Comparative Analysis of Bidirectional Buck/Boost DC-DC Converter and Interleaved Bidirectional Buck/Boost DC-DC Converter for EV applications

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Abstract.

Electric vehicles are getting massive popularity considering their enhanced performance and inexpensive maintenance. The efficacy of electric vehicles is determined by how well energy repository devices and power electronics converters are interfaced. In the case of Evs, DC-DC converters are crucial. In EVs, Bidirectional converters are employed since power management is vital. Bidirectional converters allow the power flow in both directions. In terms of higher efficiency, current reduction, and voltage ripple, an Interleaved Bidirectional DC-DC converter outperforms a Bidirectional DC-DC converter. This manuscript proposes a comparison of the “Bidirectional Buck/Boost DC-DC converter” with the “Interleaved Bidirectional Buck/Boost DC-DC converter”. Matlab is used to predict the behavior of both converters.

Keywords. Electric Vehicles, Bidirectional converter, Interleaved Bidirectional converter

1. INTRODUCTION

Electric vehicles have gained in popularity over the last decade as a result of more ecologically friendly power sources, minimal maintenance, and the lack of a gasoline supply. The power electronics converter serves as the primary link between the source and the load. Electric vehicles typically feature a “Bidirectional DC-DC converter” in the middle of the “source” and “battery” [1] [2]. In Electric Vehicles, the usage of energy repository devices like Batteries & Supercapacitors is a must. Many Bidirectional DC-DC converters have been proposed for the automotive electrical system, however, the Buck/Boost converter with two switches and one inductor stands out because of its simple circuit and inexpensive cost. Power flow is unidirectional in a traditional Buck/Boost converter, however, power can move in both directions with a “Bidirectional DC-DC converter”. [4]. “Bidirectional DC-DC converters” are adopted mainly to escalate and deescalate voltage levels with power flow in either forward or reverse directions. [2]. To step up the voltage Boost converter is employed and to step down the voltage Buck converter is employed [8]. During regenerative braking, the bidirectional DC-DC converter allows electricity to flow backward into a storage device. Bidirectional converters are beneficial over unidirectional DC-DC converters because of this functionality. Interleaved is a technique employed to reduce the size of the inductor and capacitor and also to excel the converter’s efficiency, & reduction in both voltage & current ripple & switching losses.

2. BIDIRECTIONAL BUCK/BOOST DC-DC CONVERTER

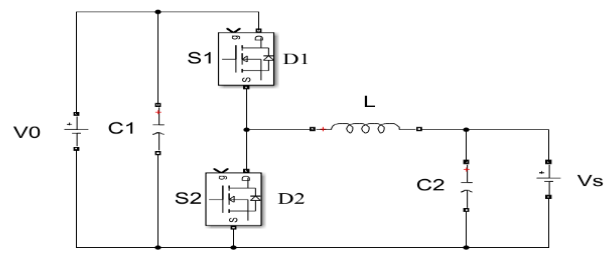

Figure 2.1. Schematic diagram of a Conventional Bidirectional DC-DC converter

A “Bidirectional Buck/Boost DC-DC Converter” comes under a “Non-isolated converter” and this converter consists of two switches, 1 inductor, and 2 capacitors which are shown schematically in Figure 2.1. The converter has 2 operating modes i.e., Forward and Backward. In Forward mode, the electricity flows from the low voltage level such as the battery to the high voltage level side, and in this approach, the converter performs as a “Boost converter” [5][6]. At the time of regenerative braking, the electricity flows back to the low voltage level side to rejuvenate the battery & the converter performs as a “Buck converter”.

