An Improved Bidirectional dc/dc Converter with Split Battery Configuration for Electric Vehicle Battery Charging/Discharging

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***Abstract*—A bidirectional dc/dc on-board chargers for EV battery charging/discharging application provides a better solution of V2G and G2V compatibility. Isolated converter prefer to deal with high power density at wide load range which is useful in EV application. The bidirectional converter performs the step-up and step-down operation at zero voltage switching for all power switches in both directions. Low voltage or battery side converter is chosen as current source converter to limit short circuit current and effective current rating of the converter. The gain of the converter is offered by input boost converter along with transformer. Additional gain is provided by end side converter with voltage double to synchronize voltage with dc grid or high voltage dc During step down mode, The converter allows a low charging current to charge the batteries. To increase charging current of the battery, the voltage has to reduced with two battery system. During charging of batteries, the split of is done to achieve high charging current. The commutation of switches is achieved at ZVS as soft-switching without snubber circuitry and the voltage across switched clamped naturally. The proposed topology is simulated using MATLAB/Simulink for a 350W battery system.**

***Index Terms*—bi-directional dc/dc converter, EV battery charging, isolated converter, soft switching,split battery.**

I. Introduction

Environment pollution and global warming are major concern of the world. According to the latest report on global warming has reported that previous 40 years has been warmer than the 20th-century average. 2016 has been the hottest year on earth. The significant rise in temperature of the earth is caused by greenhouse gases e.g. CO_2, Gasoline, gases produce after burning the fuel. Since the traffic of vehicles emits gases. As a solution for the environmental and economic problems of the society is provided by the EV's and HEV's. The government, researchers, industries are also gaining interest in this field [1]. The charging of EV batteries are classified into unidirectional and bidirectional categories [2]- [3] with onboard and off-board installation for various level of AC and DC charging [4].

The nonisolated converter has lower magnetic and less bulkiness in their installation due to the absence of transformer. but, they have to deal with low power density and reliability concern. Thus, the isolated configuration is preferred [5].

The dc/dc converter with soft switching offers high efficiency. Bidirectional dc/dc converter is useful for vehicle-to-grid (V2G) and grid-to-vehicle (G2V) due to the abilityof power flow in both direction as Fig. 1. To achieve soft switching in the bidirectional converter, the voltage at midpoint should be equal for proper voltage gain and energy transfer from low voltage to high voltage side and vice-versa. But, during soft switching, it is difficult to charge the battery with higher charging current due to the same voltage level at midpoint. The split of battery possible for grid-to-vehicle (G2V) mode of operation when the battery of vehicle split in two equal voltage part by using relay or breaker circuit configuration. In this paper, a half bridge bidirectional isolated

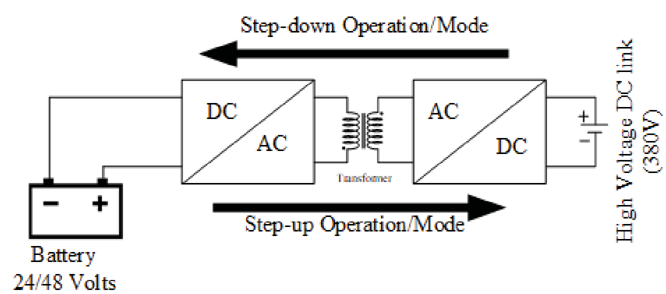

Fig. 1. General block diagram of proposed bi-directional dc/dc converter

dc/dc converter with split battery configuration is presented. Front-end low voltage side has the battery with a boost converter. This boost converter steps up the voltage by twice and fed to the isolated transformer by a dc filter capacitor. This filter capacitor works as dc filter and also represented as a resonant capacitor to offer a path for resonant current during resonance to achieve soft switching. The additional gain in step-up mode is provided by voltage doubler capacitors at high voltage end.

Section II contains operation and analysis of bidirectional dc/dc converter in the step-up and step-down mode of operation. In section III, Design of the converter is mentioned.

Section IV, a detailed simulation result and discussion about the result is done and section V is will conclude the work.

II. Operation and Analysis of Converter

The proposed improved bidirectional dc/dc converter with split battery configuration for electric vehicle battery charging and discharging is shown in Fig. 2.

