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Two Phase Bidirectional DC-DC Switching Converter With Coupled Inductor

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***Abstract*: This paper presents a high power density, high-efficiency non-isolated coupled inductor DC-DC converter with different mode. High power density of converter can achieve by operating in discontinuous current mode (DCM). Anti-paralleled diode of the transistor switch helps to discharge the capacitor. The zero voltage resonant transition (ZVRT) of transistor switch is realized and also removes the parasitic ringing in the inductor current. Complementary gate signals are used to reduce switching and conduction losses of power transistors when the converter operates in buck–boost mode. The converter operates in buck, boost, or buck–boost mode.**

***Keywords*: Bidirectional, coupled inductor, DC-DC converter, DCM, buck, boost, buck-boost, non-isolated, ZVRT.**

I. INTRODUCTION

The duplex switching DC-DC converter along with energy storage has become a promising option for many power related systems, including hybrid vehicle, fuel cell vehicle [1], and renewable energy system and so on. The system exponentially not only minimizes the cost and enhances efficiency, but also improves the performance of the system. In the electric vehicle applications, the energy generated by the electric machine is absorbed by the energy storage battery. In addition, during vehicle starting duplex switching DC-DC converter is required to absorb power from the auxiliary battery to boost the high-voltage bus, to accelerate and for hill climbing . With its ability to reverse the route of the current flow and power, the duplex switching DC-DC converters are being increasingly used to achieve power transfer between two DC power sources in either path.

In this proposed research paper, we design high efficiency two phase duplex DC-DC converter with increased power density using couple inductor method. It is capable of working in both buck mode as well as boost mode. To increase the efficiency and to reduce the parasitic ringing and also to achieve zero voltage resonant transition, complementary gate signal control mechanism is used.

In section 2 gives an overview of related work which identifies all the major research work being done in this area. Section 3 discuss about problem identification of proposed system followed by elaborated discussion in section 4. Research methodology is discussed in section 5, accompanied by experimental results in section 6. Finally section 7 summaries the paper.

II. RELATED WORK

This section discusses about the prior research work that has attempted to address the similar issues. The framework with multiple key in attributes is presented by Tao et al. [2] for duplex DC-DC converter. The author considers it as the prime module that links energy origins and components of storage. It also controls the energy for various modernized applications pertaining to renewable resources. The outcome of the study shows that the framework could be potentially used in multiple types of energy origins. Similar attempts were also witnessed by the study conducted by Chiu et al. [3]. The author has presented the multiple key in attribute for designing DC-DC converter for efficiently maintaining the output voltage from numerous energy origins. Some of the energy origins discussed in the study is fuel-cells, wind-turbines, PV array etc. The outcome of the study shows that the system posse's highly straightforward system setting with minimal components and also it is cost effective. Enhance version of above study was done by Mishima et al. [4] by presenting a soft switched duplex DC-DC converter. Targeted for signifying its usage in automotive system, the study uses dual half bridge circuits cumulatively along with maximized frequency transformer. The outcome of the study shows a better efficiency as the system interface acts as a bridge between minimal voltage energy origins and maximal voltage DC bus line. Effective usage of zero voltage switching can be found in the study of Peng et al. [5] for designing duplex DC-DC converters. Characterized by non-trivial topology of circuits, the system also ensures realization of soft-switching with cost effective measures. The outcome of the study exhibits maximized efficiency and hassle-free management in comparison to conventional full or half bridge duplex DC-DC converters. The study on energy conversion circuits was found in literature of Santhi & Rajaram et al. [6]. The author has attempted to design the system exclusively for battery-fuel hybrid systems with numerous minimized components of energy conversion mechanism using push-pull DC-DC converters. Similar study was also found in research work of Yamamoto et al. [7] where the author have proposed a full-bridge circuits based on push-pull duplex DC-DC converters and its management mechanism. The outcome of the study shows effective operation of charging and discharging mechanism between high and low voltage current. Different from mainstream research activity, Camara et al. [8] have presented a super capacity and novel modelling of battery for the purpose of accomplishing a novel energy management tactics. The mechanism is also found supported by artificial mechanism of storage designed using polynomial controller. In order to handle numerous energy sources, literature exists to show evidence in the study conducted by Bhattacharya and Giri [9]. The authors have proposed a topology designed from multiple energy port that has potential ability to manage numerous energy sources with simple operation. The outcome of the study shows minimal output-current ripple evaluated over wide variety of test load. The system was also found to have better capability of parallel-battery energy owing to its modular structure. The secondary outcome of this study also exhibits potential minimization of inductance leakage for coupled inductor. A unique contribution towards research work in duplex DC-DC converters is made by Jin et al. [10] using triple level design aspects. The outcome of the study exhibits exponential minimization of inductor of the triple level type converters for enhancing the dynamic responses of the cumulative systems.