2.1 Boost mode

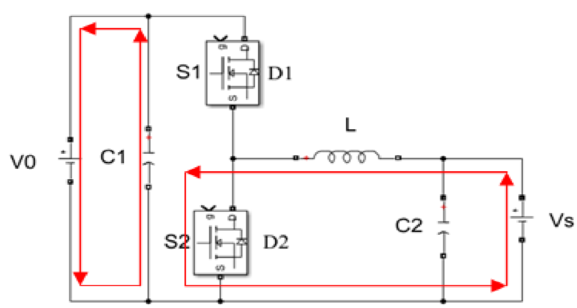

Figure 2.1.1. When S2 is ON

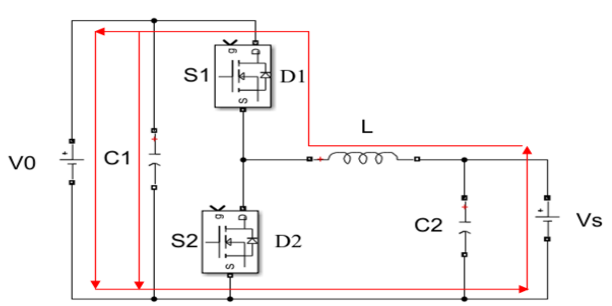

Figure 2.1.2.when D1 is forward biased

Figure 2.1.1 shows how current is flowing when S2 is ON & S1 is OFF. Inductor charges & the current will increase linearly. Figure 2.1.2 is when diode D1 is ON, S1 & S2 are OFF and diode D2 is reverse biased. The energy accumulated in the inductor will start discharging through diode D1. In this mode, the energy from the source and inductor will be fed to the load, thus there will be a step up in voltage level.

2.2 Buck mode

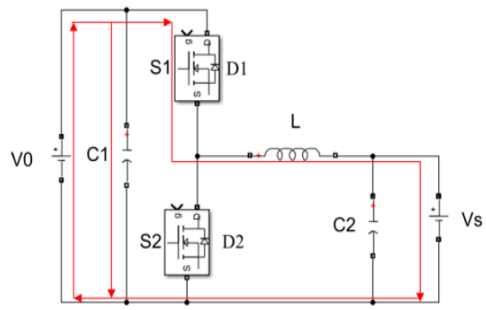

Figure 2.2.1. when S1 is ON

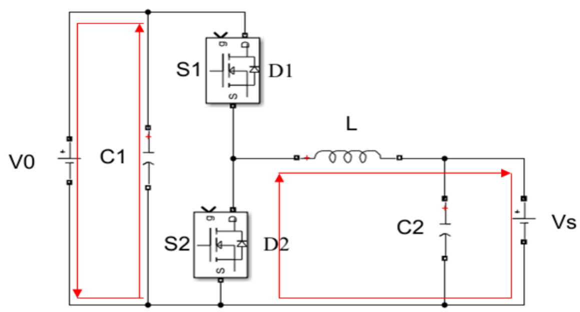

Figure 2.2.2.when D2 is forward biased

Figure 2.2.1 shows how current is flowing when S1 is ON, S2 is OFF & both the diodes D1 & D2 are reverse biased. The energy stored in the inductor will discharge in a negative slope. Figure 2.2.2 shows when diode D2 is ON, D1 is reverse biased & S1 and S2 are OFF. During regenerative braking, this mode of operation is employed to charge the battery.

2.3 Converter Design Calculations

The output voltage for the Bidirectional Buck/Boost converter is obtained by (2.3.1)

$$Vo = \frac{Vs}{(1-D)} \tag{2.3.1}$$

Inductor ripple current & Voltage ripple can be calculated by using (2.3.2) & (2.3.3)

$$\Delta Il = \frac{VsD}{Lf} \tag{2.3.2}$$

$$\Delta Vc = \frac{VsD}{8Lf^2C} \tag{2.3.3}$$

Inductor and Capacitor values can be calculated using (2.3.4) & (2.3.5)

$$L = \frac{VsDR}{2fVo} \tag{2.3.4}$$

$$C = \frac{DVs}{16Lf^2V0} \tag{2.3.5}$$

Where V_0 - output voltage, Vs - input voltage, D - duty ratio, f - switching frequency, L - Inductor, R - equivalent resistance & C - capacitor.

