IMPLEMENTATION OF CLOSED LOOP CONTROL OF 12 -12 VOLTS ZERO VOLTAGE SWITCHING DC-DC CONVERTER

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Abstract : To achieve high efficiency with power density a full bridge DC-DC converter topology is used. This aims for high power applications and lower Electromagnetic interference. The proposed paper analyses and presents a Phase modulated series resonant converter which is implemented to increase the efficiency of the system. Zero Voltage Switching has been used to minimize the switching losses. This paper aims at designing of closed loop Zero Voltage Switching Phase modulated series resonant converter. The input of 12 Volts is applied on the source side and expected to get regulated 12 Volts as the output. The said converter consists of Pulse generation control, control circuit and resonant tank circuit. MATLAB-SIMULINK software package is used for the simulation purpose. The hardware is also been implemented and expected results are obtained.

***Index Terms* - Full bridge converter, Phase modulated topology, Series resonant converter, Zero Voltage Switching (ZVS).**

I. INTRODUCTION

For high power applications and power conversions series resonant converter plays very important role. By adding a capacitor in series with leakage inductance of the transformer a resonant circuit is formed. Instead of varying switching frequency, the duty ratio is varied and this results in Phase modulated series resonant converter (PMSRC). If converter is operating above the resonant frequency Soft switching can be achieved. This concept can be extended for higher wattage applications using similar design and different specifications. Fig. 1 shows the block diagram of the proposed converter for which a feedback path is implemented to obtain the stable operation and constant output voltage of 12 V.

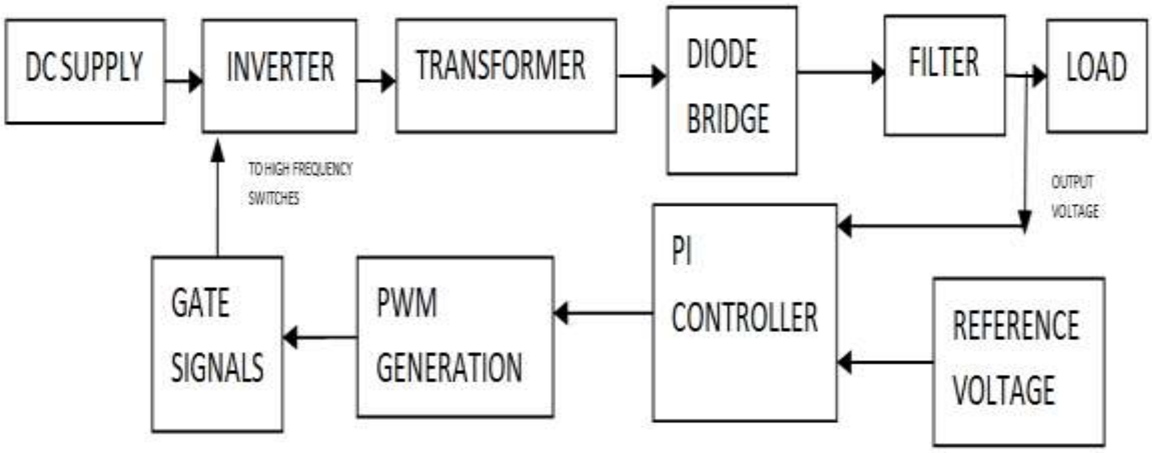

Fig. 1: Block diagram of the proposed converter

1.1 Concept of Phase Modulated Converter

Phase Shifted Pulse Width Modulated Converter is a Phase Modulated Converter (PMC) with full bridge topology. Basic principle of operation of PMC is as follows:-

Lossless switching is possible in converters like double ended converter, push-pull, half bridge, full bridge etc, if duty ratio is kept fixed. To control the input with duty ratio fixed schemes other than variation of duty ratio have to be employed. Phase modulation can be implemented for a full bridge converter. Phase modulation means varying phase difference between two legs of the bridge, i.e. phase difference between V_A and V_B. Phase difference is varied by introducing phase lag or time delay in switching of PMC.