III. PROBLEM IDENTIFICATION

Duplex DC-DC power converter has been selected to achieve high power density and high efficiency. Usually, to increase the power density, the design adopts small inductor with multiphase to operate in discontinuous conduction mode (DCM). The problem with DCM operation is the parasitic ringing caused by the inductor and the device output capacitance during turn-off condition, this results poor efficiency and trivial EMI noises. The disadvantages related to the DCM are inductor voltage parasitic ringing and hard switching turn-off and increased turn-off loss. The lossless snubber capacitor can be added across the transistor switch for soft turnoff, it requires certain amount of energy stored in the inductor to discharge the capacitor energy before device is turned on.

IV. PROPOSED SYSTEM

A non-isolated duplex DC-DC converter technology is to combine a buck mode and a boost mode converter. In order to achieve high power density, the converter is designed to operate in discontinuous conducting mode (DCM) such that the passive inductor can be minimized. The DCM operation introduces a large current ripple, so it is necessary to cancel the high-frequency switching current ripple. Using coupled inductor approach we can reduce the ripple in the current. Another major advantage of the DCM operation is zero turn-on loss and thus low diode reverse recovery loss. However, the DCM operation largely increases turn-off loss because the main switch is turned off at twice the load current or higher. This is the major negative side effect of the inductor size reduction. It also causes inductor current parasitic ringing because the inductor tends to oscillate with the device output capacitance during device turn-off period. The efficiency can be suffered with all these side effects induced by the DCM.

The snubber capacitor added across the transistor switch for soft turnoff, if IGBT is used as a switch large snubber capacitance required where as in case of MOSFET small snubber capacitance required or in some case it eliminated. Snubber capacitor requires certain amount of energy stored in the inductor to discharge the capacitor energy before device is turned on. By use of a complementary gating signal control scheme to turn on the originally non-active switch and the current is diverted into the anti-paralleled diode of the active switch so that the main switch is turned on under zero-voltage condition. The soft switching operation can be considered a zero-voltage resonant transition (ZVRT) switching technology. Thus both soft switching turn-on and -off are achieved. Because of the continuation of this diverted current, the inductor current parasitic ringing also disappears.

The inductor design has a significant impact on the system performances, such as the realization of complementary control ZVRT soft switching, device switching loss, system volume, inductor power loss etc. It is necessary to optimize the inductance with all the design considerations. The design and optimization of power and efficiency can be done by selecting proper circuit parameters.

The relationship between inductor peak current I_{peak}, minimum current I_{min}, and inductor RMS current I_{RMS} can, where T_s is the switching period, I_{load} is the load current, ΔI is the inductor ripple current, *p* is the load power are shown in below equations.

$$\Delta I = \frac{1}{2} \cdot \frac{v_{in} - v_o}{L} \cdot \frac{v_o}{v_{in}} . T_s \tag{1}$$

$$I_{load} = \frac{p}{v_o} \tag{2}$$

$$I_{Peak} = I_{load} + \Delta I \tag{3}$$

$$I_{\min} = I_{load} - \Delta I \tag{4}$$

$$I_{rms} = \sqrt{I_{load}{}^2 + \frac{\Delta I^2}{3}} \tag{5}$$

The optimization of the inductor design should satisfy the zero-voltage switching condition under all operating conditions shown in figure 1. During dead time t_d the load current is remains same for particular time and soft switching turn off, zero voltage turn on can be achieve by giving proper gate control signal.