3. INTERLEAVED BIDIRECTIONAL BUCK/BOOST DC-DC CONVERTER

The interleaved approach was introduced to reduce the size of filtering components. An interleaved converter is a parallel arrangement of 2 or more converters having a phase shift of 360°/n [7]. Figure 3.1 depicts the schematic diagram of a 2-phase interleaved bidirectional dc-dc converter. Switches operate at 180°, resulting in 180-degree out-of-phase inductor currents [3]. The sum of inductor currents, which has a slight peak-to-peak variation and a frequency double that of lone inductor currents, is the incoming current to filter capacitor C1 and load. Current splits into parallel pathways, resulting in lower conduction losses with fewer switches. This Interleaved Bidirectional converter will also operate in two modes i.e., Forward & Backward mode. In forward mode, the converter performs as "Boost converter" & in backward mode the converter performs as "Buck converter".

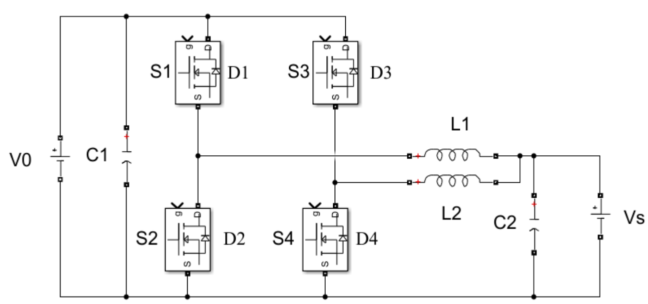

Figure 3.1. Schematic diagram of Interleaved Bidirectional dc-dc converter

3.1 Boost mode of operation (Forward mode)

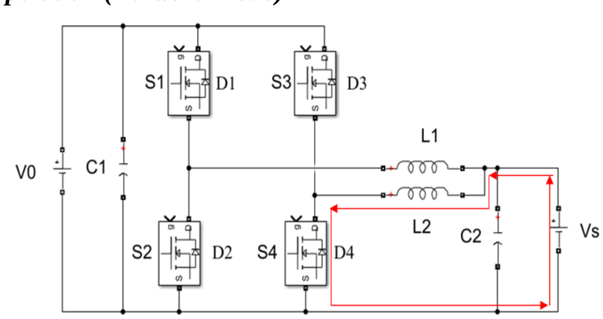

Figure 3.1.1.when S4 is ON

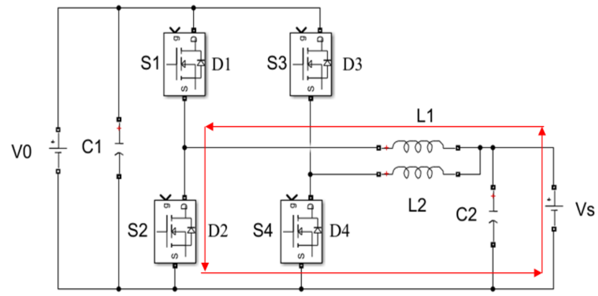

Figure 3.1.2.when S2 is ON

In this mode, S2 & S4 are ON and S1& S3 are OFF. D2 & D4 are reverse biased D1 & D3 are forward biased. The current inductors L1 & L2 increase linearly. To deliver electricity to the load, the battery discharges.