By introducing time delay in switching keeping output voltage constant, the input voltage can be varied by varying phase difference of PMC [1].

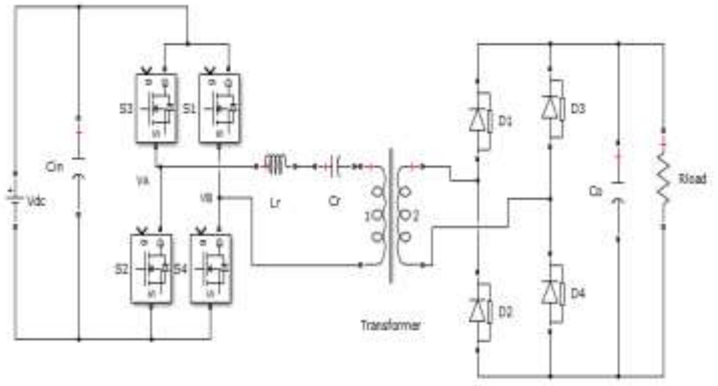

Fig. 2: Full bridge SRC converter topology

The full bridge series resonant converter circuit implemented in the present paper is shown in fig. 2. A full bridge series resonant converter consists of four switches S1, S2, S3 and S4 with a resonant tank on the primary side of the high frequency transformer. On the secondary side, there exists a diode bridge to convert AC signals to DC. To remove the ripple content present in the output DC voltage, a capacitor is used on the output side.
Schematic of PMC whose input is ac waveform to the transformer having phase difference of 90º is shown in fig. 3

High power densities can be achieved with lower losses. Soft switching can be achieved with either Zero Current Switching [ZCS] or Zero Voltage Switching [ZVS]. To operate the converter in ZVS mode the converter should have operating frequency greater than resonant frequency and to operate the converter in ZCS mode, the operating frequency should be lesser than resonant frequency. A DC-DC converter is required to efficiently deliver well regulated, low-ripple current to the load connected to it [2].
To maintain the voltage at a defined value across the DC link, a full bridge rectifier is selected. When the controller is connected in the feedback path, the output voltage should be maintained equal to the reference value [3].

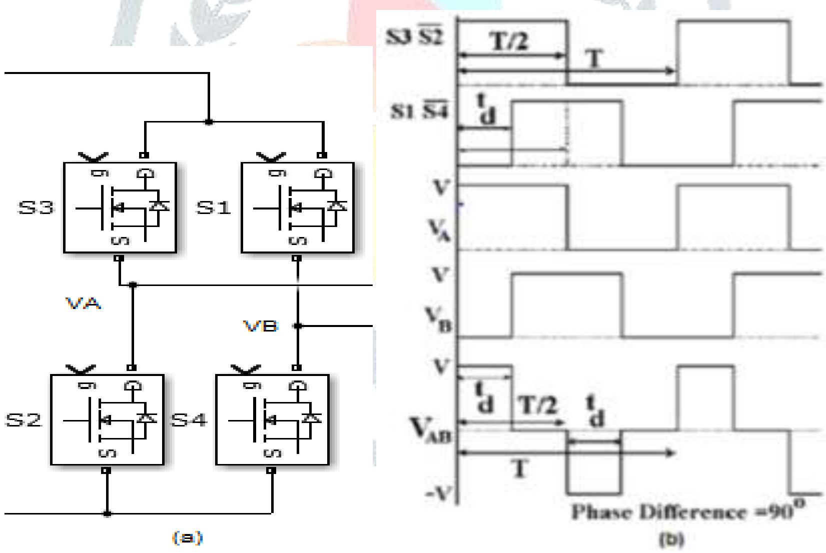

Fig. 3: (a) Schematic of Phase modulated converter
(b)Waveform with phase difference of 90º

In fig. 3(b), t_d is time delay (in seconds) in switching two legs and T is switching time period (in seconds).