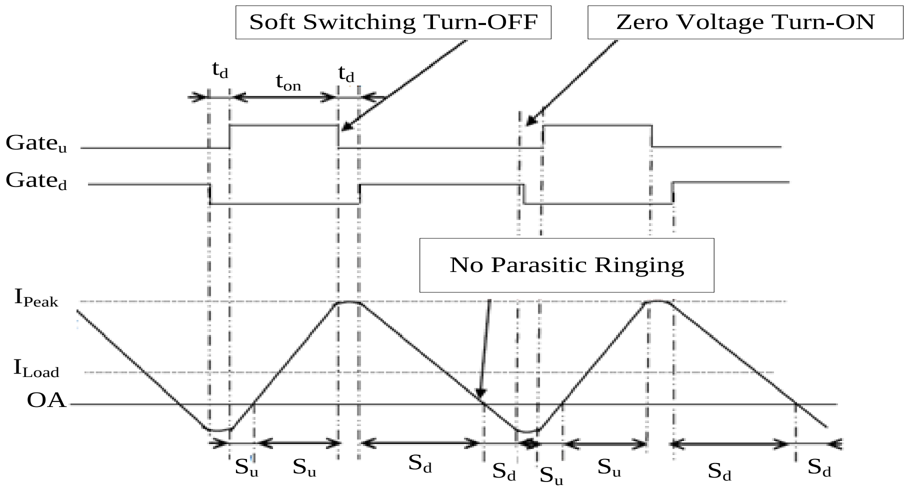


Figure 1: Soft Switching turn off and Zero voltage turn on.

Realization of gate signal complementary control ZVRT soft switching depends on the emergence of inductor negative current, which can be acquired by limiting inductance to be less than the value L_{cr} expressed in (6), *p* is the load power. This inductance allows the converter operating under the boundary condition between DCM and CCM (Continuous Conduction Mode).

$$L_{cr} = \frac{1}{2} \cdot \frac{v_{in} - v_o}{p} \cdot \frac{v_o{}^2}{v_{in}} . T_S \tag{6}$$

V. RESEARCH METHODOLOGY

Two phase duplex DC-DC converter design is shown in figure 2, there are two dc sources including high side bus voltage source V_H and low side battery source V_L representing both voltage sources of the two-way duplex DC-DC converter.

With two voltage sources, the averaged inductor current i_L or averaged output current i_o can flow in both directions, instead of flowing only in one direction in one voltage source application. Resistor R_1 represents either high-side source internal resistance in charging and discharging modes or load in boost resistive load application. Resistor R_2 represents either low-side source internal resistance for both charging and discharging modes or load in buck resistive load application. Capacitor C_H and C_L indicate the bus capacitor bank and the output capacitor at battery side respectively. Four active switches, Q_1 to Q_4, are controlled by gate control signal.

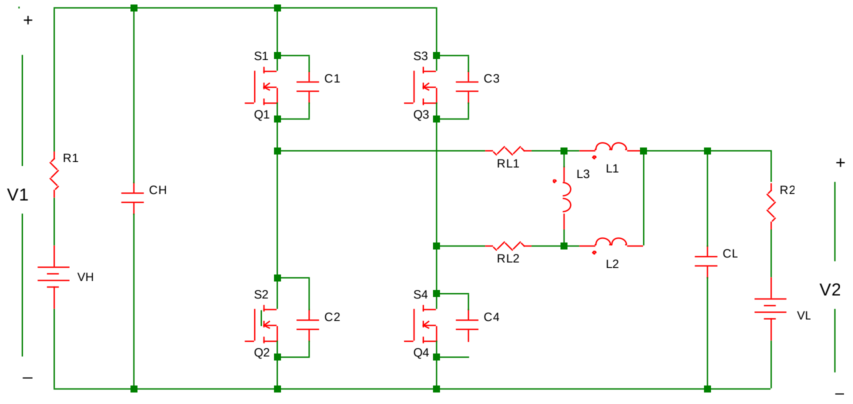
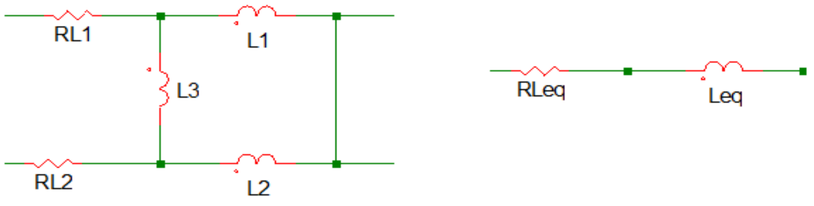


Figure.2: Two phase duplex DC-DC converter with coupled inductor.