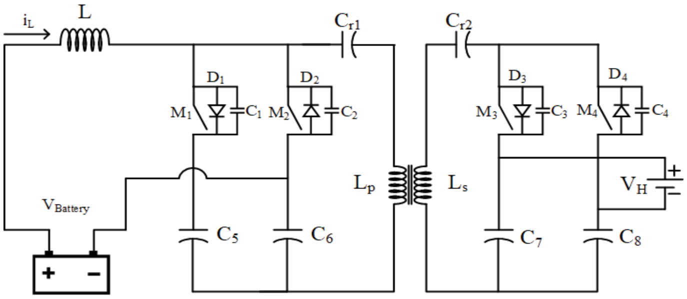

Fig. 2. Proposed isolated bi-directional dc/dc converter

During Step up mode, the two batteries are connected in series to realize the low voltage side. The Batteries connected in series assumed to be identical. The front end boost converter step-up voltage and applies to transformer's input for power transfer to end converter. During step-up mode the switch M_1, M_2 are operated at high frequency. The different mode of the operation is explained in this section. The switch M_3 and M_4 remain turned off for entire step-up process.

During step down mode, the high voltage is divided by voltage divider and applied to the transformer for power transfer to the low voltage side. The low voltage side step-down converter further step down the voltage and applied to the battery for charging. The batteries connected in series are transferred to the parallel connection by relay and circuit breaker operation as shown in Fig. 3. The parallel connection of batteries improves the Ah capacity of the battery at the same voltage. Since two batteries are connected in parallel equivalent voltage is half of the series connection. The reduced batteries voltage is used to charge batteries with a higher charging current. During step-down mode, the switch M_3 and M_4 conducts and remaining switches are turned off for the entire step down or charging battery mode. In Fig. 3(a) series connection, (b) parallel connection is shown and Fig. 3(C) shows the connection for possible interchange.

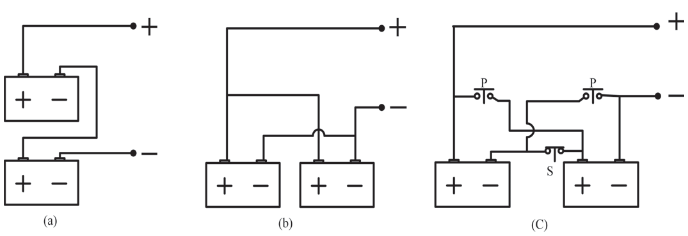

Fig. 3. Series and Parallel connection of batteries for split battery configuration(a) series connection,(b) parallel connection, (C) connection for possible interchange.

The working of proposed bidirectional dc/dc converter with split battery configuration for EV battery charging/discharging can be explored in two modes.

1) Step-Up Mode
2) Step-Down Mode

A. Step-Up Mode

This mode is related to discharging of battery to the high voltage side. The working of converter can be explain in five mode. During step up mode end side converter switches are remain OFF and front end converter switch are Operated at very high frequency. The steady state operation of step-up mode is explained in following mode.

1) Mode I [Fig. 4:From t_0 to t_1]
In this duration switch M_2 is turn on and Inductor L stores energy. Switch M_1 and high voltage side diode are in off state and output voltage is maintained by output side dc link capacitors C_7 and C_8.

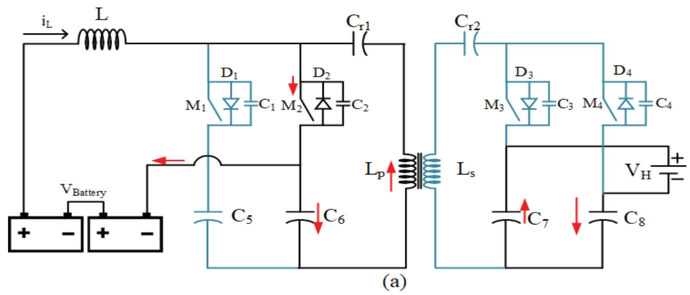

Fig. 4. Step-up Mode-I

2) Mode II [Fig. 5: From t_1 to t_2]
During this mode both front end switches are remain off and energy stored in inductor and resonant capacitor is discharge by parasitic capacitance C_2. at the end of this mode parasitic capacitance C_2 fully charges and C_1 is discharged.