The current through the device is made zero by external means just prior to the turn-off in the ZCS converters, thus eliminating the turn-off losses. In the ZVS converters, turn-on losses are eliminated by making the voltage zero across the device. Resonant converters & Resonant Switch converters add extra resonating LC tank circuit to achieve soft switching by making the device current or the voltage sinusoidal, and switching at the zero crossing instants of the current or the voltage.

Overall switching period of the converter is determined by the resonant circuit [4]. Resonant Transition converters combine the low switching loss characteristics of the resonant converters and the low conduction loss and constant frequency characteristics of the PWM converters. The Phase modulated converter presented in this paper offers ZVS transitions. To have high efficiencies even at high switching frequencies, soft switching techniques are the key factors [5].

The operation is identical to the square wave PWM full bridge converter. These features make Phase modulated converter as the preferred topology for high voltage and high frequency applications. Operation principle of this converter is explained in section II. A resonant converter is also suitable for the applications where there is a wide range of variation on the input side. The output filter inductor can be eliminated if resonant converter is implemented [6].

II. PRINCIPLE OF OPERATION

The basic operation principle of the phase modulated converter is brought out by the following three points

- In any converter, like the push-pull, half-bridge, full-bridge etc., by keeping the duty ratio fixed, it is possible to design for Zero Voltage switching.
- In a full bridge converter, Phase Modulation is the simplest alternative scheme to control the output with duty ratios fixed.
- The output capacitance should be significant, for high voltage and high frequency applications. This gives the low ripple filtered output.

To turn-off MOSFET and to turn-on the complimentary MOSFET, a definite dead-time T_{delay}, has to be allowed in the same arm. Next section discusses the factors affecting ZVS.

III. FACTORS AFFECTING ZVS

To obtain ZVS, it is clear that large magnetizing current and leakage inductance should have desired polarity. The discharge current to the transformer primary is done by turn-on of a MOSFET to get ZVS. To discharge switch output capacitances, soft switching technique for zero-voltage-switching (ZVS) uses resonant currents [7]. The primary current should maintain the proper polarity till the capacitance is fully discharged. Total primary current reverses at heavy loads. Hence T_{delay} has to be smaller at heavy loads. Ideally, T_{delay} should be load dependent. At light loads, the primary current of the transformer has its peak value during the transition from the right leg which reflects as the secondary current of the transformer with the highest current on the output filter capacitor from which ZVS can be achieved [8]. Higher circulating currents on light loads decreases the efficiency of the circuit. The parameters affecting ZVS are magnetizing current that aids ZVS but if it increases, it may lead to higher stress and conduction losses. Section IV discusses about Series Resonant Converter.

IV. SERIES RESONANT CONVERTER

The SRC aids in intrinsic low switching losses that allows operating at higher switching frequencies and taking advantage of inevitable parasitic inductances as a part of resonant tank, lower electromagnetic interference (EMI) levels, higher power density, a single capacitor as output filter.SRC is preferred for high input applications and high efficiency performance. A diode bridge is connected on the secondary side of the transformer to rectify the AC voltage and provide DC voltage on the load side along with a filter capacitor to eliminate the ripple content [9].
The following assumptions are considered for the analysis:

1) The converter switching frequency is constant and greater than the resonant frequency.

2) The converter uses the phase-shift modulation scheme and has settled in steady-state operation.

3) Output capacitor is large and output voltage is constant with no ripple. The variation range of V_{out} is from zero to V_{in} .

In SRCs, the transformers are usually designed to have minimum losses and this requires selecting the maximum flux density of the magnetic core in the linear region of the *B*–*H* curve. Also, for a proper transformer a tight coupling between primary and secondary windings, is required. Thus, the magnetizing current can be safely neglected as far as the voltage gain and soft-switching aspects are concerned.

In practice, the specifications of an output-voltage-regulated DC–DC converter usually designed such that regulation must be less than 1% for the maximum peak-to-peak voltage ripple at the output terminal. In a SRC, the output capacitor provides the low impedance path for the AC component of the rectified current after the diode bridge. Because of the large magnetization inductance of the transformer, there is only one possibility for the resonant current to flow, i.e., through the rectifier bridge. Therefore, the SRC is operational only if the condition $V_{in} \geq nV_{out}$ [10].