Inductor parasitic resistance and MOSFET turn-on resistance are also concerned in the model; since they are a serious factor for reduce the ripple in inductor current. There are three energy storage components are input capacitor C_H, output capacitor C_L and inductor L. With this circuit model, the derived power plant can be used for battery charging and discharging modes or boost and buck mode applications, since all these cases can employ the same equivalent circuit. In operating modes, either battery charging mode or discharging mode, there are always two subintervals, one is t_{on} and another is t_{off} as shown in Figure1. In the first subinterval, the switch Q_1 and Q_3 are on with phase delay of 180^o, Q_2 and Q_4 are off, and in second subinterval the switch Q_1 and Q_2 are off, Q_2 and Q4 are on with phase delay of 180^o. The inductor current is continuously very and we can achieve maximum power density.

In buck mode operation, the low side voltage V_L is zero, R2 is treated as a resistive load and R_1 is negligible, the model behaves like a standard second-order buck converter. The averaged inductor current is always greater than zero. So inductor averaged current I_L always positive, which indicates the unipath current flow in buck mode. In Boost Mode the R_1 indicates a resistive load, where V_H does not exist and R_2 is negligible and module behaves like a second order system. The averaged inductor current is always less than zero. So inductor averaged current I_L is always negative, which indicates the unipath current flow in boost mode. In buck-boost mode the battery internal resistance R_2 is as small as tens of milli, which is negligible because its voltage is much smaller than the voltage sources. The battery on the low side is also a strong voltage source. On the high side, there is a large capacitor bank C_H, if the high side is treated as a voltage source. With only one inductor current as the state variable, the system behaves like a first-order system. But the inductor current has some ripple in this method. A coupled-inductor method is introduced for improvement of power stage design to reduce the core loss by flux ripple cancellation in the coupled inductor current shown in figure 2.

In couple inductor method there are four switches. The inductor L_1carry current I_{L1}, inductor L_2 carries current I_{L2}, and inductor L_3 carries current I_{L3}. Here the resistance R_{L1} and R_{L2} are equal and inductor L_1 and L_2 are equal. By state-space equation the current pass through L_3 is become zero, I_{L1} and I_{L2} are equal.



(a) (b)

Figure 3 (a) Coupled inductor and (b) Equivalent module.

The coupled inductor current i_{L3} is zero, which means equivalently there is no voltage drop at L_3. This means the voltage second applied on inductor L_3 for each switching period is balanced naturally. Since the positive volt-second applied on the L_3 is equal to the negative volts second applied on L_3, it is reasonable. Summarily the inductor L_3 does not exist, so circuit in Figure 3(a) can be equivalent to circuit shown in Figure 3(b). The coupled inductor equivalent value L_{eq} is L_1 or L_2 divided by 2 and equivalent resistance R_{Leq}(ESR of Leq) is R_{L1} or R_{L2} (ESR of L_1 and L_2 respectively) divided by 2.

VI. EXPERIMENTAL RESULTS

High efficiency, high power coupled inductor DC-DC converter is design and experiment is conducted on buck, boost and buck-boost mode in Simulink.

