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Isolated Double Buck DC – DC Converter for Battery Charging and Electroplating Applications

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Abstract: A double step down DC-DC converter with isolation and greater efficiency with large buck operating capability is proposed for battery charging, electroplating applications etc. This converter has an extra capacitor in the input side of the transformer. The voltage stress experienced by three switches of the transformer input side is half of the source voltage due to Zero Voltage Switching (ZVS) resulting in lower output capacitor energy of the switches. Thus, this DC-DC converter utilizes lesser leakage inductance and lower voltage stress compared to the existing full bridge converters. Large leakage inductance leads to high circulating current, excessive voltage spikes across the secondary rectifier diodes and the oscillation-generating Electromagnetic Interference (EMI) problem. The objective is to simulate in MATLAB Simulink and develop the hardware of proposed converter with good isolation for battery charging applications. The modes of operation of the converter is analysed and the simulation and hardware results are provided to validate the merits of the converter.
Keywords: DC-DC converter, Isolation, Battery Charging, Zero Voltage Switching (ZVS), Electromagnetic Interference (EMI)

I. INTRODUCTION

The forward [2], half-bridge (HB) [3], full-bridge (FB) [4] and three-level (TL) converters [5] are used for Distributed Power System (DPS) such as telecommunications, computer technology, and information technology, because they provide the step-down function and isolation. The DPS generally consists of a power factor correction (PFC) circuit and an isolated DC-DC converter. The DC-DC converter requires both isolation and high step-down conversion ratio. DC-DC converters are used in transferrable electronic devices such as mobile phones, desktop computers and laptops, LED drivers, photovoltaic systems to increase the energy transfer and as power optimizer in wind turbine. However, these converters suffer from large leakage inductance and high voltage stress leading to high circulating current, excessive voltage spikes across the secondary rectifier diodes and the oscillation-generating Electromagnetic Interference (EMI) problem [6].

II. LITERATURE SURVEY

The forward converter is used in low to medium power applications due to high reliability and simple structure. However, it suffers from transformer reset problem and a limitation in the maximum duty ratio. The conventional HB converter is employed in industrial applications due to its lack of the transformer saturation problem, while providing a simple control strategy and structure. But soft-switching is not possible and the voltage stress of switches is equal to the input voltage. Even though the asymmetrical HB converter can attain soft switching, the diodes at the secondary side of the transformer have asymmetrical voltage stress. The phase-shifted pulse-width modulation (PS-PWM) FB converter is widely used as all the switches at the primary side achieve soft switching operation. Although the PS-PWM converter realizes soft switching with the phase-shift control scheme, it needs relatively large transformer leakage inductance (or separate inductor in series with transformer) to achieve Zero Voltage Switching (ZVS) under a light load condition. Conventional FB and PS-PWM converters are vulnerable to transformer saturation caused by the DC offset current of the transformer. To prevent this, a DC blocking capacitor is connected in series with the transformer. To reduce voltage stress of switching devices, the HB three-level are used as it is free from transformer saturation and voltage stress of four switches reduces to half of input voltage. But two extra clamping diodes are essential and this circuit cannot achieve soft switching without auxiliary circuit [3]. With higher switching frequency, value of the passive components, such as inductors and capacitors, can be minimised and power converter is more cost-effective.

III. PROPOSED ISOLATED DOUBLE STEP DOWN DC-DC CONVERTER

The converter circuit is shown in Fig. 1 and its various operating modes are given in Table.1. With one extra capacitor C_i, the converter has following advantages over the conventional two-phase interleaved DC-DC converter [1]. There is no current unbalance problem between L_1 and L_2 due to the charge balance condition of the C_i. Therefore, no additional current sensing circuit and control scheme is required. Secondly, voltage stress of the three switches (S_1, S_3 and S_4) becomes half of input voltage. The switches are turned on and off at zero crossing of voltage to achieve Zero Voltage Switching (ZVS) leading to lower switching loss, lower EMI and higher efficiency. The primary side of the transformer consists of four switches and input capacitor. The secondary side of the transformer consists of four diodes, output capacitor, inductor and resistor. The $C_{s1} - C_{s4}$ and $D_{s1} - D_{s4}$ represent the output capacitances and body diodes of the switches $S_1 - S_4$ respectively. The two gate signals of switches $S_1$and S_3 (or S_2 and S_4) are complementary with finite dead time, and S_1 and S_2 are phase-shifted by 180° and the capacitor C_i voltage is half of the input voltage.