The proposed paper deals with Series Resonant Converter (PM-SRC) which is operating at a fixed switching frequency and is duty ratio controlled with Zero Voltage Switching to eliminate switching losses. The PM-SRC is also referred to as the phase Modulated SRC or pulse width modulated SRC [11].

It consists of a full bridge inverter feeding a series resonant tank. The tank current is rectified and filtered using a capacitive filter to produce the required DC voltage. This method can be implemented for high voltages. High voltage is obtained using a step up transformer and voltage multiplier circuits. Low voltage on the secondary side can be obtained from high voltage using a step down transformer. Control is achieved through phase modulation. Conduction of switches on the leading leg of the inverter is phase shifted with respect to the conduction of switches on the lagging leg resulting in a quasi-square excitation voltage.

Parasitic inductance of the transformer becomes part of the resonant inductance *Lr*. By including the resonant capacitor *Cr* and exciting the tank with a voltage waveform *V*, having frequency close to the tank resonant frequency, the effective impedance offered by the parasitic inductance to power flow is reduced. The circuit offers ZVS when operated above resonant frequency; this is preferred for a MOSFET based inverter [12].
Discrete time domain modeling can be used to derive a linearized small-signal phase-shift to output voltage transfer function for the PM-SRC. This can be used for linear closed loop PI control design for the stable operation [13].

Design of the converter is as follows,

In the proposed paper, the converter input voltage is 12V with the expected output of 12V having the regulation of ±1%. The closed loop simulations are carried out using MATLABS software and the expected output is obtained as per the calculations. Input voltage (Vi) = 12V, Output Voltage (Vo) = 12V. For the experimental purpose the load applied is 0.26watts. This can be extended to higher wattage ratings upto few kilowatts and can be implemented with proper design. The operating frequency considered in the proposed model is 100 kHz. The designed equations of the resonant capacitance and inductance are given in equations 1 and 2,

$$Cr = \frac{k}{(2*\pi*fs*Q*Rp)} \qquad \text{Equation 1}$$

$$Lr = \frac{k*Q*Rp}{(2*\pi*fs)} \qquad \text{Equation 2}$$

Where, $k = \frac{fs}{fr}$

Cr = Resonant capacitor

Lr = Resonant inductor

fs = Switching frequency

Q = Quality factor

Rp = Resistance of the primary circuit

This section is followed by section V which shows the simulation results.

V. SIMULATION RESULTS

The simulation is carried out using MATLAB software package. In the feedback path a PI controller is connected for which a constant value of 12V and the output voltage sample is fed. The output of the PI controller is given to the pulse generation scheme. The gate pulses are generated according to the variation in the output voltage and switching of high frequency switches takes place which maintains the output voltage constant for varying load. Fig. 4 shows the proposed simulated circuit considering the closed loop operation.