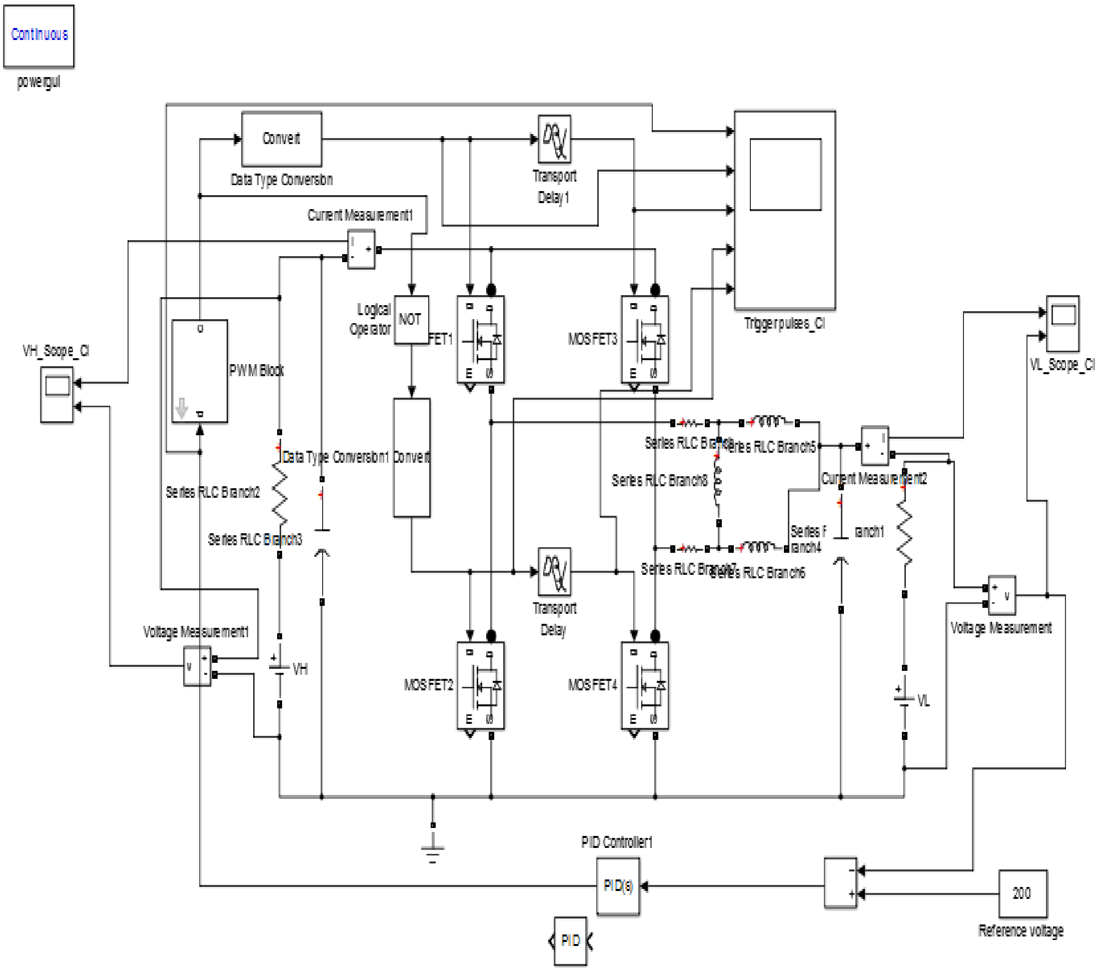


Fig4: Simulink Module

Table1: Simulation Parameters for buck mode

VH	VL	CH=CL	L1=L2	L3	RL1=RL2	R1	R2	D	fsw
280V	0	150μF	0.5μF	- 2.2μF	33mΩ	30mΩ	100Ω	0.63	20KHz

The figure 5 shows inductor current and voltage variation in buck mode. In buck mode V_L is zero, this is battery charging mode. During t_{on}, Q1 and Q3 (Ref Fig2) conduct with 180^o phase difference and charge the inductor and inductor current is increased. Where as in the $t_{off,}$ Q2 and Q4 conduct with 180^o phase difference and the inductor current is decreased. Here more the duty cycle larger the inductor current and battery voltage and vice-versa.

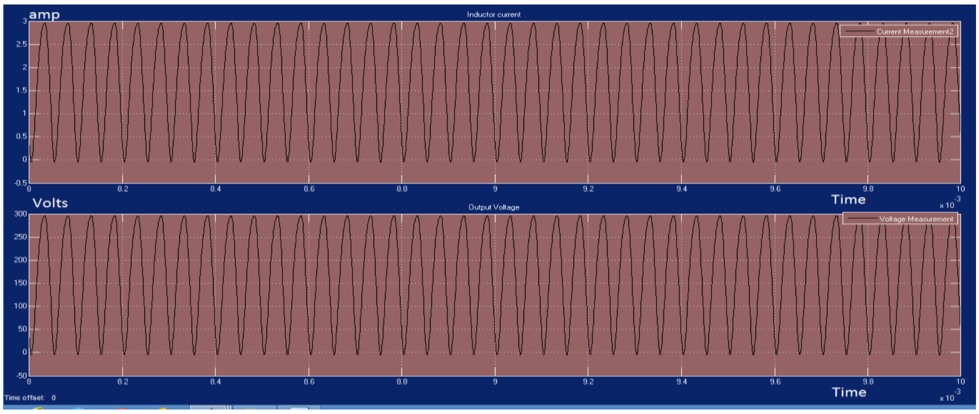


Figure 5: Inductor current and output voltage variation in duplex Buck mode DC-DC converter using MOSFET