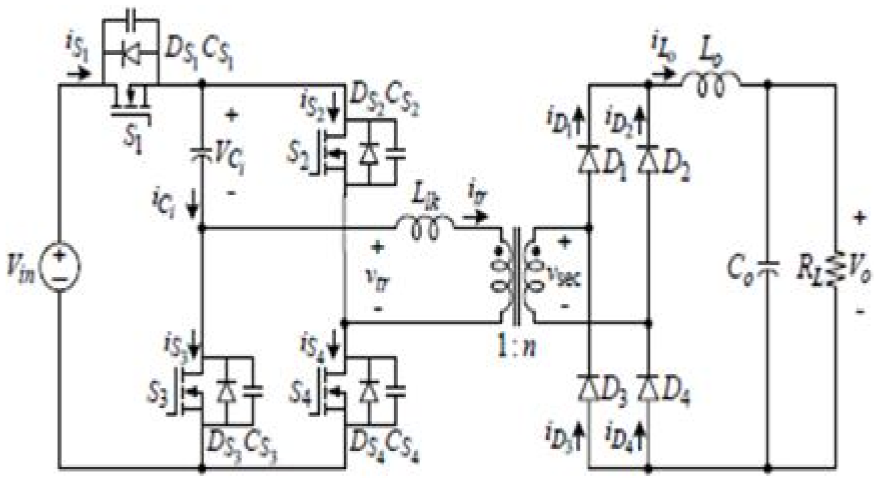

Fig. 1. Proposed isolated double step down DC-DC converter with ZVS

A. Mode 1

Switches $S_1$and $S_4$are turned-on while rectifier diodes D_1 and D_4 conduct. The input power is delivered to the output. Capacitor is charged and the leakage inductance (L_{lk}) stores energy. Since the capacitor voltage (V_{ci}) is equal to $\frac{V_{in}}{2}$, transformer primary voltage (v_{tr}) also becomes $\frac{V_{in}}{2}$, and the switch voltage is equal to input voltage.

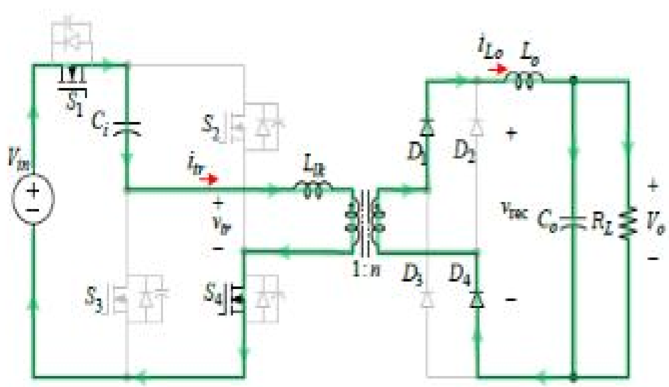

Fig. 2. Operating Mode 1 of proposed DC-DC converter

B. Mode 2

Switch S_1 is turned-off and S_4 remains on. The capacitors C_{s_2} , $C_{s_3}$are discharged and C_{s_1} is charged by the energy stored in the L_{lk} , respectively . When C_{s_3} is fully discharged, then D_{s_3} is turned-on , the energy stored in L_{lk} has to charge $C_{s_1}$and Discharge $C_{s_2}$and C_{s_3} . Therefore, $1/3$ rd of energy in the L_{lk} is used for ZVS operation for switch S_3.

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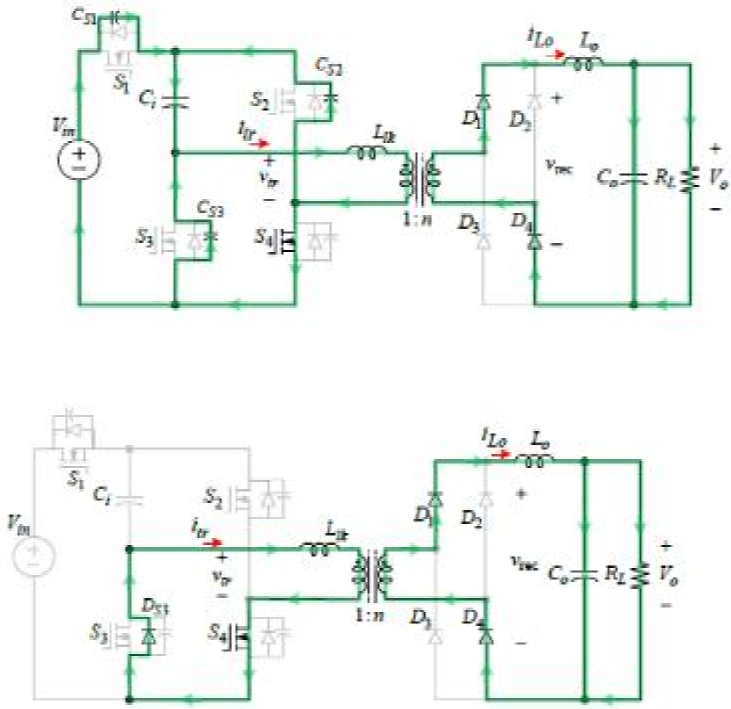

