A Cost-Effective Design and Analysis of Full Bridge LLC Resonant Converter

Kaibalya Prasad Panda, Sreyasee Rout

Abstract—LLC (Inductor-inductor-capacitor) resonant converter has lots of advantages over other type of resonant converters which include high efficiency, more reliable and have high power density. This paper presents the design and analysis of a full bridge LLC resonant converter. In addition to the operational principle, the ZVS and ZCS conditions are also explained with the DC characteristics. Simulation of the LLC resonant converter is performed in MATLAB/ Simulink and the practical prototype setup is analyzed in Proteus software. The result is verified through analysis and design of a low cost, 200 watt prototype converter.

Keywords—LLC, Proteus, Resonant converter ZCS, ZVS.

I. INTRODUCTION

RENEWABLE energy generation plays a vital role in power generation. To get high efficiency of these systems, commonly DC-DC converters are coupled with the DC storage system. Load resonant converters are extensively used in many applications like LCD monitors, wind energy conversion systems, power supply design surface etc. An LLC resonant converter is one among such load resonant converter with advantages of high efficiency, low noise, compact design, and reliable system. LLC resonant converter overcomes drawbacks associated with the PWM converters such as high switching loss, high electromagnetic interference (EMI) noise, design complications, etc. Two basic types of resonant converters are Series resonant converter and the Parallel resonant converter. Both converters operate identically and energy circulating in the resonant circuit is tapped which supplies to the output.

In a series resonant converter (SRC), resonant component inductors and capacitors are connected in series with the load which is incapable of regulating the output under light loading conditions. A wide range of frequency variation is also required to regulate the output. In the parallel resonant converter, components are arranged in parallel with the load where the circuit inherently requires a high circulating current which makes it difficult in large load variation applications. To overcome limitations of the conventional resonant converter, an advanced structure called as the LLC resonant converter is designed [1], [2].

Series parallel resonant converters are commonly called as LLC resonant converter which consists of two inductors and one capacitor forming a resonant circuit. Voltage regulation over wide ranges and zero voltage switching (ZVS) can be achieved over the entire load range in such converters. The

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output DC voltage in resonant converter contains low harmonics and thus the overall efficiency of the system is more. The PWM switching explained in literature [3]-[5] generate more harmonics whereas; LLC resonant converter operates at zero voltage. So, THD becomes less.

This paper presents the design of a simple and compact prototype design of the LLC resonant converter which is described in following sub-sections: In Section II, the presented converter topology is described with DC characteristics. Further; in Section III, operational modes of the converter and design parameters are clearly explained. In Section IV, simulation and results are presented. The circuit is designed using MATLAB/Simulink environment and also in proteus software which shows a less THD output on the AC side of the converter due to the considerable reduction of higher order harmonics. Simulation results are verified by experimental results. The experimental setup and its operation are described in Section V.

II. FULL BRIDGE LLC RESONANT CONVERTER

In this paper, a full bridge LLC resonant converter topology [6]-[8] is described. Fig. 1 shows presented full bridge LLC resonant converter. Input DC voltage is converted to AC by the help of a full bridge rectifier circuit and energy is transferred to the resonant tank circuit consisting of Lm, Lr, Cr and load is connected in parallel with Lm.
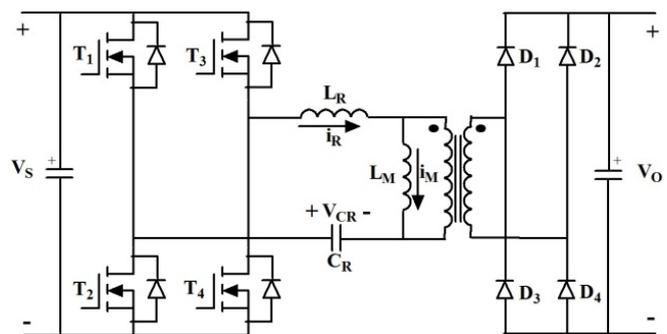

Fig. 1 A full bridge LLC resonant converter

The DC characteristic of the converter is dependent on two resonant frequencies which are given in (1) and (2):

$$f_1 = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_2 = \frac{1}{2\pi\sqrt{(L_m + L_r)C_r}} \tag{2}$$