Table2: Simulation Parameters for boost mode

VH	VL	CH=CL	L1=L2	L3	RL1=RL2	R1	R2	D	fsw
0	120V	150µF	0.5µF	-2.2µF	33mΩ	100Ω	30mΩ	0.65	20KHz

The below figure 6 shows load current and output voltage variation of boost mode converter. In boost mode V_H voltage is zero and V_L voltage is used to boost the generator buses.

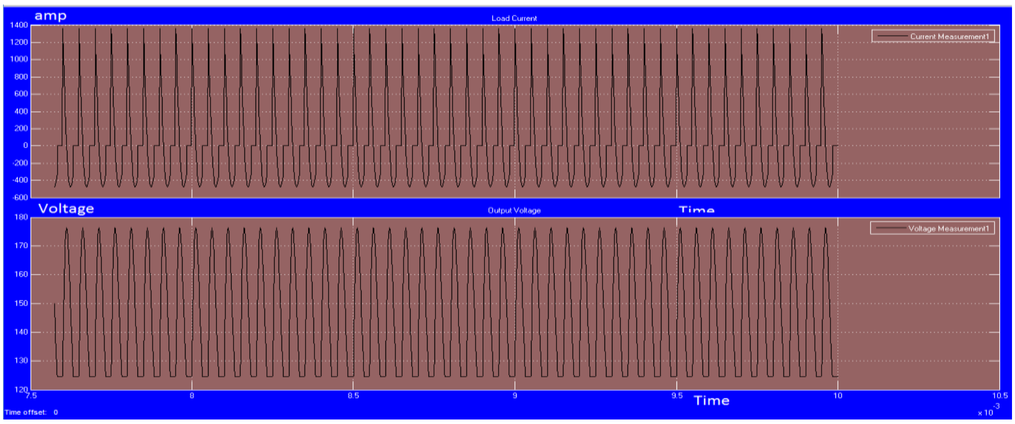


Figure 6: Load current and output voltage variation in duplex Boost mode DC-DC converter using MOSFET

Table3: Simulation Parameters for buck-boost mode

VH	VL	CH=CL	L1=L2	L3	RL1= RL2	R1=R2	D	fsw
280V	120V	150µF	20.5µH	-91µF	36mΩ	1Ω	variable	20KHz

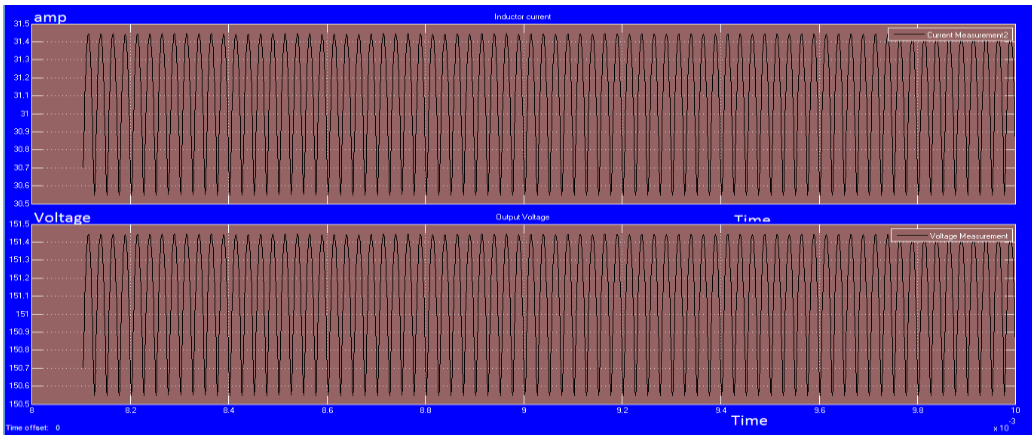


Figure 7: Inductor current and output voltage variation in duplex buck-boost mode DC-DC converter using MOSFET at low voltage side (Battery side) for duty cycle = 0.57