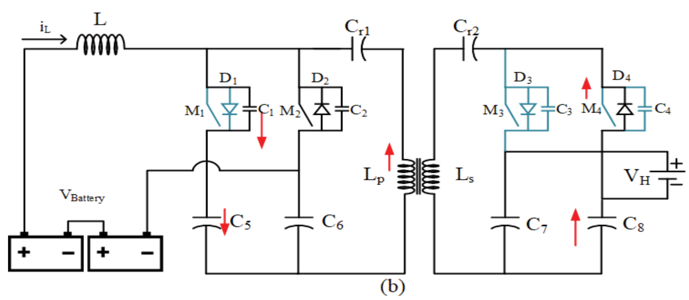

Fig. 5. Step-up Mode-II

at the end, Voltage across switch M_2

$$V_{M1} = \frac{V_L}{1-D} \tag{1}$$

Where,D is duty cycle of switch.

3) Mode III [Fig. 6: From t_2 to t_3]
In this mode, M_1 start conducting with ZVS and resonant current flow in between primary of transformer and C_5 and switch M_1.

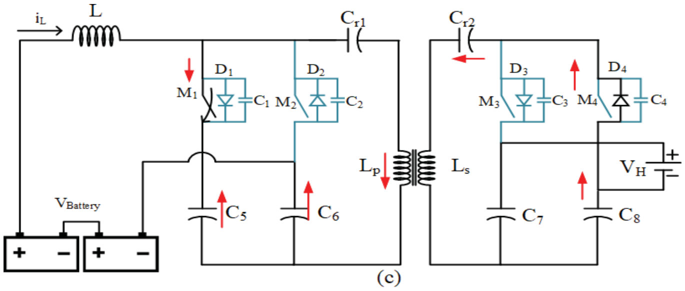

Fig. 6. Step-up Mode-III

The resonant current i_{rc1} is

$$i_{r1} = \frac{V_M - V_p}{\sqrt{\left(\frac{1}{C_5} + \frac{1}{C_r}\right)^2 + (L_p)^2}} \sin\omega_r t \tag{2}$$

current in the primary inductor.

$$i_L = i_{Lt_0} - \frac{V_L - V_{C5} - V_{C6}}{L} . t \tag{3}$$

where, ω_r is resonant frequency of current.

$$\omega_r = \sqrt{\frac{C_5 + C_{r1}}{L_p C_5 C_{r1}}} \tag{4}$$

switch M_1 conducts power transferred in secondary side of transformer circuit.Output voltage is maintained by output capacitor.

4) Mode IV [Fig. 7: From t_3 to t_4]
In this mode, parasitic capacitor C_1 is charged by C_2 and i_{r1}, During this mode M_2 and M_1 are in off state . At instant diode D_4 is reversed biased and D_3 conducts, and switch voltage is $V_{M2} = \frac{V_H}{1-D}$; V_{M1}=0. The current through diode D_2:

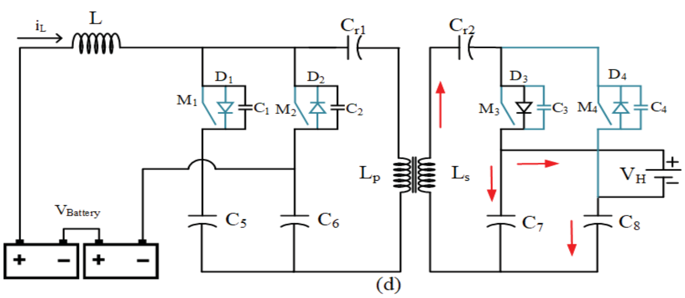

Fig. 7. Step-up Mode-IV

$$i_{D2} = i_L - i_{r1} \tag{5}$$

$$V_{C1} = \frac{V_H}{n(1-D)} \tag{6}$$

where, n is transformation ratio of transformer.

5) Mode V [Fig.8 : From t_4 to t_5]
In this mode, M_2 Turn ON with ZVS and Resonant processed in between transformer winding C_{r1} and C_6.

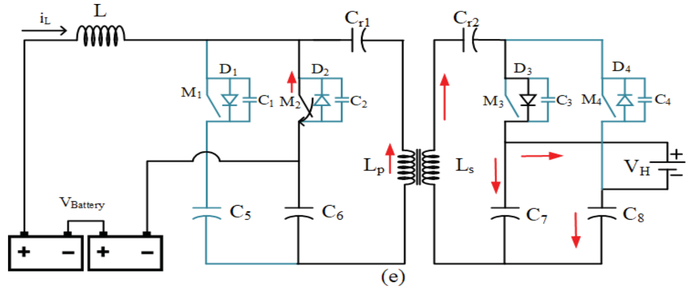

Fig. 8. Step-up Mode-V

During this mode, The resonant current is

$$i_{r1} = \frac{-V_{c6} + V_p}{Z_r} \sin\omega_r t \tag{7}$$

Where, $Z_r = \sqrt{\frac{L_p(C_6+C_{r1})}{C_6 C_{r1}}}$ and $\omega_r = \sqrt{\frac{C_6+C_{r1}}{L_p C_{r1} C_6}}$