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Under light loading condition, peak of the characteristics moves close to f_2 and under heavy loading condition, peak moves close to f_1.
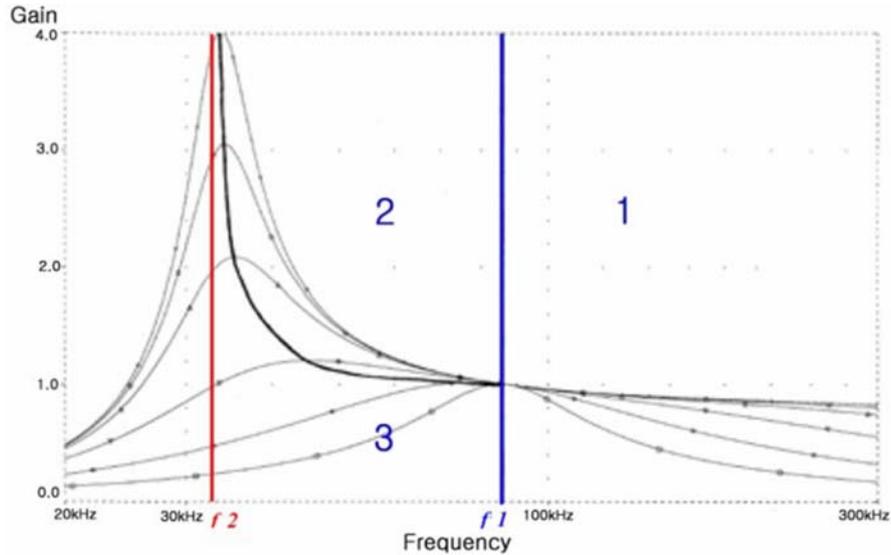

Fig. 2 DC characteristics of the presented converter

Under different loading condition, a DC characteristic shown in Fig. 2 is partitioned into different regions. Region 1 is the operating region of the proposed converter in which ZVS condition is naturally achieved. Region 2 is categorized where the load condition between f_1 and f_2 decides the converter operation under ZVS and ZCS condition. This is called as multi-resonant converter region. Converter is fully operated in ZCS mode in the overloaded region marked as Region 3.

MOSFETs are generally preferred for designing of the LLC resonant converter; which allows high frequency operation ensuring less switching loss. This can be achieved by choosing proper values of L_m, L_r and C_r.

III. OPERATIONAL MODES OF THE PROPOSED CONVERTER

The mode of operation of the proposed full bridge LLC resonant converter [9], [10] is divided into five different modes which are as follows:

- **Mode 1 (t_1):** During this mode, switches T2 & T3 are switched on and then the power is fed from the input voltage source to the load resistance. The primary side inverter current decays gradually in resonant manner through the diode D1 & D4 and secondary current flows to the load.
- **Mode 2 (t_2):** In this mode, only the magnetizing current appears in the primary side and secondary side current becomes zero at ZCS. Thus the diode D1 & D4 turns off.
- **Mode 3 (t_3):** T1 & T4 are turned on during this mode and T2 & T3 are turned off at ZVS. Current flows in the load circuit through the diode D2 & D3.
- **Mode 4 (t_4):** During this mode, the primary side inverter current reverses its polarity and simultaneously secondary side current rises gradually from zero. ZCS turn on of diode D2 & D3 can be obtained in this mode and power is

injected from the voltage source to the load through the resonant tank circuit.

- **Mode 5 (t_5):** In this mode, power from the voltage source is transferred to the load in resonant manner. At the end of this mode, polarity of the magnetizing current changes which initiates the next half cycle in the same manner as described in the above modes.

Fig. 3 represents the output waveforms in different modes. Current through the resonant inductor L_r, L_m and voltage across the resonant capacitor C_r is also shown in the same.
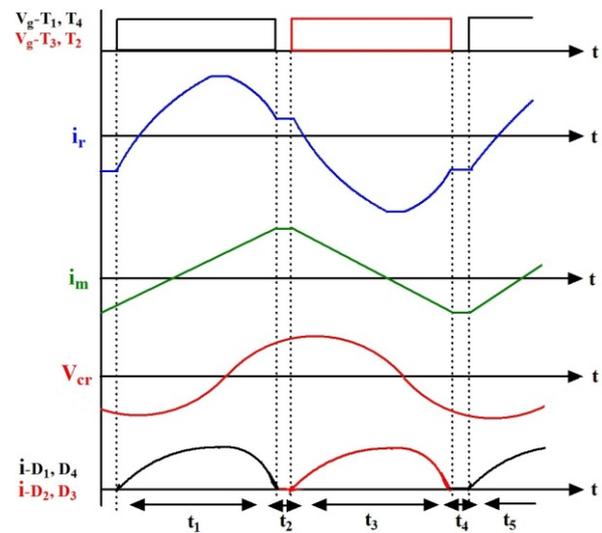

Fig. 3 Output waveform of the proposed LLC resonant converter

The design parameters are calculated using the gain equation as described in some of the references, [11]-[13], taking harmonics approximation into consideration. The gain function is given by,

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$$G_C = \left| \frac{L_1 f_1^2}{\left[f_1^2 \left(L_1 + 1 \right) - 1 \right] + j \left[\left(f_1^2 - 1 \right) L_1 Q f_1 \right]} \right| \qquad (3)$$

$$f_1 = f_s / f_r \qquad (4)$$

$$L_1 = L_m / L_r , L_m = t_{dead} / 16 C_s f_{r1} \qquad (5)$$

$$Q = Z_r / R_{ac} = \sqrt{L_r / C_r} \left/ n^2 R_o , C_r = 2\pi f_{r1} / Z_r \right. \qquad (6)$$

where, f_1 = normalized frequency, L_1 = Inductance ratio, Q = Quality factor, n = turns ration of the transformer i.e. N_p/N_s,

t_{dead} = dead time of the driving circuit, C_S = output capacitance of the switches, Ro = effective load resistance.