Fig. 3. Operating Mode 2 of proposed DC-DC converter

C. Mode 3

Switch S_3 is turned-on and S_4 remains on. The stored energy of the leakage inductance freewheels through switch S_4 and D_{S_3} , thus v_{tr} becomes zero and the switch S_2 voltage is equal to the capacitor C_i voltage. Switch S_3 is turned-on while diode D_{S_3} conducts. Thus, switch S_3 achieves the ZVS operation.

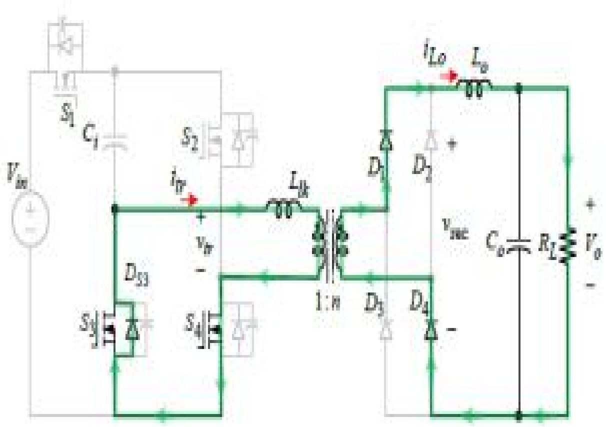

Fig. 4. Operating Mode 3 of proposed DC-DC converter

D. Mode 4

Switch S_4 is turned-off and S_3 remains on. The current in the output filter inductor (L_o) freewheels through the all rectifier diodes. C_{S_2} is discharged again and C_{S_4} is charged. After C_{S_2} is fully discharged by the stored energy of the leakage inductance, diode D_{S_2} is turned-on . The stored energy in L_{lk} freewheels through D_{S_2} and C_i and no current passes through switch S_2 until the transformer current polarity changes from positive to negative.

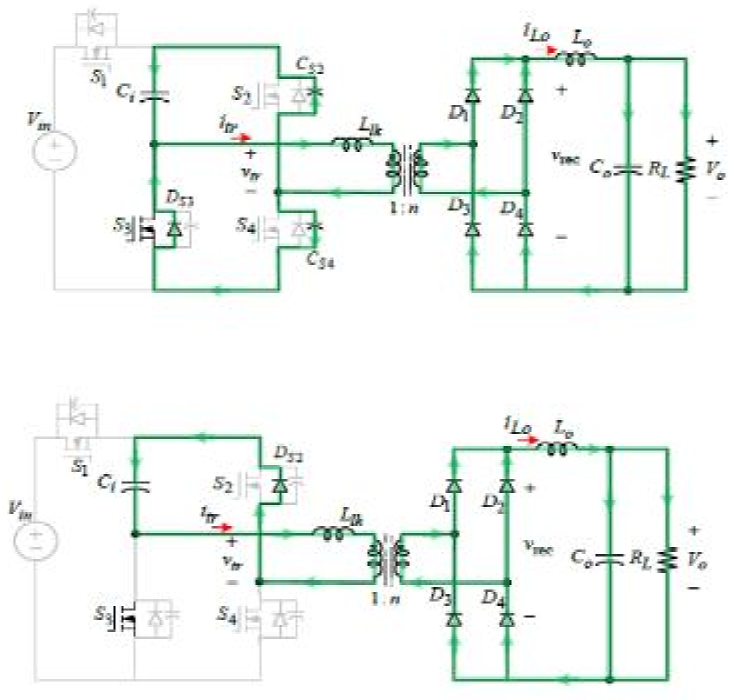

Fig. 5. Operating Mode 4 of proposed DC-DC converter

E. Mode 5

Rectifier diodes D_2 and D_3 conduct while switches S_2 and $S_3$are turned-on. The stored energy in C_i is mostly delivered to the output through the transformer and partly stored in L_{lk}. In this mode, v_{tr} is equal to $\frac{V_{in}}{2}$.