3.2 Buck mode of operation (Backward mode)

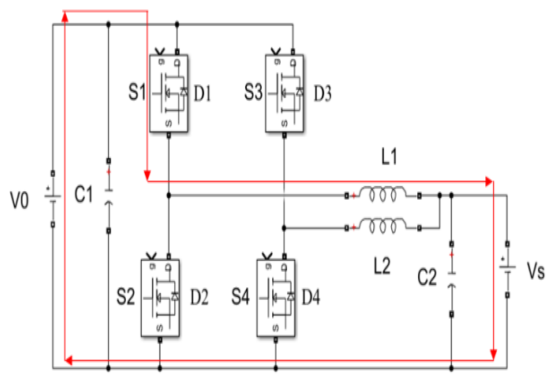

Figure 3.2.1. when S1 is ON

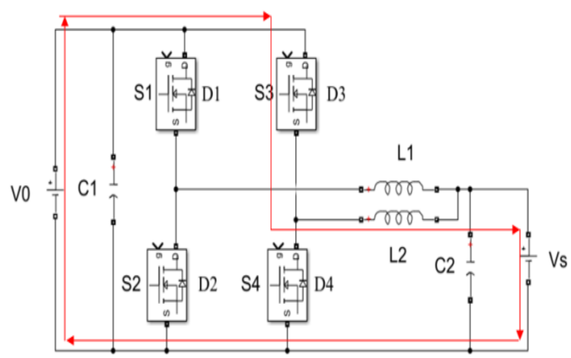

Figure 3.2.2.when S4 is ON

In this mode, S1 and S4 are ON and S2 & S3 are OFF. D1 & D4 are reverse biased and D2 & D3 are forward biased. The power flow is reversed from the load to charge the battery. The inductor current will turn negative as the power flow reverses. The battery is charged from the load during regenerative braking in this mode.

3.3 Converter Design Calculations

The output voltage for Interleaved Bidirectional Buck-Boost converter is obtained by (3.3.1)

$$Vo = \frac{Vs}{(1-D)} \tag{3.3.1}$$

Inductor ripple current & Voltage ripple can be calculated by using (3.3.2) & (3.3.3)

$$\Delta Il = \frac{(Vs-Vo)(1-D)}{L(2f)} \tag{3.3.2}$$

$$\Delta Vc = \frac{VsD}{32Lf^2C} \tag{3.3.3}$$

Inductor and Capacitor values can be calculated using (3.3.4) & (3.3.5)

$$L = \frac{DR}{4f} \tag{3.3.4}$$

$$C = \frac{VsD}{32Lf^2Vo} \tag{3.3.5}$$

Where V_o - output voltage, Vs - the input voltage, D - duty ratio, f - switching frequency, L - Inductor, R - equivalent resistance, and C - capacitor.