IV. SIMULATION AND RESULT

The LLC resonant DC-DC converter is composed of the bridge driver, the LLC resonant tank and the rectified DC load. The LLC DC-DC resonant tank excited with an AC source. This LLC resonant tank is composed of series resonant capacitor Cr, series resonant inductor Lr, parallel resonant inductor Lm and equivalent load resistor Req. The simulation uses MATLAB/SIMULINK software and for experimental verification, proposed converter is moreover designed using PROTEUS software. The simulation circuit is shown in Fig. 4.
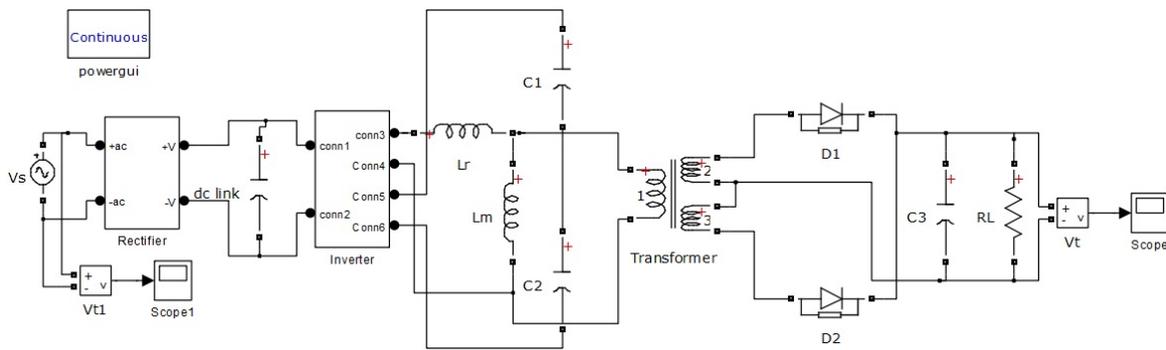

Fig. 4 Simulation circuit for the proposed LLC converter

The internal subsystem contains single phase full bridge rectifier together with single phase full bridge inverter circuit which is shown in Figs. 5 & 7 respectively. Output voltage waveforms of the same are shown in Figs. 6 & 8 respectively. By changing the value of leakage inductance smooth output can be obtained which is shown in Fig. 9.

V. PROTEUS DESIGN FOR PROPOSED CONVERTER

LLC tank circuit behaves like a selective tuned circuit, i.e. it produces approximately a sine wave inverter output current and voltage waveform of switching frequency fs. The proposed converter in closed-loop is simulated by PROTEUS software. When the operating frequency is higher than the frequency at the peak voltage gain of the LLC resonant tank with different load conditions, MOSFET achieves a ZVS condition in their turn-on transition.

In order to provide ZVS condition, there should be inductive impedance; so that the resonant current will lag behind supply voltage. The magnetizing inductor Lm should be able to supply the required amount of inductive energy. The value of Lm is selected such that the magnetizing current should not be more than 20% of the resonant current [14]. Literature study shows; to reduce the conduction losses the value of Lm should be high, but to have a successful ZVS its value should be as small as possible.

The following components are used in designing the simulation circuit.
1. TRAN-2P2S - Transformer
2. IN4007 - Diodes
3. Capacitor
4. Resistor.
5. LM7812 - IC
6. IN4742A
7. IC555- Timer chip
8. IRF540- N-Channel MOSFET
9. BC547
10. RV- Variable resistor
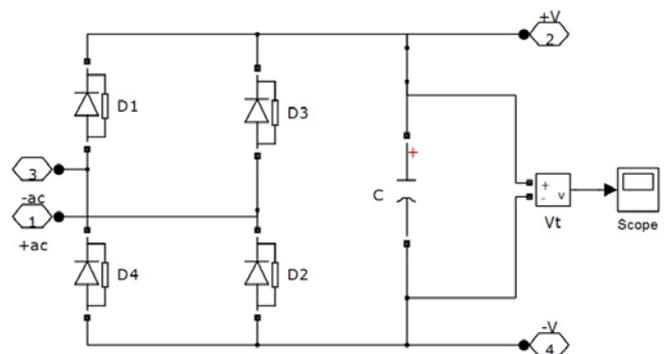11. 1210-121k
12. ATMEGA8 microcontroller