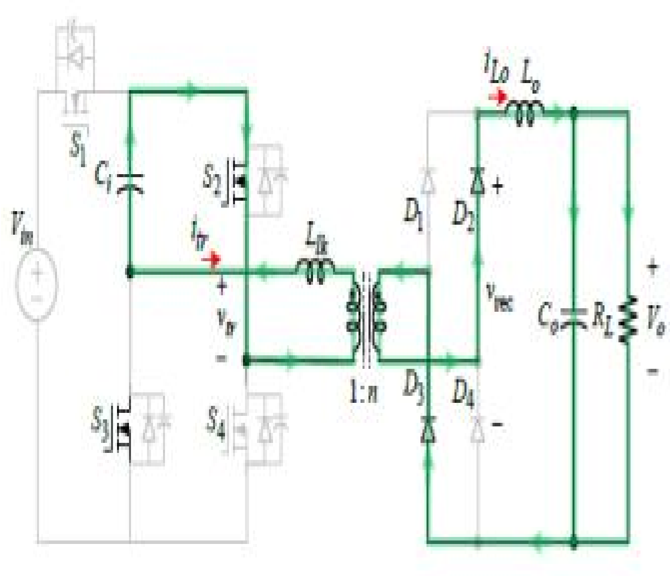

Fig. 6. Operating Mode 5 of proposed DC-DC converter

F. Mode 6

Switch S_2 is turned-off and S_3 remains on. C_{S_2} is charged and C_{S_4} is discharged. After C_{S_4} is full discharged by the energy in L_{lk}, diode D_{S_4} starts conducting. The stored energy in L_{lk} freewheels through switch S_3 and diode D_{S_4}.

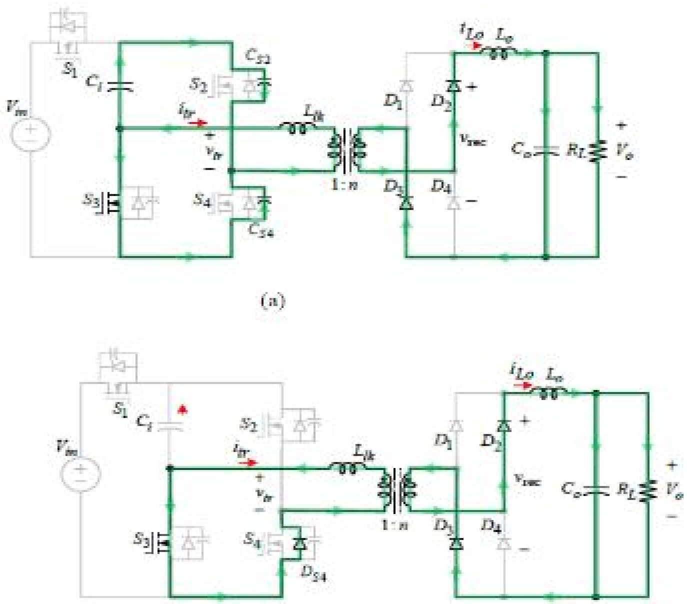

Fig. 7. Operating Mode 6 of proposed DC-DC converter

G. Mode 7

Switch S_4 is turned-on while D_{S_4} conducts, thus switch S_4 achieves the ZVS operation. The stored energy in L_{lk} freewheels through the switch S_3 and diode D_{S_4} and V_{tr} becomes zero.