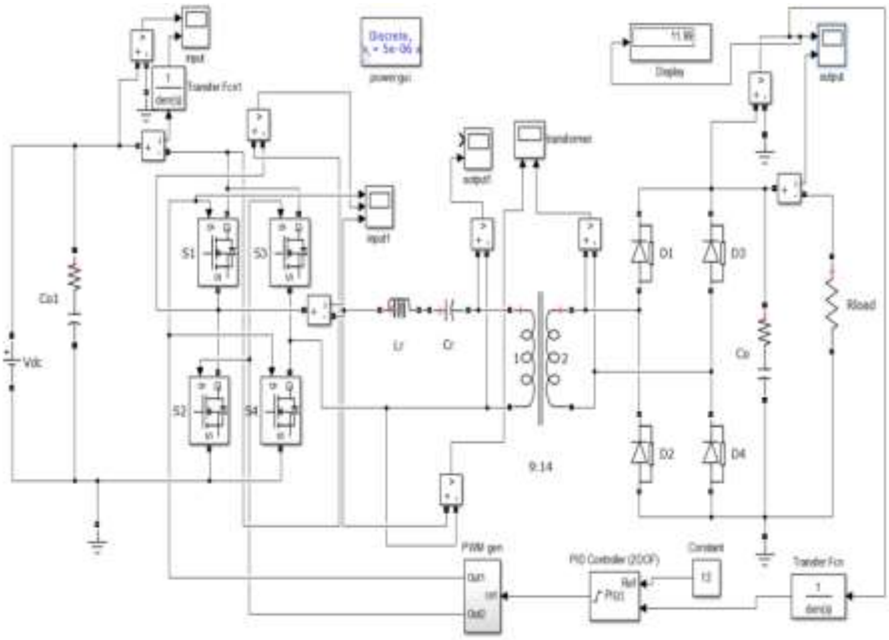

Fig. 4: Circiut used for simulation

Fig. 5 shows the simulated waveform of primary bridge voltage. Y-axis is the magnitude of the voltage and X-axis is the time in seconds.

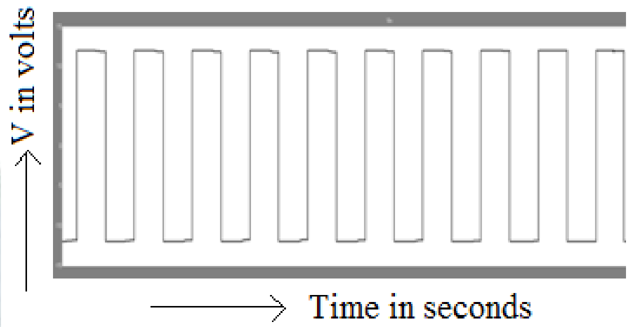

Fig. 5: Primary side bridge voltage – 12V

Fig. 6 shows simulated waveform of the resonant tank voltage which is aiding ZVS operation. When the gate pulse is turned on, the voltage across the switch is zero and continues in zero voltage itself even after the switch is off because of the resonance effect. The magnitude of the voltage is 12V across the switch.

First waveform in fig. 6 shows the gate pulse and the second waveform is the drain to source voltage (Vds) i.e. voltage across the switch i.e. 12V where, Y-coordinate is voltage and X-coordinate is the seconds.

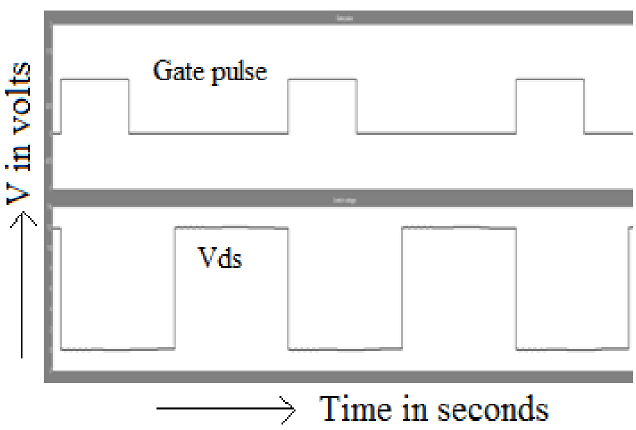

Fig. 6: ZVS waveform

The simulated output voltage of the converter is shown in fig. 7 for the closed loop operation at load resistance of 100ohms and the output voltage magnitude of 12V. In the graph Y-axis refers to voltage in volts and X-axis refers to time in seconds.

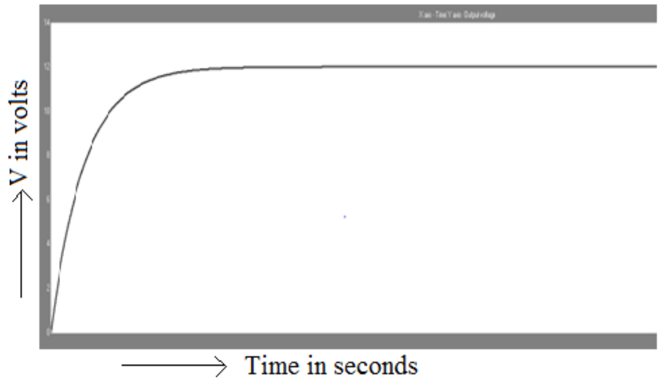

Fig. 7: Output voltage for 100ohms load

By implementing full bridge converter along with the resonance effect and soft switching technique, required output can be obtained for varying load conditions.