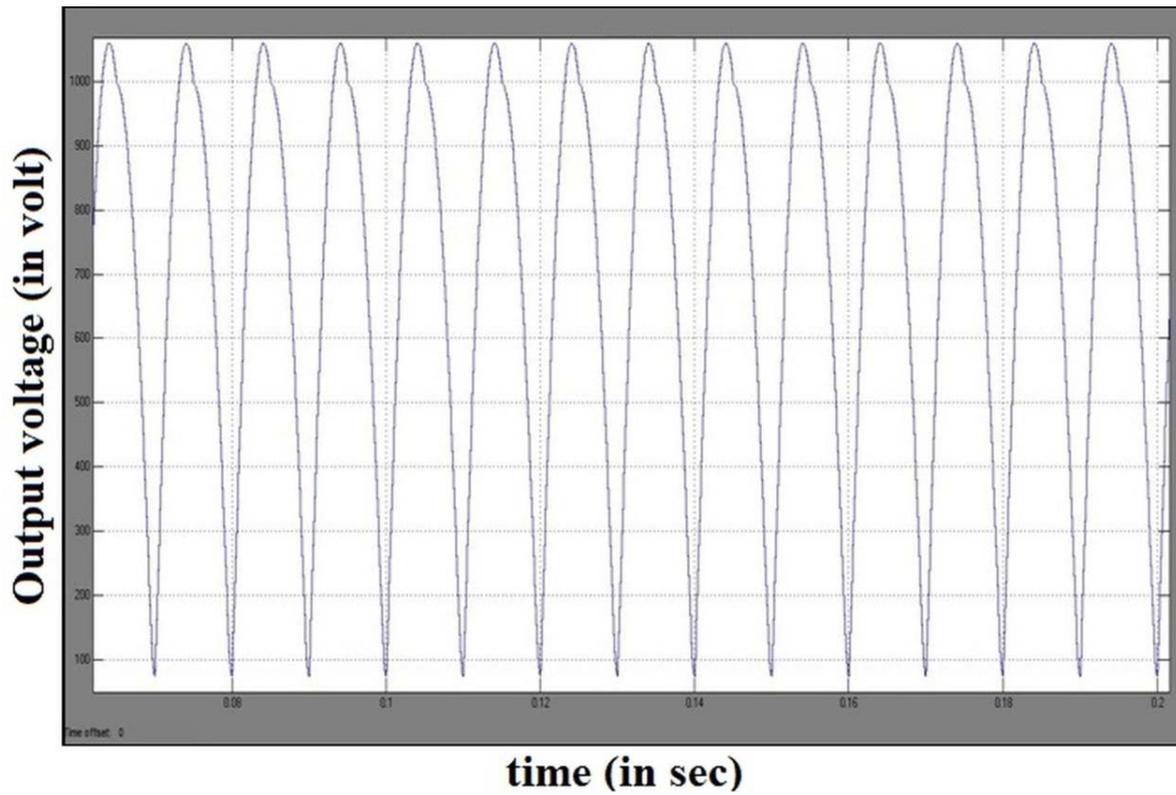Fig. 5 Simulation of rectifier subsystem block
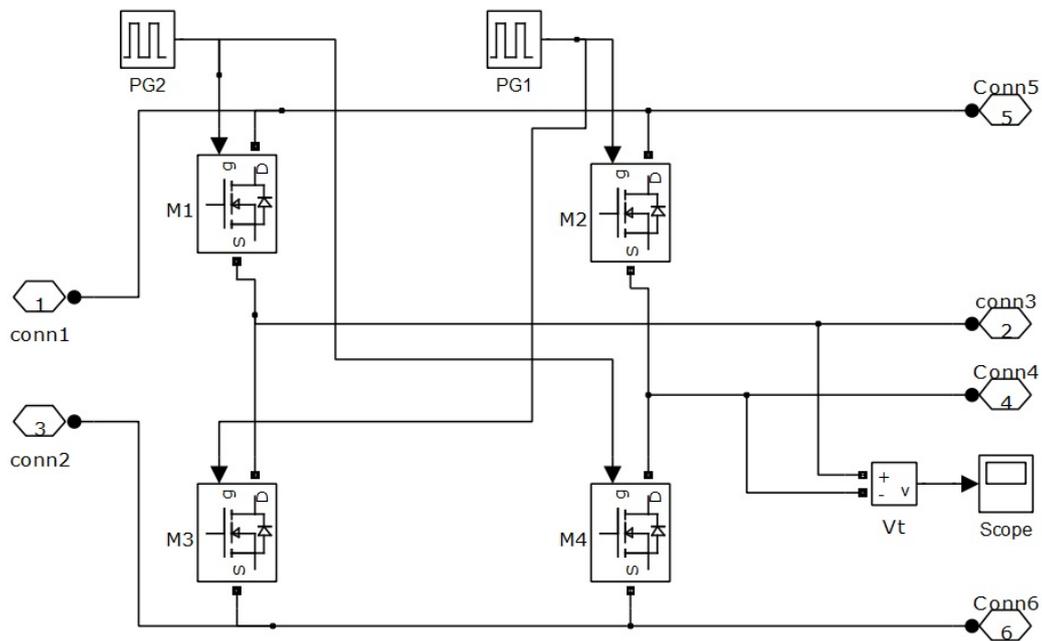
Fig. 6 Output of rectifier circuit