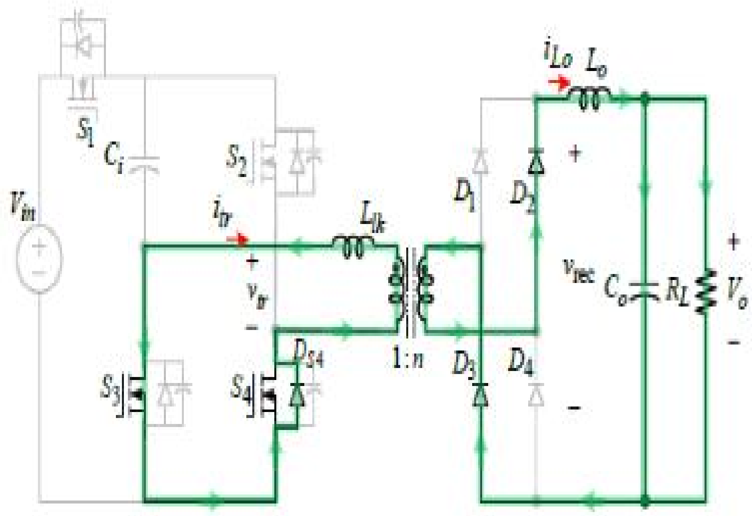

Fig. 8. Operating Mode 7 of proposed DC-DC converter

H. Mode 8

Switch S_3 is turned-off and the energy in L_o freewheels through the rectifier diodes. C_{S_2} and C_{S_3} are charged and $CS1$ is discharged . After C_{S_1} is fully discharged, diode D_{S_1} is turned-on. The stored energy in L_{lk} freewheels through diodes D_{S_1} and D_{S_4}. Switch S_1 is turned-on while D_{S_1} conducts and no current passes through switch S_1 until the transformer current polarity changes from negative to positive

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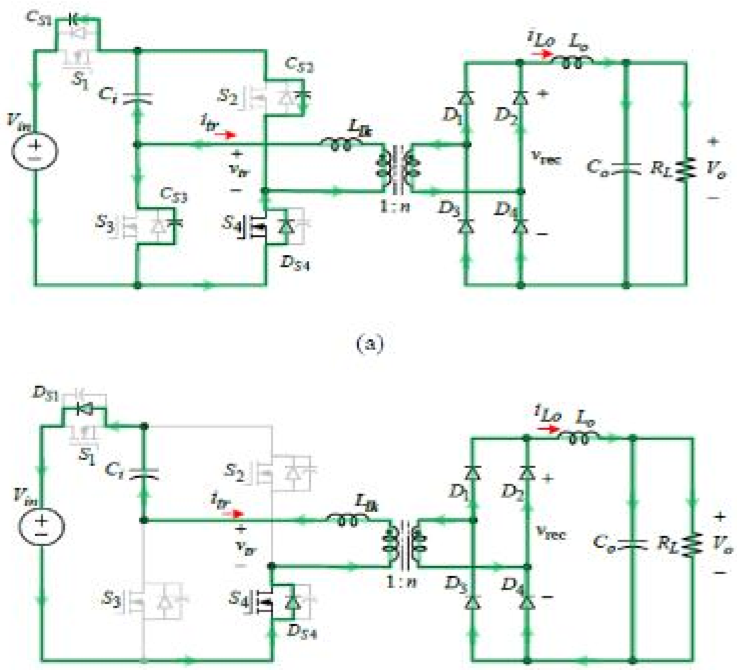

Fig. 9. Operating Mode 8 of proposed DC-DC converter

TABLE 1
OPERATING MODES OF THE CONVERTER

Conducting Switches	Non-conducting switches	Conduction path	Result
S_1,S_4	S_2,S_3	D_1-L_0-R_L-D_4	Power transfer
S_4	S_1,S_2,S_3	S_4-D_{S3}	D_1-L_O-R_L-D_4
S_3 , S_4	S_1 , S_2	S_4 -D_{S3}	D_1-L_O-R_L-D_4
S_3	S_1 , S_2, S_4	D_{S2}-C_I	Freewheels through all diodes
S_2, S_3	S_1 , S_4	C_i-S_2	D_2-L_o-R_L-D_3
S_3	S_1, S_2, S_4	D_{S4}-S_3	D_2- L_0-R_L-D_3
S_3, S_4	S_1, S_2	D_{S4}-S_3	D_2 –L_O-R_L-D_3
S_4	S_1, S_2, S_3	D_{S1}-D_{S4}	Freewheels through all diodes

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IV. SIMULATION OF THE PROPOSED CONVERTER

The proposed converter was simulated in MATLAB SIMULINK as shown in Fig. 10 and the desired waveforms were obtained. The gate trigger pulses, inductor current and output voltage waveforms are given in Fig. 11 and Fig. 12. The specifications of the circuit are: Power (P_o) =3 kW, supply voltage (V_{dc})=400 V, load voltage (V_o) =40 V, switching frequency (f_{sw}) = 50 kHz, output inductor (L_o)=70μH, capacitance (C_i) =50 μF, inductor (L_{lk})=2.5μH.