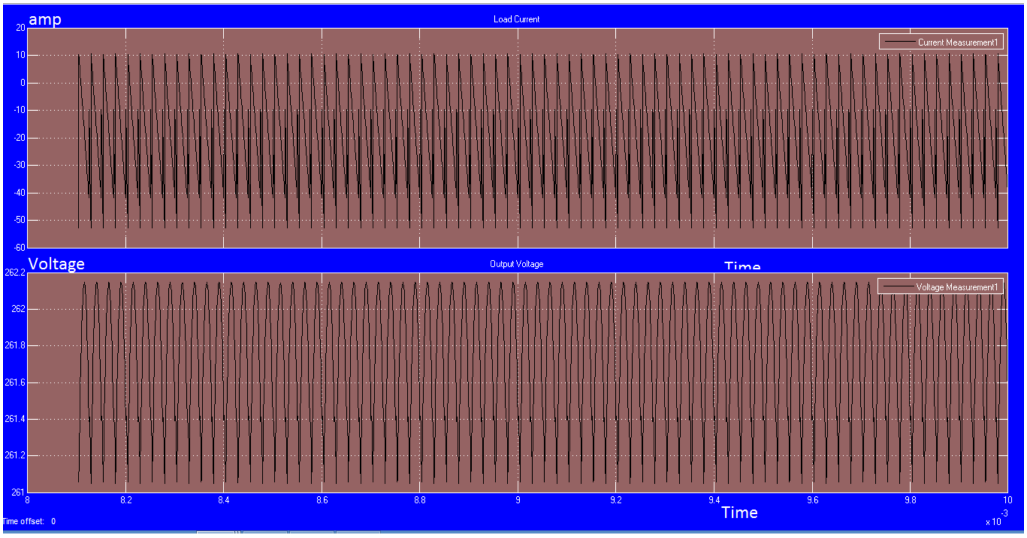


Figure 8: Load current and output voltage variation in duplex buck-boost mode DC-DC converter using MOSFET at high voltage side (Load side) for duty cycle = 0.57

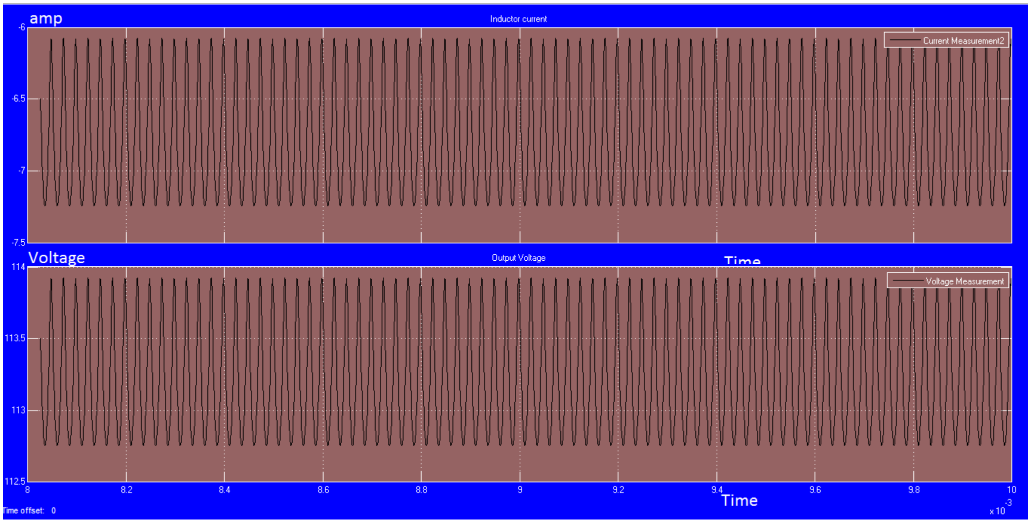


Figure 9: Inductor current and output voltage variation in duplex buck-boost mode DC-DC converter using MOSFET at low voltage side (Battery side) for duty cycle = 0.38