Fig. 7 Simulation of inverter subsystem block

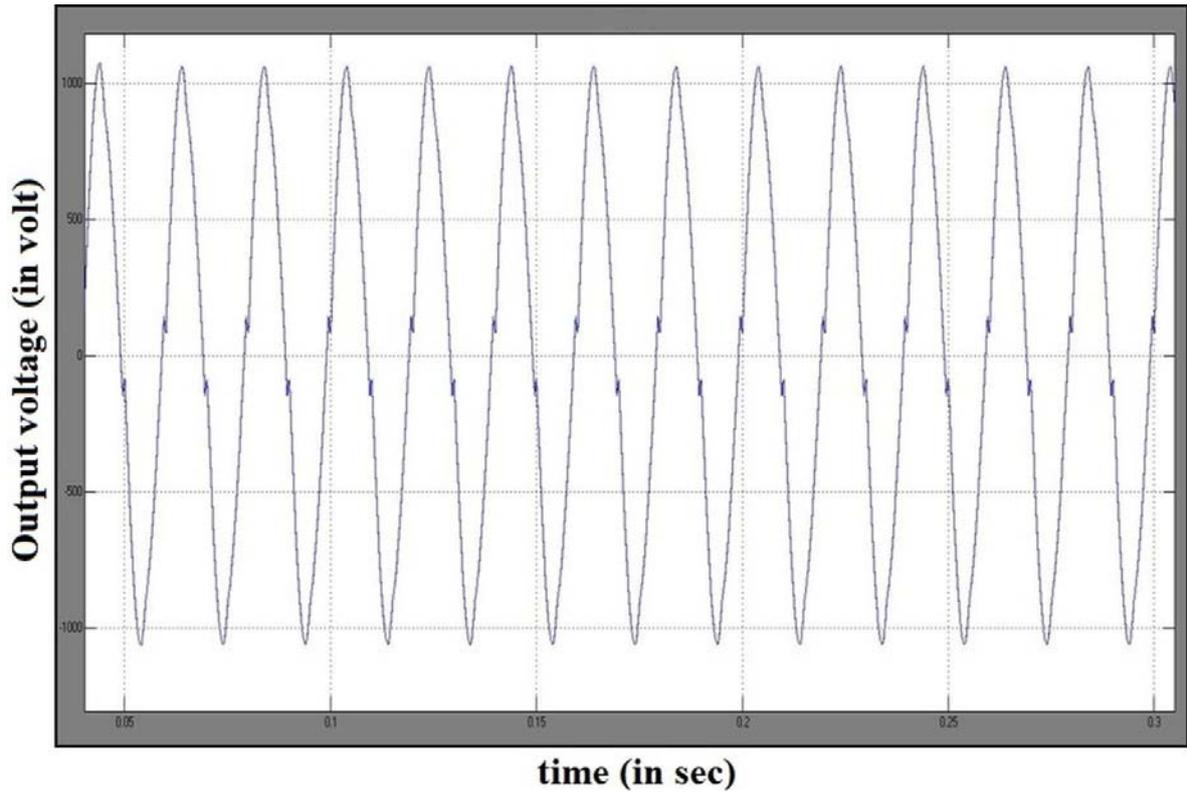World Academy of Science, Engineering and Technology
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Fig. 8 Output of inverter circuit
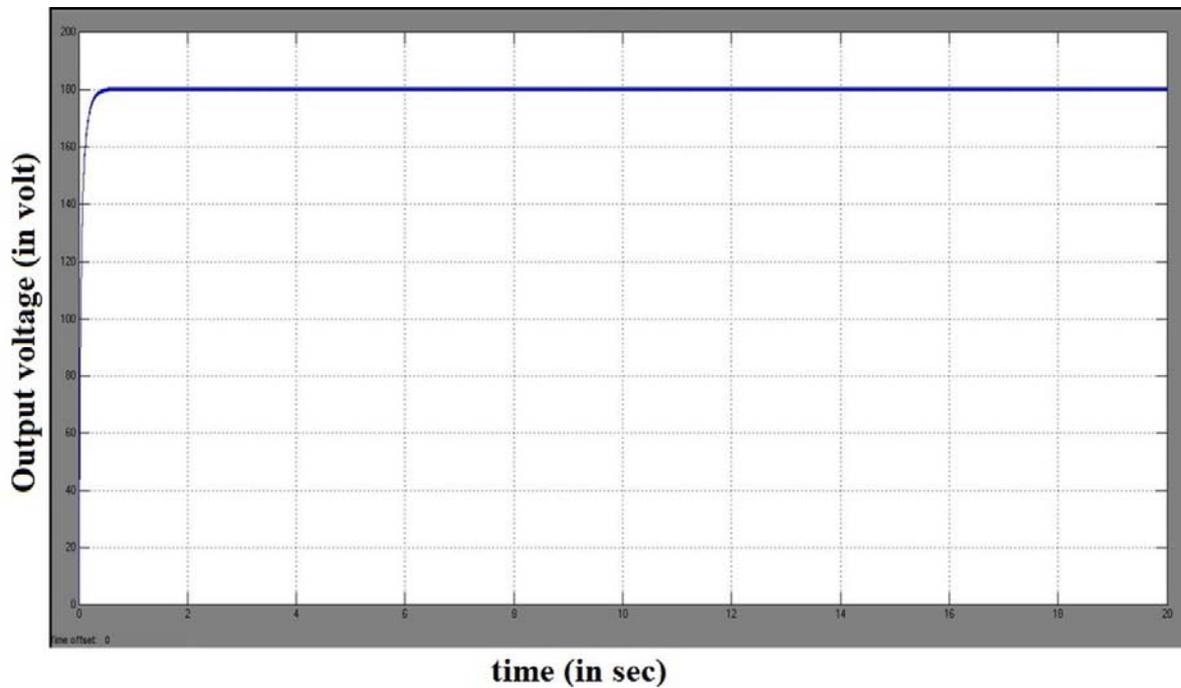
Fig. 9 Output voltage waveform on loading condition obtained from simulation