Z_r is known as characteristic impedance of resonant circuit. Current through boost inductor is

$$i_L = i_L(t4) + \frac{V_L}{L} \tag{8}$$

B. Step-down Mode

The complete working of isolated converter can be explain in five mode during step-down mode. Front end converter switch remain off for complete step-down operation. steady state operation of step-down mode is explained from mode-I to mode-V.

1) Mode I [Fig.9 : From t_0 to t_1]
In this mode, converter operate like VSC, Switch M_4 is turned On and power is transferred to low voltage side through transformer and body diode of switch D_2

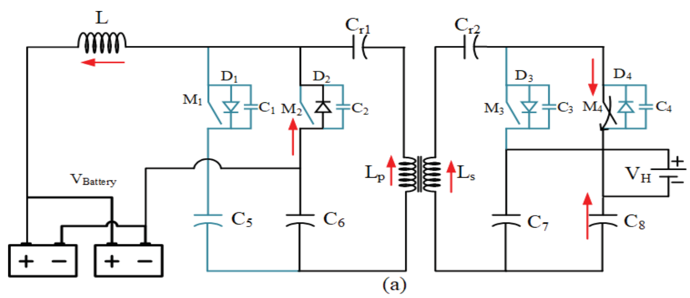

Fig. 9. Step-down Mode-I

2) Mode II [Fig.10 : From t_1 to t_2]
In this mode, Switch M_4: Turn OFF; Parasitic Capacitance C_3 and C_4: Charges and Discharges respectively.

At the end, C_3: completely Discharged; C_4: Charge by V_H; In this duration resonant current-

$$i_{r2} = \frac{V_H + nV_{C6}}{nZ_r} sin\omega_r (t - t_0) \tag{9}$$

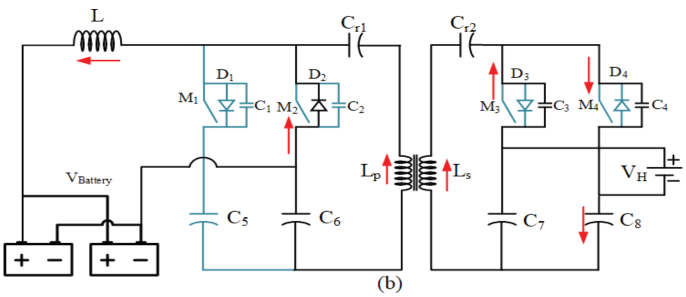

Fig. 10. Step-down Mode-II

3) Mode III [Fig.11 : From t_2 to t_3]
In this mode, resonant current flows through the body diode of switch hence, a zero voltage across switch is noticeable ZVS can be apply by gated on for switch M_3. in the duration resonant current through switch M_3 is-

$$i_r = \frac{V_s + 0.5V_H}{Z'_r} sin\omega_{r'}(t - t^-) \tag{10}$$

where $\omega_{r'}$ is resonant frequency. $\omega_{r'} = \sqrt{\frac{C_7+L_s}{C_s C_{r2}}}$ and $Z'_r = \sqrt{\frac{(C_7.L_s+1)}{C_{r2} C_7 L_s}}$

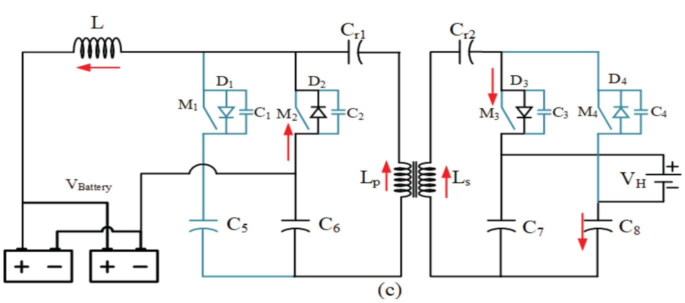

Fig. 11. Step-down Mode-III

4) Mode IV [Fig.12 : From t_3 to t_4]
In this mode, M_3: Turn ON with ZVS; $\frac{V_H}{2}$ is applied on secondary of transformer. Resonant is produces between transformer secondary capacitor C_{r2} and C_7.