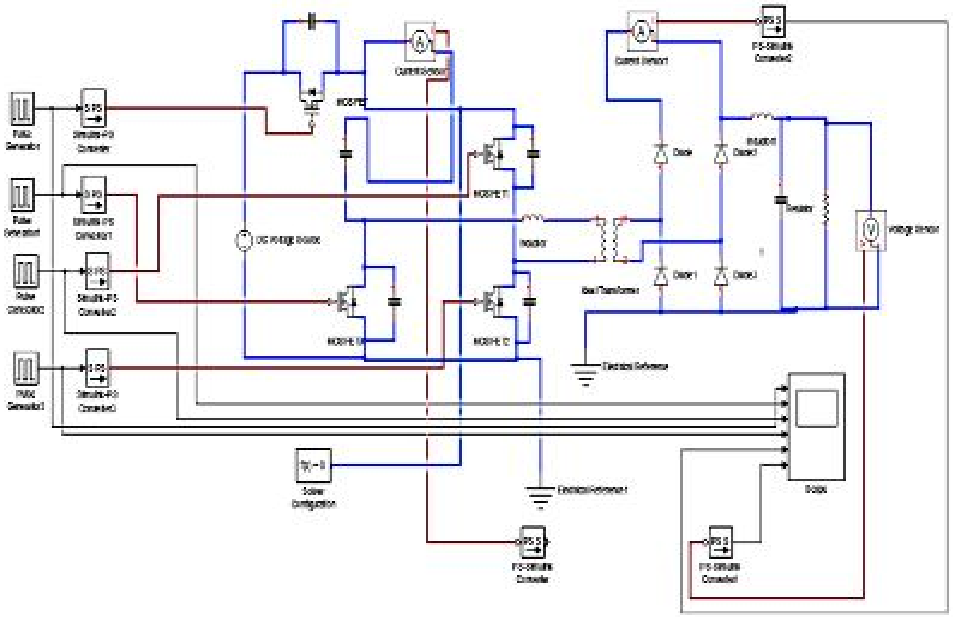

Fig. 10. MATLAB simulation model of proposed DC-DC converter

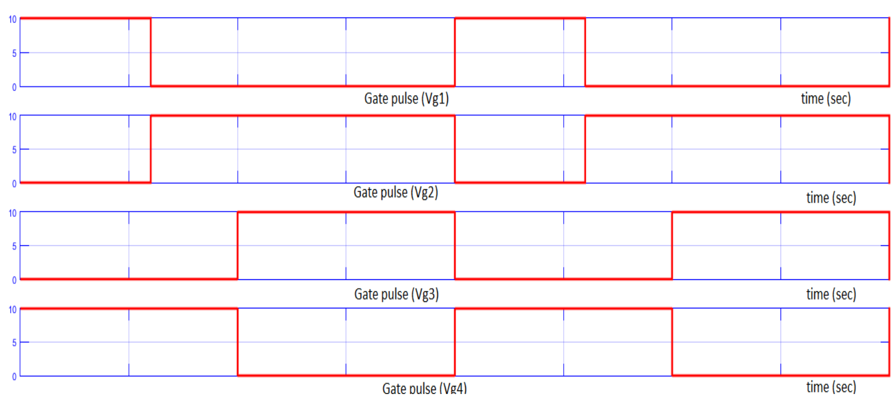

Fig. 11. Gate pulses for proposed DC-DC converter

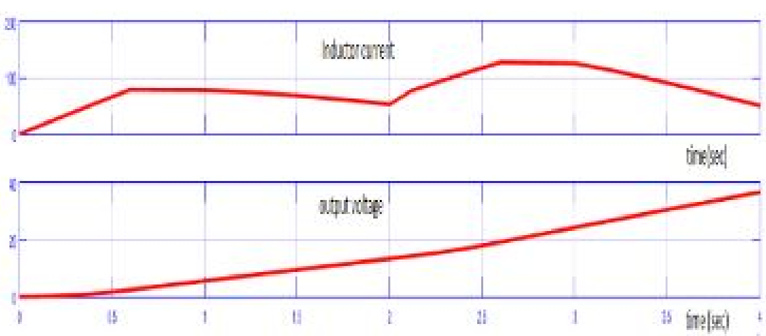

Fig. 12. Inductor current and output voltage waveforms

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The proposed converter was simulated in MATLAB SIMULINK for battery charging application as shown in Fig. 13. The inductor current and transformer primary voltages obtained are shown in Fig. 14.