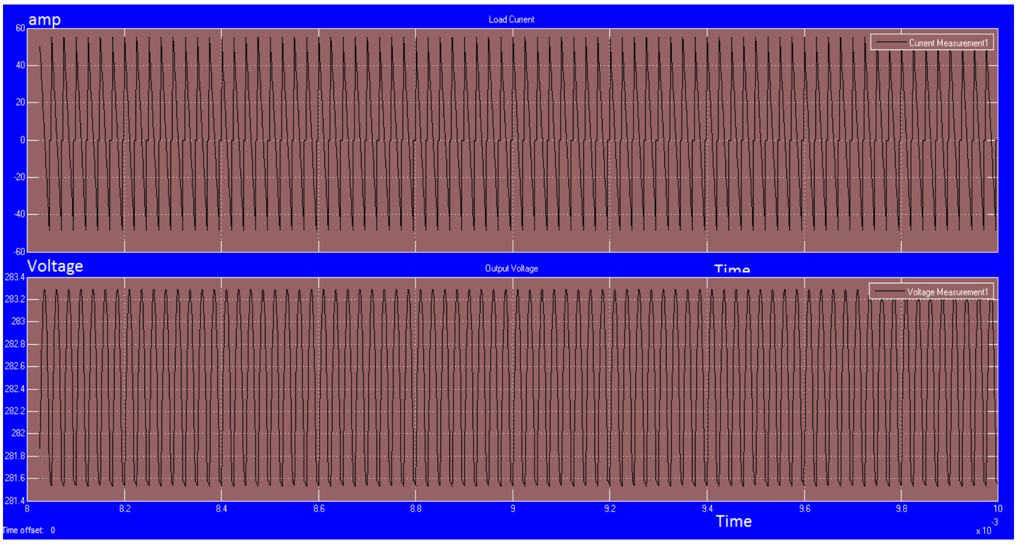


Figure 10: Load current and output voltage variation in duplex buck-boost mode DC-DC converter using MOSFET at high voltage side (Load side) for duty cycle = 0.38

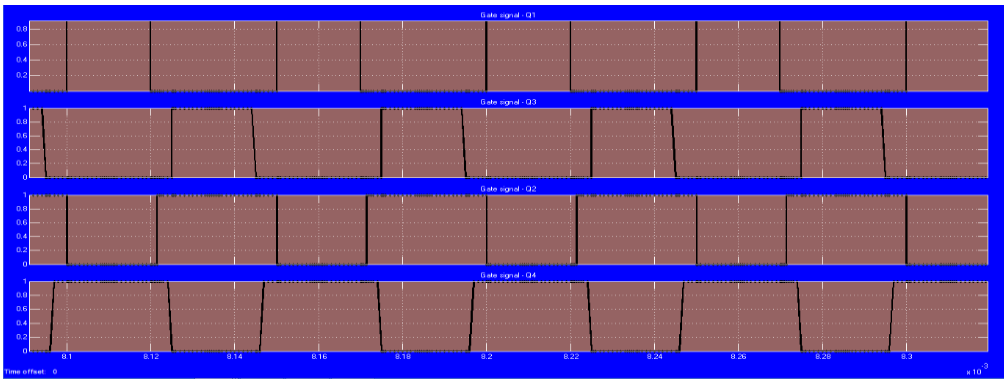


Fig 11: Gate pulses to Q1, Q3, Q2 and Q4 respectively

In coupled inductor buck-boost mode the inductor current is positive and battery is in charging mode for D ≥ 0.42 and induct current and battery voltage is increased by increasing the duty cycle above 0.42 and reduced the inductor core ripple in the circuit. For D ≤ 0.41 the inductor current is negative and battery is in discharging mode.

VII. CONCLUSION

A high-efficiency, high power density coupled inductor DC-DC converter is proposed in this paper. The ripple in inductor current in DCM mode is reduced by choose proper inductor value. Complementary gating signal control is proposed and its performance is verified by the realization of ZVRT turn-on soft switching. This scheme eliminates parasitic ringing of the inductor current caused by the interaction between the inductor and device output capacitor. High efficiency and high power density of buck boost and buck-boost modes with couple inductor is achieved by discontinuous current mode.

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