4. SIMULATION MODEL AND SIMULATION RESULT OF BIDIRECTIONAL BUCK/BOOST DC-DC CONVERTER

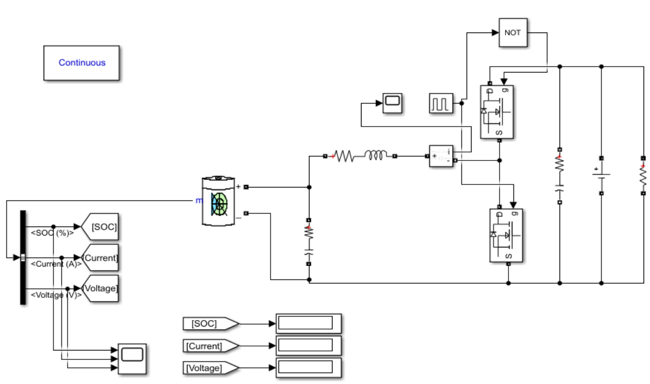

Figure 4.1.Simulation model of Bidirectional converter

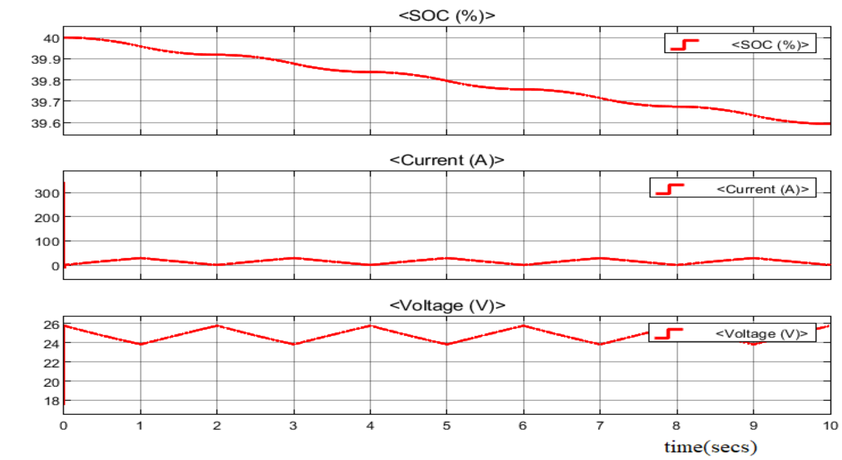

Figure 4.1.2.Simulation results of discharging mode
With SOC – 39.59%, Current – 3.527e-5A, Voltage – 25.76V

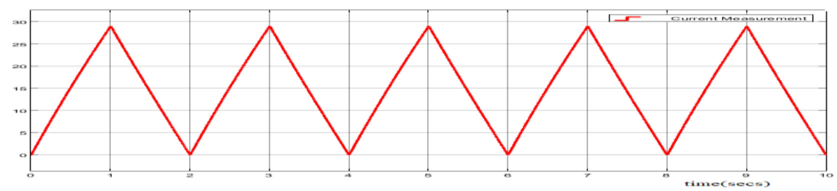

Figure 4.1.3. Inductor current ripple of L (Boost mode)

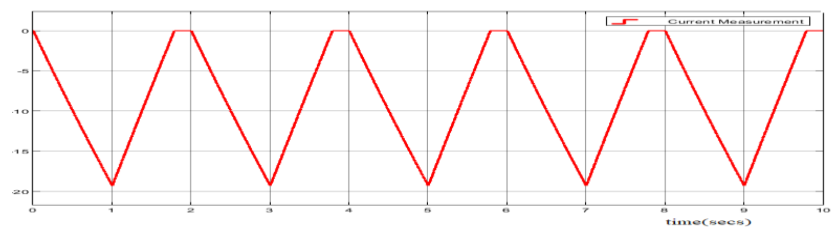

Figure 4.1.4. Inductor current ripple of L (Buck mode)

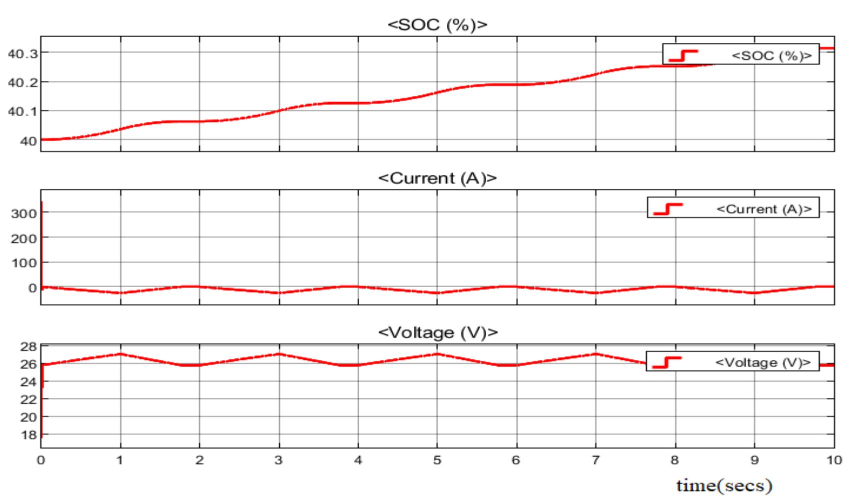

Figure 4.1.5.Simulation results of charging mode
With SOC – 40.31%, Current – 3.542e-5A, Voltage – 25.77V