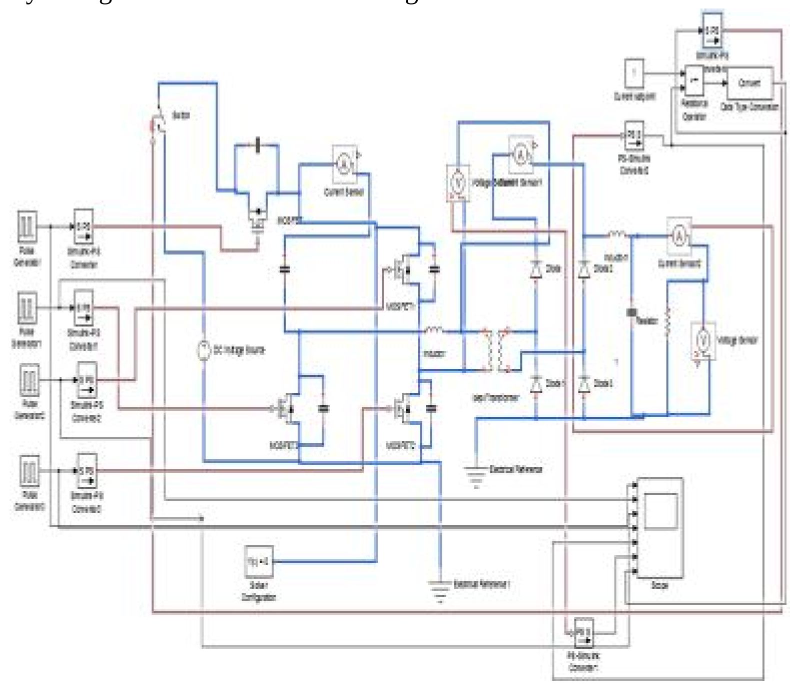

Fig. 13. MATLAB simulation model of proposed converter for Battery charging application

Fig. 14. Inductor current and transformer primary voltage waveforms

V. HARDWARE IMPLEMENTATION

The 7805 regulator IC converts the input DC voltage of 15V to 5V to provide supply to the ATmega328/P. LM7805 is a three-terminal positive regulator which provides a fixed output voltage. MOSFET IRF840 is used as the converter switch due to lower gate current and high switching frequency. Its large input impedance doesn't load the circuits. MOSFET switches are triggered at the gate using square pulses generated by ATmega328/P. The program to control the triggering of switches is preloaded in the controller. The square pulses produced by microcontroller are of 5V magnitude and insufficient to trigger a power MOSFET. A MOSFET driver IC (TLP250) amplifies TTL or CMOS logical signals to a higher voltage (8-12V) to fully turn on the MOSFET. When driving larger MOSFETs, higher gate capacitance (thousands of pF) pose an issue and a 3.3V or 5V signal is often not enough. TLP250 also works as an opto-coupler with isolated input and output stages. The ATmega328P is a low power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. The ACS7145A current sensor provides economical and precise solutions for AC or DC current sensing in robotics and automotive applications. Relay is an electromagnetic device which is used to isolate two circuits electrically and connect them magnetically. They are very useful devices and allow one circuit to switch another one while they are completely separate. They are often used to interface an electronic circuit (working at a low voltage) to an electrical circuit which works at very high voltage.

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The proposed converter is used for battery charging with automatic cut off. A 15V DC is supplied to TLP250 driver IC and 30V DC input voltage to converter is stepped down to 15V by the converter and 15V appears as pulsed input to the transformer. At the secondary side of the transformer, 8V will appear which is used for charging the battery. The current sensor ACS714 senses the current flowing through the battery and compares it with a set point value. If the compared value is equal to the set point value, battery is fully charged and it will automatically activate the relay unit to cut off the input supply to the converter. Hence battery will not charge further. Otherwise the relay unit will not activate and hence battery continues charging. The complete hardware setup is given in Fig. 15.

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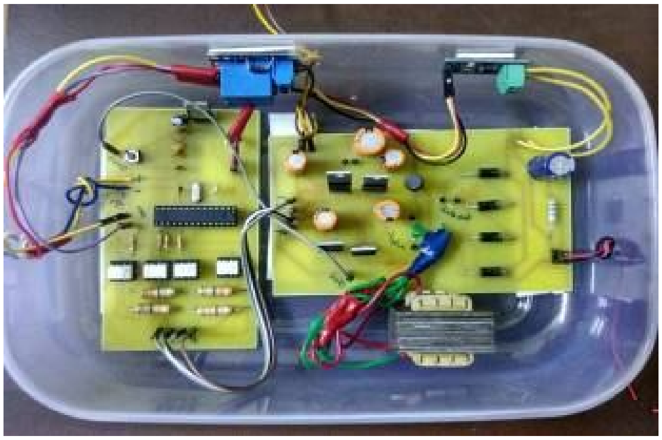

Fig. 15. Hardware setup of proposed converter for Battery charging application

VI. CONCLUSION

The isolated double step down DC-DC converter has greater efficiency than the existing converters owing to lower voltage stress of the switches which allows the converter to work at a wider ZVS range with decreased switching losses. This converter is well suitable to applications that require isolation with large step down in voltages. The converter was simulated in MATLAB environment for battery charging application and the hardware was realised and results were obtained. The isolated double step down DC-DC converter can be implemented with solar panels for battery charging applications and in cases where large DC is available for low voltage applications.