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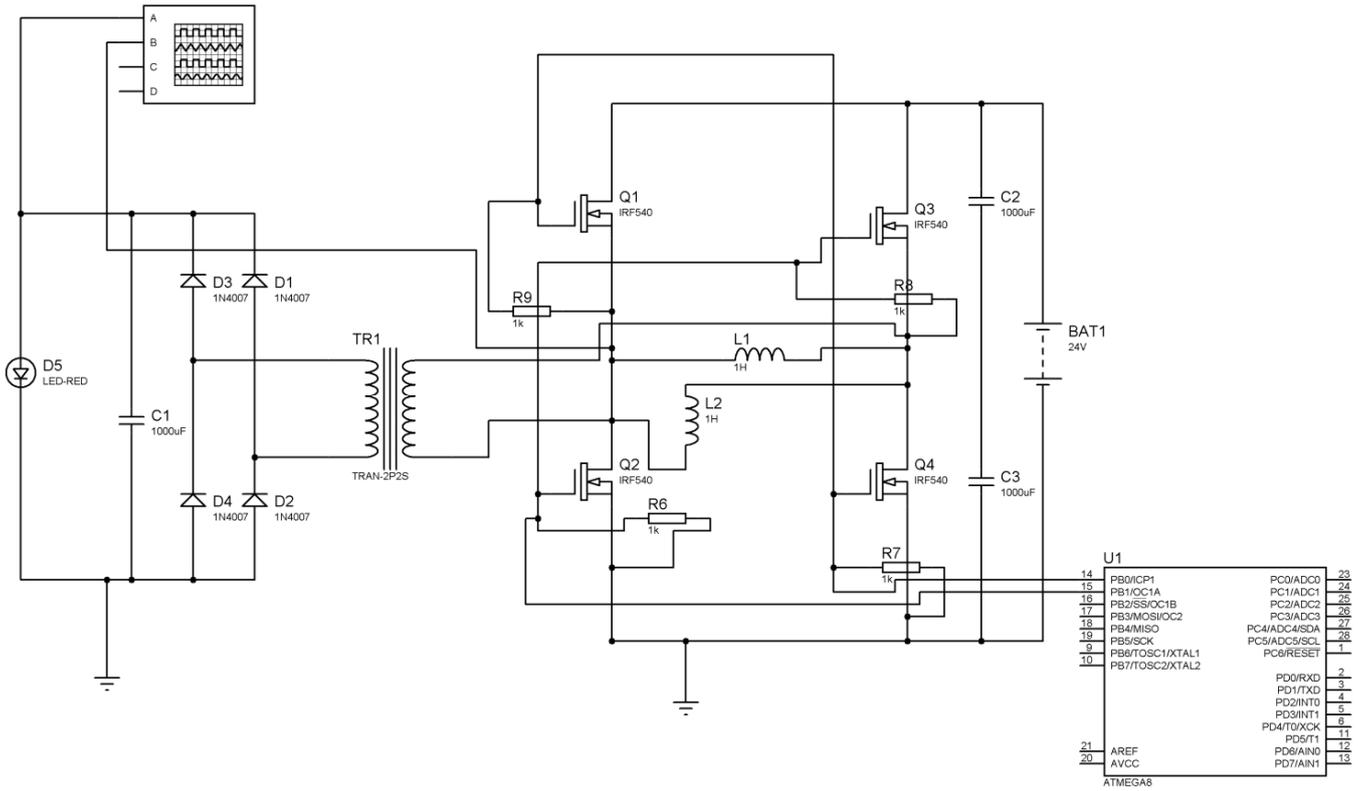International Journal of Energy and Power Engineering
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Fig. 10 Proposed circuit design using proteus
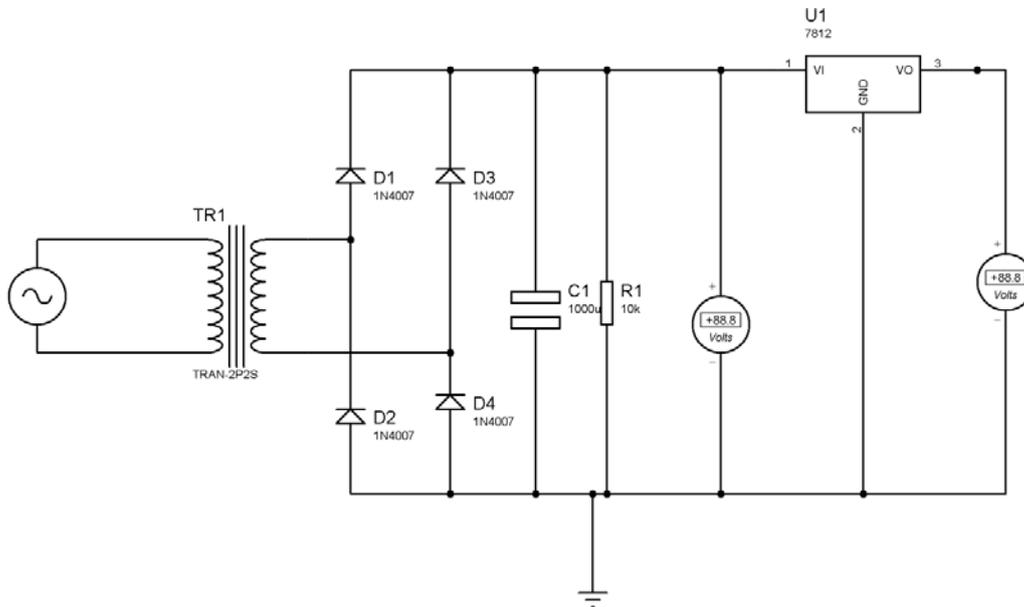
Fig. 11 Rectifier circuit design using proteus