5. SIMULATION MODEL AND SIMULATION RESULTS OF INTERLEAVED BIDIRECTIONAL BUCK/BOOST DC-DC CONVERTER

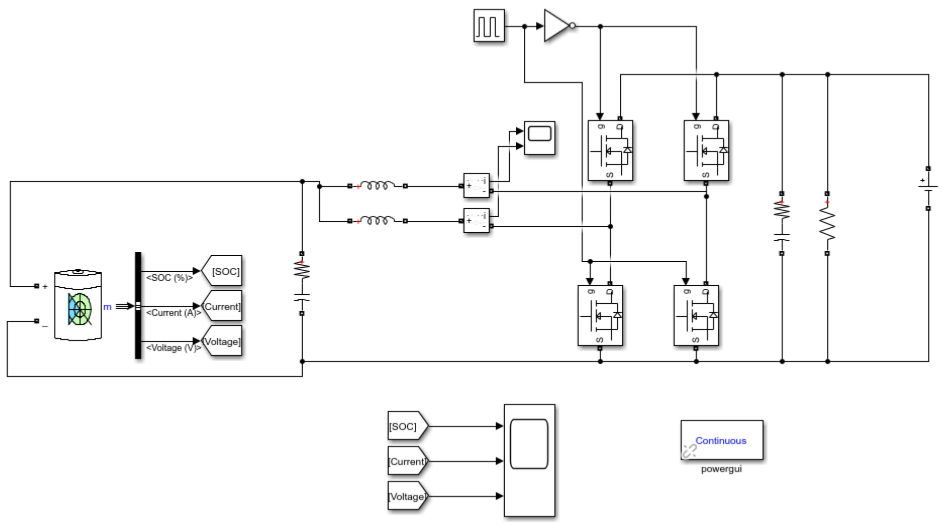

Figure 5.1.Simulation model of Interleaved Bidirectional converter

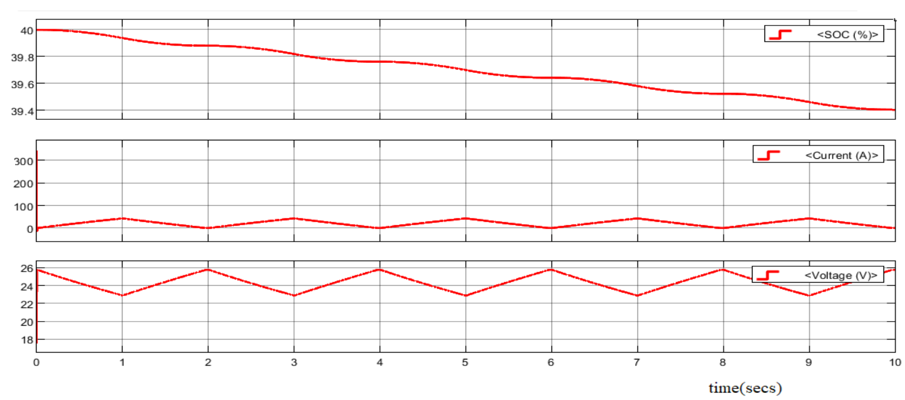

Figure 5.1.2. Simulation results of discharging mode
With SOC – 39.4%, Current – 7.046e-5A, Voltage – 25.76V

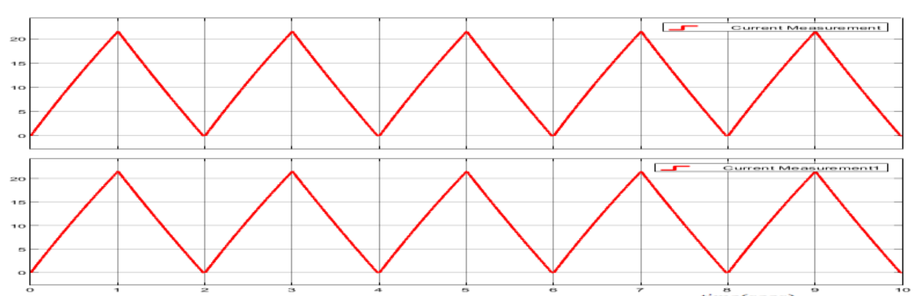

Figure 5.1.3. Inductor current ripple of L1 & L2 (Boost mode)