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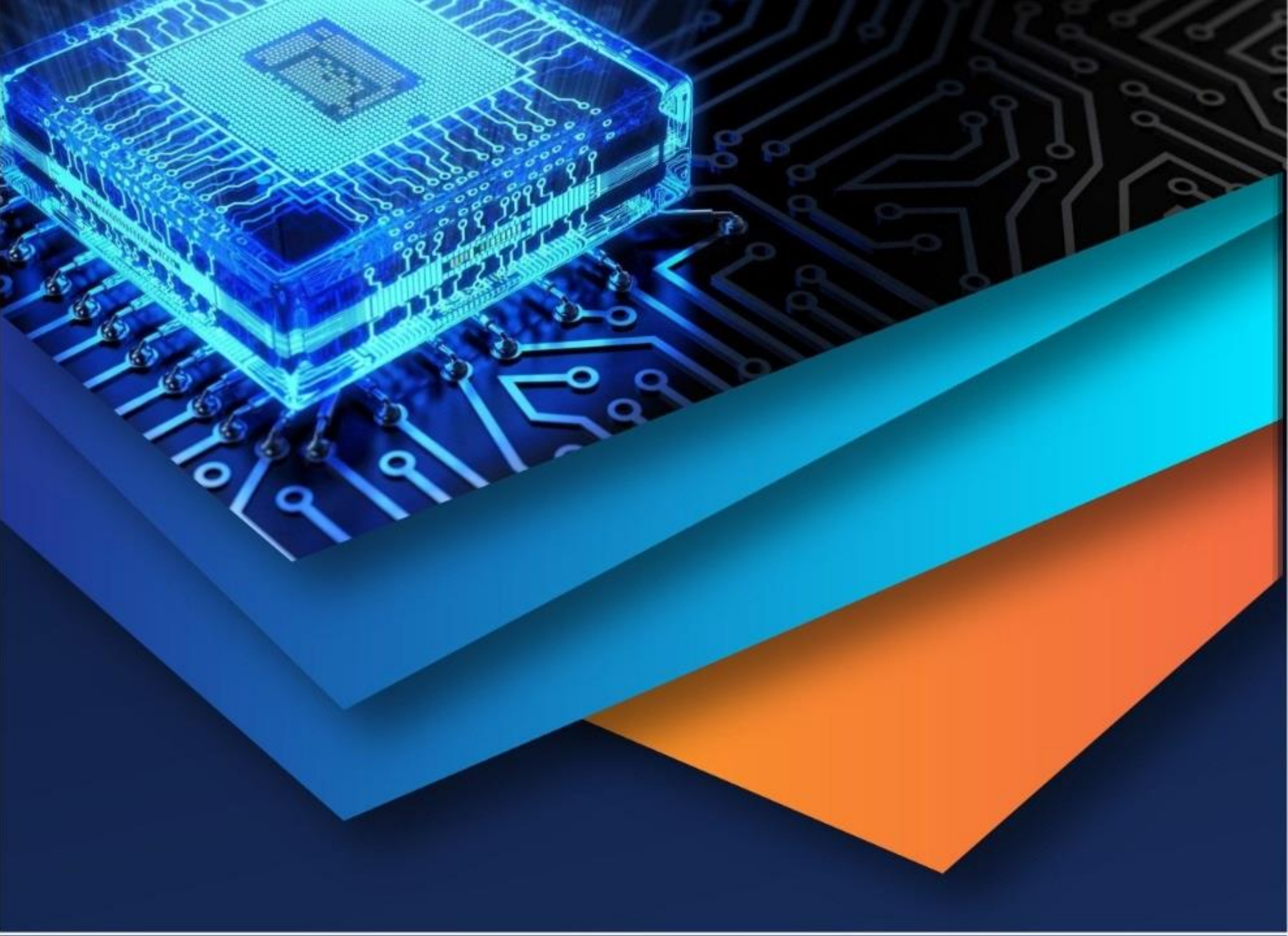

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