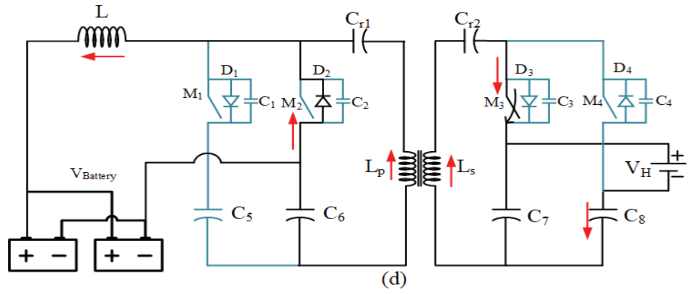

Fig. 12. Step-down Mode-IV

5) Mode V [Fig.13 : From t_4 to t_5]
In this mode, Parasitic capacitor C_3 and C_4 charges with V_H and discharges respectively by resonant current i_{r2} after complete discharging of C_4 diode starts conducting. thus produces zero voltage across switch M_4. Thus, switch can be turn on by ZVS.

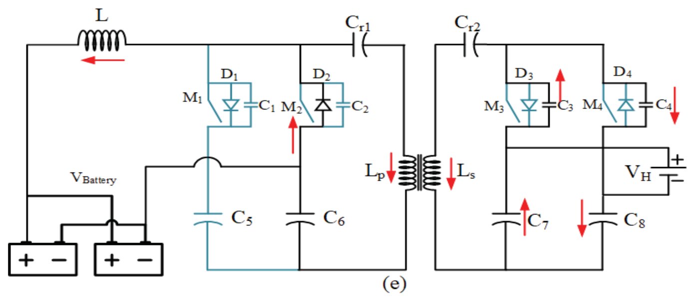

Fig. 13. Step-down Mode-V

Current through circuit during resonance is :

$$i_{r2} = \frac{V_s + 0.5V_H}{Z_{r'}} .sin\omega'_r (t - t^-) \tag{11}$$

Where, $\omega'_r = \sqrt{\frac{C_8 L_s + 1}{C_8 C_{r2}}}$ and $Z'_r = \sqrt{\frac{C_8 + Cr2)L_s}{C_8 L_s}}$ current through anti parallel diode D_4 is same as resonant current.

6) Mode VI [Fig.14 : From t_5 to t_6]
In this mode, switch M_4 turns on with ZVS. Therefor switch M_4 is subjected to resonance current with diode D_1.

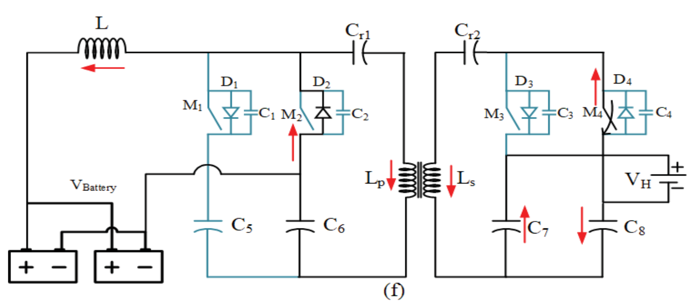

Fig. 14. Step-down Mode-VI

III. Design of The Converter

In this section,The design of isolated bidirectional dc/dc on following assumptions-

1) Voltage ripple is assumed negligible.
2) All switches and component are treated as ideal.
3) Value of Inductor is given by:

$$L = \frac{V_{in}D}{\Delta I_{in}f_s} \quad (12)$$

4) Output filter capacitor

$$C_o = \frac{I_o}{8f_sDV_o} \quad (13)$$

IV. Simulation and Simulation Results

The proposed bidirectional dc/dc isolated converter is simulated by using SIMULINK 9.0. to verify the theoretical concepts of dc/dc isolated converter. .Table I presents the value of different parameter used in simulation.

TABLE I
Simulation Parameter

Parameter	Values
Switches M_1 to M_4	MOSFET
L	100μ H
Resonant Capacitor (C_{r1}, C_{r2})	1μF
High Voltage side Capacitor (C_7,C_8)	100μF
Low Voltage Side Capacitor(C_L)	10μF
Step up Switching Frequency	100kHz
Step down frequency	140 kHz
Low Voltage (V_L)	24V/48V
High Voltage(V_H)	380V

Fig. 15 to 18 shows the steady state switching characteristics of all switches during step-up mode of the converter. This is also noticeable that all switches are ZVS turn ON. and diode are turned OFF with zero current. Since, This converter has a property of isolation so converter can perform at light and heavy load. Body diode conduction across switch enforce ZVS triggering of the switch. Fig. 15,16.