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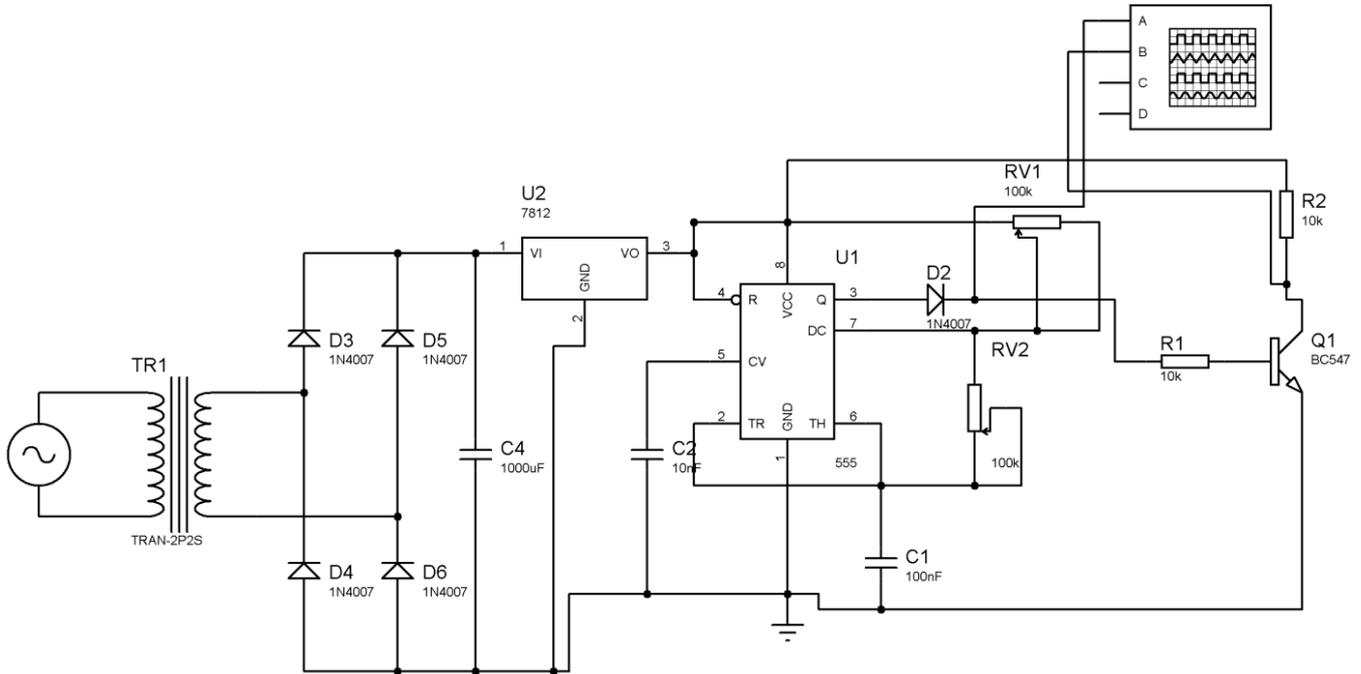Vol:10, No:8, 2016

