. The converter efficiency is around 82% for 9.6W output power for RL load.

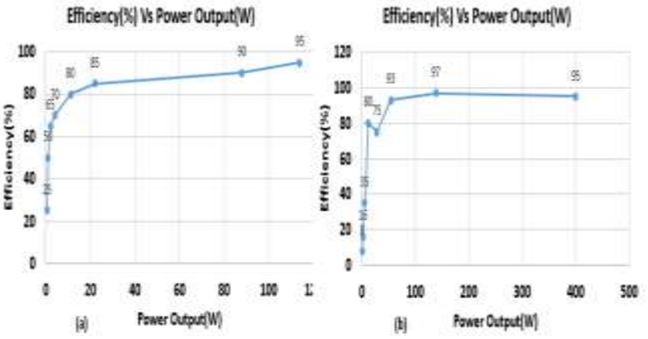


Figure -14: Efficiency Vs Power out (a)Boost (b)Buck

4.4 Gain Vs Duty Ratio curve

The plot of voltage gain as a function of duty ratio is shown in Figure 19. According to this figure, the voltage gain is 2.4 when the duty cycle is equal to 72% in Buck mode and if duty ratio is smaller than 42% the gain reduces. Also, if the voltage gain is 1.4 when the duty cycle is equal to 72% .

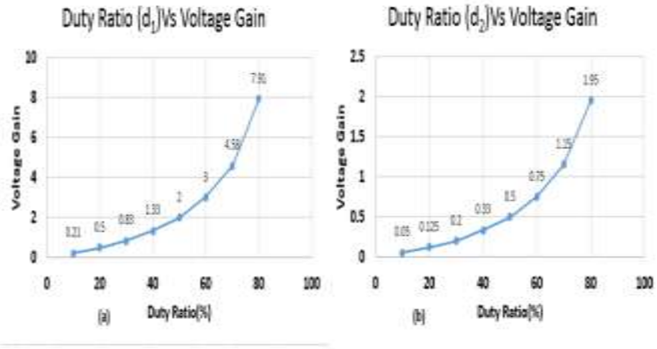


Figure -15: Gain Vs Duty ratio (a)Boost (b)Buck

5. CONCLUSIONS

A dual output voltage DC-DC converter topology is presented in this project. A novel buck-boost converter with only one controlling switch. The current and voltage stress analysis of the switching device available in the converter is carried out to ensure the proper selection of the switching devices. The measured efficiency of the converter in both Buck and Boost modes is 86% and 90% with R load respectively. The efficiency of the proposed buck-boost converter is highest among those converters having the same number of elements. These advantages make component selection for the proposed converter much easier, and it can be used directly in applications needing a negative voltage source.

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