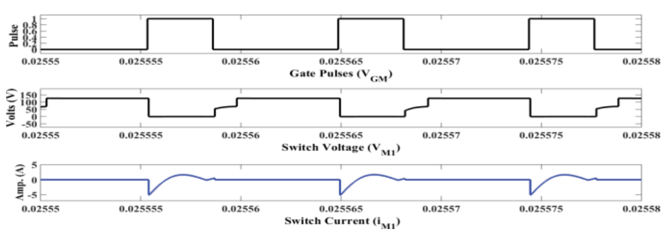

Fig. 15. Steady state simulation waveform during step-up mode for Switch M_1, Gate Signal pulse V_{GM1},V_M1 and i_{M1}

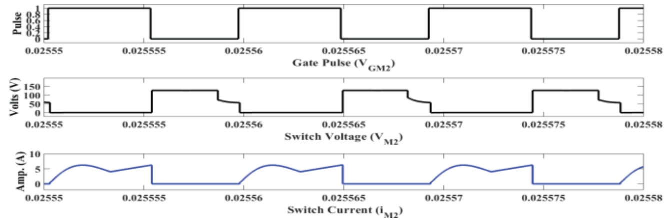

Fig. 16. Steady state simulation waveform during step-up mode for Switch M_2, Gate Signal pulse V_{GM2},V_{M2} and i_{M2}

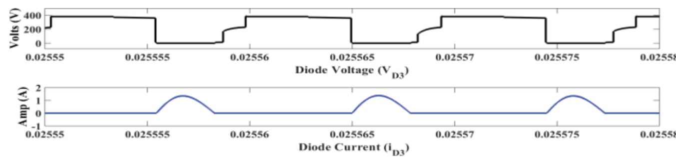

Fig. 17. Steady state simulation waveform during step-up mode for Diode D_3 for V_{D3} and i_{D3}

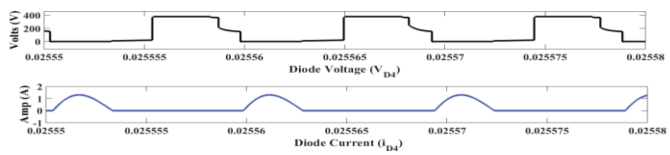

Fig. 18. Steady state simulation waveform during step-up mode for Diode D_4 for V_{D4} and i_{D4}

The end side converter diode of switch M_3 conducts and com mutated after natural current zero and thus there is no recovery losses. Similarly, diode D_4 commutates with zero recovery losses. Fig. 17 and 18 shows the simulation result for diode D_3 and D_4.

Fig. 19-22 shows the result in step-down mode, result shows the ZVS of all switches and ZCS for front end body diode.

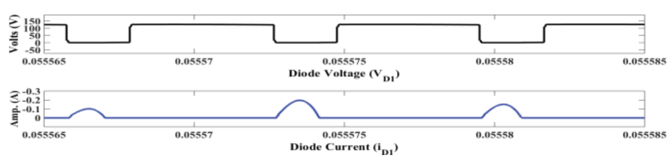

Fig. 19. Steady state simulation waveform during step-down mode for body diode of switch M_1, V_{D1} and i_{D1}

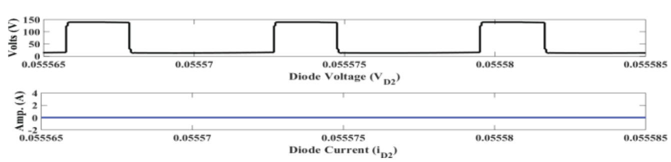

Fig. 20. Steady state simulation waveform during step-down mode for body diode of switch M_2, V_{D2} and i_{D2}