Fig. 12 Pulse generator circuit design using proteus

Fig. 13 Output obtained from proteus simulation

VI. EXPERIMENTAL SETUP

A prototype of the proposed LLC resonant converter is developed as shown in Figs. 14 & 15 with design values of the components are calculated using (1)-(6). The quality factor is also calculated which depends on the loading. Due to the easy availability of input AC supply is used in designing the circuit. It is then converted to DC by using rectifier circuit. AVR programmer has been used for programming of ATmega8 microcontroller and ICs are used which can generate pulses for the MOSFETs. Results obtained from the prototype are shown in Figs. 16 & 17 respectively which illustrates the proposed converter is well operating under soft switching as well as under full loading conditions.

The following components are used in designing the prototype of proposed converter.
1. Step-down transformer
2. Rectifier Circuit
3. IC7812
4. IC7805
5. ATMEGA8 microcontroller
6. IR2110
7. IRF540N
8. Inductor
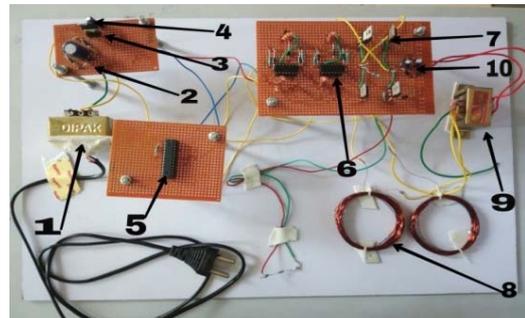9. Step-up Transformer
10. Rectifier Circuit
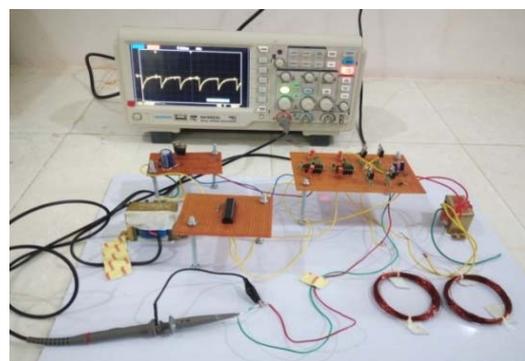

Fig. 14 Experimental setup of proposed circuit

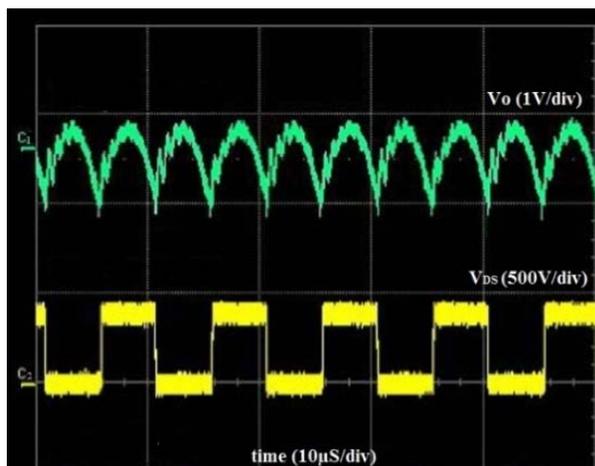Fig. 15 Experimental setup with its output

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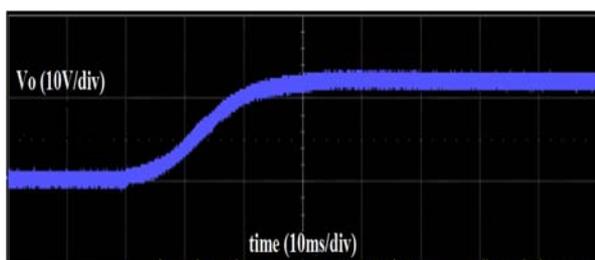Fig. 16 Output voltage waveform at full load condition

Fig. 17 Output voltage during soft start condition

VII. Conclusion

In this paper, optimal design and analysis of full bridge LLC resonant converter is presented. Comparison, advantages and drawbacks associated with various types of LLC resonant converters are explained. ZCS and ZVS condition of rectifier and MOSFETs are analyzed from the DC characteristics of presented converter. Due to ZVS and ZCS switching of the converter, the higher order harmonics are reduced. A full bridge LLC resonant converter is simulated using two different software environments. The results are verified with the compact and efficient low cost 24V, 200 watt prototype design which shows the efficiency of the proposed converter exceeds more than 90% with full load condition due to reduction in THD.

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