For different load conditions, the output from the circuit is designed to obtain constant output of 12V. This can be observed from fig. 8 and fig. 9. In both the waveforms Y-axis is the voltage magnitude and X-axis is the time in seconds.

Fig. 8 shows the output voltage of 12 V for the load resistance of 98ohms.

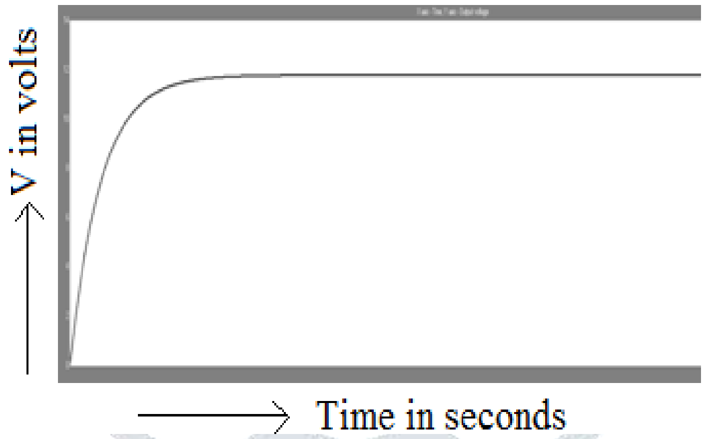

Fig. 8: Output voltage for 98ohms load

Constant output voltage waveform of 12 V for 103ohms load is shown in fig. 9.

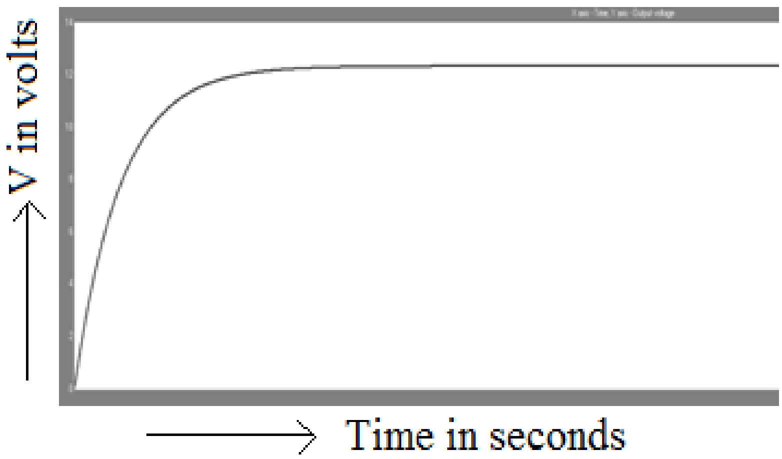

Fig. 9: Output voltage for 103ohms loads

Bode plot for the implemented converter is shown in fig. 10 which gives the stability details. The stability details are obtained using MATLAB software tool.