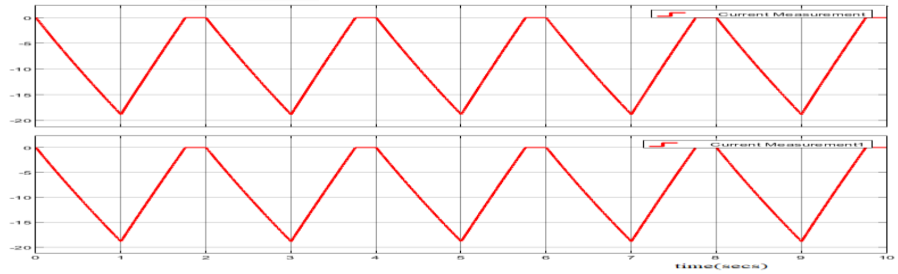

Figure 5.1.4. Inductor current ripple of L1 & L2 (Buck mode)

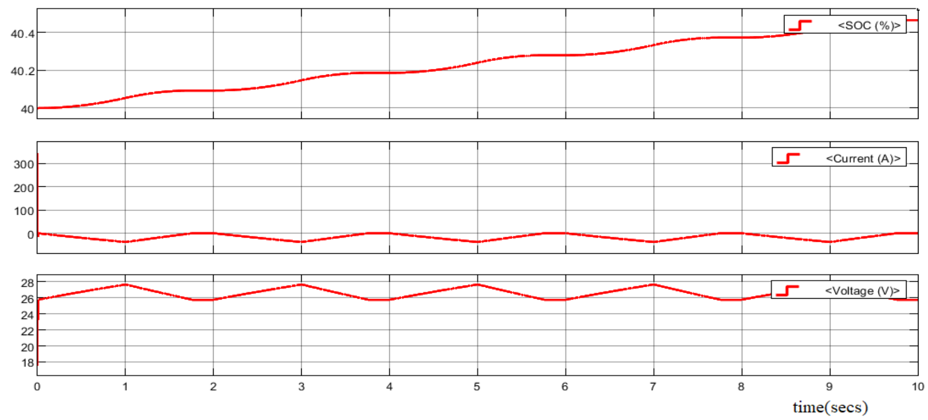

Figure 5.1.5. Simulation results of charging mode
With SOC – 40.37%, Current – 7.059e-5A, Voltage – 25.77V

5. COMPARISON BETWEEN BIDIRECTIONAL AND INTERLEAVED CONVERTER

Parameters	Bidirectional Buck-Boost	Interleaved Bidirectional Buck-Boost
Input Voltage	24V	24V
No of switches	2	4
Inductor	1	2
Voltage stress	48.02V	48V
Current stress	25.2	18.8
Current Ripple	9.65	9.35

Table 6.1.Comparison table of Bidirectional and Interleaved Bidirectional DC-DC converter

7. CONCLUSION

The comparison of a “Bidirectional Buck/Boost converter” and an “Interleaved Bidirectional Buck/Boost converter” is presented in this manuscript. Through mathematical analysis and simulation results, these two converters are analyzed. The voltage ripple and current ripple are reduced by using interleaved technique thus increasing efficiency & switching losses are also reduced, whereas in bidirectional dc/dc converter voltage ripple & current ripple are more. By using interleaved technique current and voltage stresses are also reduced. The “Interleaved Bidirectional DC-DC Converter” is highly suitable for an EV application, as per simulated results.

8. REFERENCES

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