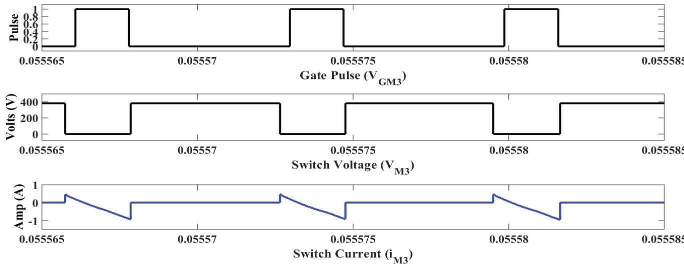

Fig. 21. Steady state simulation waveform during step-up mode for Switch M_3, Gate Signal V_{GM3},V_{M3} and i_{M3}

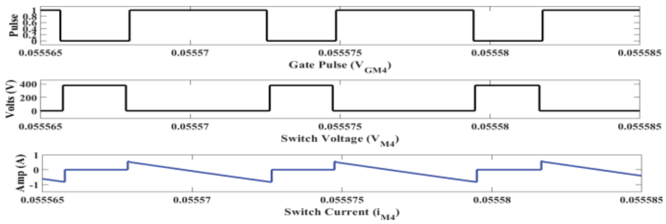

Fig. 22. Steady state simulation waveform during step-up mode for Switch M_2, Gate Signal V_{GM4},V_{M4} and i_{M4}

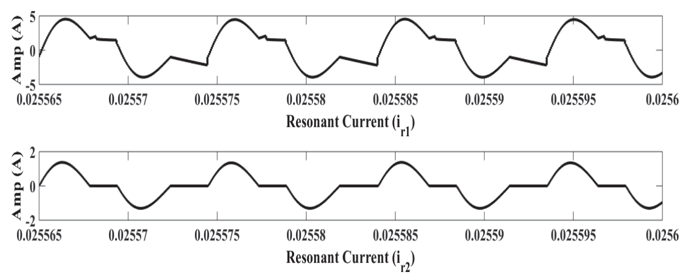

Fig. 23. Resonant Current

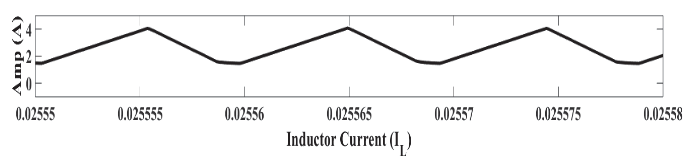

Fig. 24. Inductor Current

This is noticed from simulation that the all switches has ZVS and ZCS for body diode. So, the losses of converter are reduced. The voltage across the switches at turn on and off is clamped without any snubber circuitry therefore voltage clamped naturally. Resonance is occurred in between transformer and other component of circuit. Fig. 22 and 23 shows the resonance current and high and low side voltage profile in both mode. Fig. 24 shows that inductor current also in limited range and it limit the size of inductor.

V. Battery State of Charge/Discharge

The simulation has performed for proposed battery split bidirectional dc/dc converter with lithium-ion batteries block. In step-up mode, the series connected battery offer a proper discharging of battery. since, flow of current depends on the difference of voltage. therefore, During step-down mode a low charging current is identified with series connection of batteries. which cause a slow increase in SOC. The split of batteries promote SOC faster in comparison to previous series connection. The simulated result of SOC for charging and discharging is shown in Fig. 25.

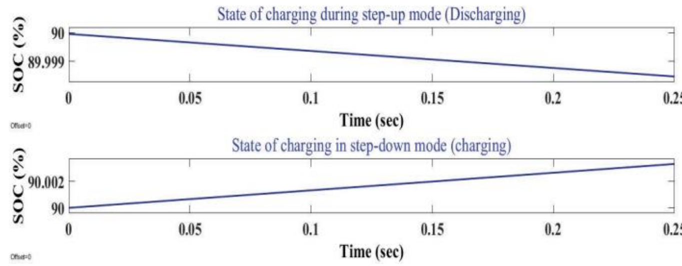

Fig. 25. Inductor Current

VI. Summary and Conclusion

An improved bidirectional dc/dc converter with split battery configuration for EV battery charging/discharging has proposed. The proposed converter is suitable for electric vehicle lithium-ion battery charging and discharging.The converter offers low losses, natural voltage clamping and soft switching of the converter switch in either direction. Since, isolated topology offer high power density the converter is useful with heavy load.Both side output voltage are very smooth or about constant. so, voltage ripple or voltage regulation is better during one mode to other mode. During charging mode the charging current is increase by 2X time at same step down voltage by splitting the batteries.These feature of bidirectional converter have been identified in MATLAB/Simulink by simulation for 350 W battery system.

VII. Acknowledgment

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