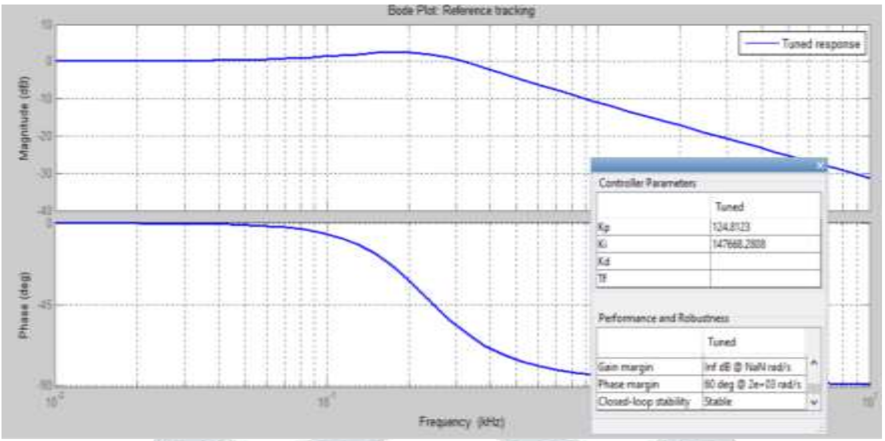

Fig. 10: Bode plot of the proposed converter

The plot has the bandwidth frequency of 2 kHz and phase margin of 60º. From the bode plot it has been observed that Gain Margin (GM) is infinity which implies the system is stable for the designed values. This section is followed by the hardware implementation of the circuit.

VI. HARDWARE IMPLEMENTATION

The practical hardware circuit of the proposed Phase modulated series resonant converter is shown in figs.11, 12 and 13. The MOSFET switches used are IRFPE50. The transformer has the ferrite core with the turns ratio 9:14.

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Fig. 11: Primary circuit

The high frequency switches convert the applied 12 volts dc voltage to ac voltage at the frequency range of 100kHz. The ac signals are supplied to the resonant tank circuit consisting of an resonant inductor, capacitor and transformer. The secondary of the transformer is connected to the diode bridge. The diode bridge rectifies ac voltage to dc voltage. The diodes used for harware circuit is MUR400 series. The ripple content present in the waveform is filteredout using filter capacitor. The hardware arrangement of rectifier bridge and filter capacitor is shown in fig.12.

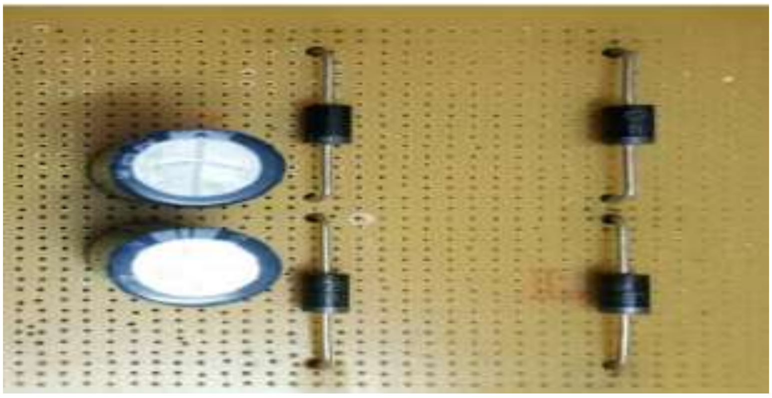

Fig.12: Secondary side diode bridge

Fig. 13 shows the LED load connected to the circuit. The designed circuit operates for the different loading conditions i.e for decreased and increased loads.

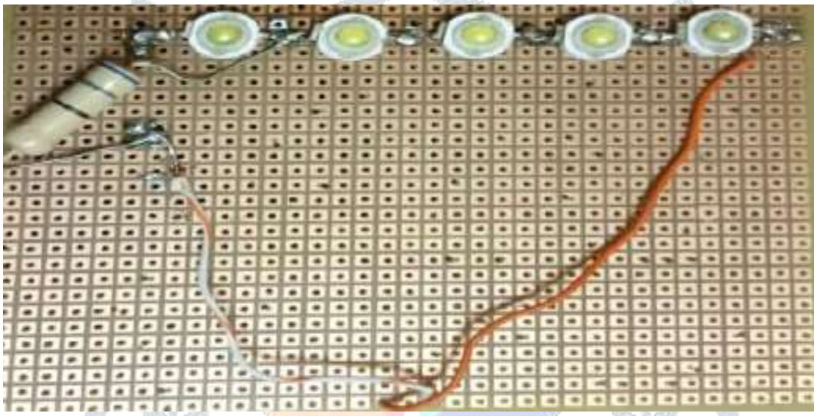

Fig. 13: LED load

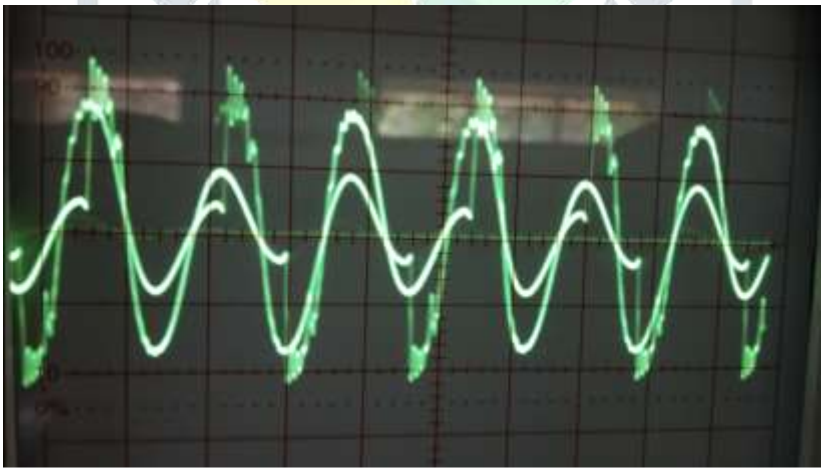

Fig. 14: Primary voltage across the transformer including resonant L and C

Fig. 14 shows the primary ac voltage waveform across the transformer including the resonant components i.e. resonant inductor and resonant capacitor.

A PI controller is added in the feedback path for the stabilization of the signals. A sample of output voltage is taken and fed to the PI controller. The output of the PI controller is fed to the PWM generation scheme, where the pulses are generated according to output voltage. If the output voltage is greater than the required level, it steps down the voltage by controlling the PWM pulses and regulates the gate signals that operate the switches and vice-versa.

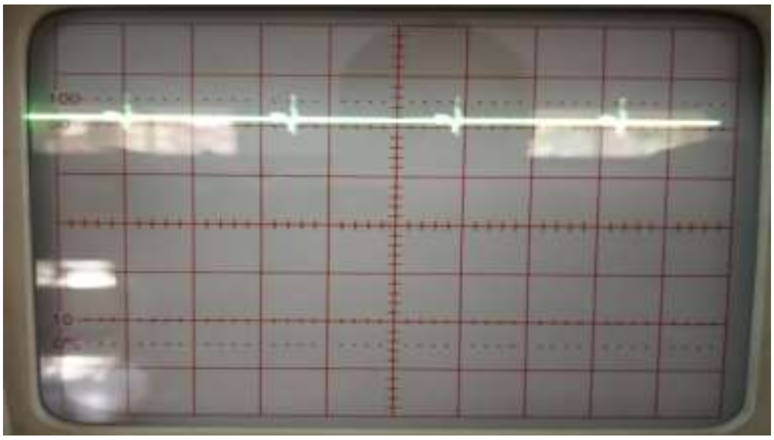

Fig. 15: Output voltage across the load

Fig. 15 shows the filtered rectified output voltage of magnitude 12 V across the load for the closed loop system. Even on changing the loading conditions, the output voltage is remained same with the magnitude of 12V.

VII. CONCLUSION

The full bridge Series resonant converter is designed and simulated with Zero Voltage Switching for its operation. The converter is designed for the input voltage of 12Volts and to obtain constant output voltage of 12Volts with the regulation of ±5% for the full load output power. The converter designed works within the given limits satisfactorily maintaining constant regulated output voltage. The converter is simulated using the MATLAB software package. For the closed loop operation of the converter, a PI controller is added in the feedback path. For various load conditions, the circuit is providing a constant output voltage. The relavant waveforms are obtained. From the bode plot, it is shown that the system is stable for the desined values.

The hardware is also implemented for the closed loop operation. For the change in the loading conditions, the output voltage of 12 V is maintained constant.

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