

## LLC Resonant Converter for Battery Charging Application

G. Subitha Sri and Dr. D. Subbulekshmi

*School of Electrical Engineering, VIT University, Chennai*  
*Associate professor, School of Electrical Engineering, VIT University, Chennai*

### Abstract

This paper describes about the LLC resonant converter used for the battery charging application. LLC resonant converters have many advantages when compared with other converters in terms of high efficiency, less switching losses. It is also capable of operating in narrow switching frequency where zero current switching can be achieved. This converter is designed for the output range of 15V-20V with a input of 30V, with a efficiency ranging from 88~92%. Low conduction loss and low switching loss are the two important characteristics of the resonant converters. This feature makes the proposed topology in the application of battery charging. With the help of the constant voltage high efficiency is obtained and regulated by closed loop control. Simulations of both open and closed loop are performed and their design procedures are included.

**Keywords**— LLC converter, zero current switching (ZCS), battery charger, PI controller.

### INTRODUCTION

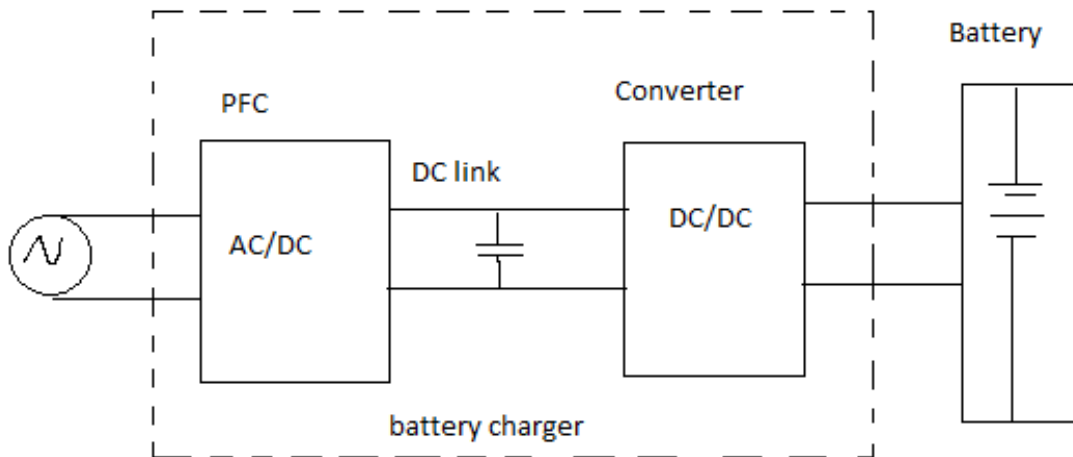
As the concern about the global warming, fuel depletion, and some of environmental issues the use of hybrid electric vehicle are increased. The battery used in vehicle should be in such a way that it should satisfy the features such as smooth and quick charging, high power density, high efficiency. By improving the capacity of voltage and current the algorithm for batter charging becomes complicated.

The most commonly used battery charging architecture is shown in fig. 1 It consist of mainly two stages, namely power factor correction PFC stage and DC-DC converter stage. The power factor correction stage is a continuous conduction mode of boost topology.

In this paper the main focus is the DC-DC converter which plays an important role in battery charger by regulating the output current and voltage. The characteristics of the battery depend on this stage[1]. LLC converters are selected as a suitable converter because of this various features such as wide operating range, high efficiency, low electromagnetic interference, high power density, soft switching at both primary and secondary sides.

From the fig 1, it is inferred that when the AC input is given to the PFC stage the boost voltage is obtained which is combined with the DC link and given as input for the DC-DC converter. The converter provides the constant voltage for the battery to be charged.

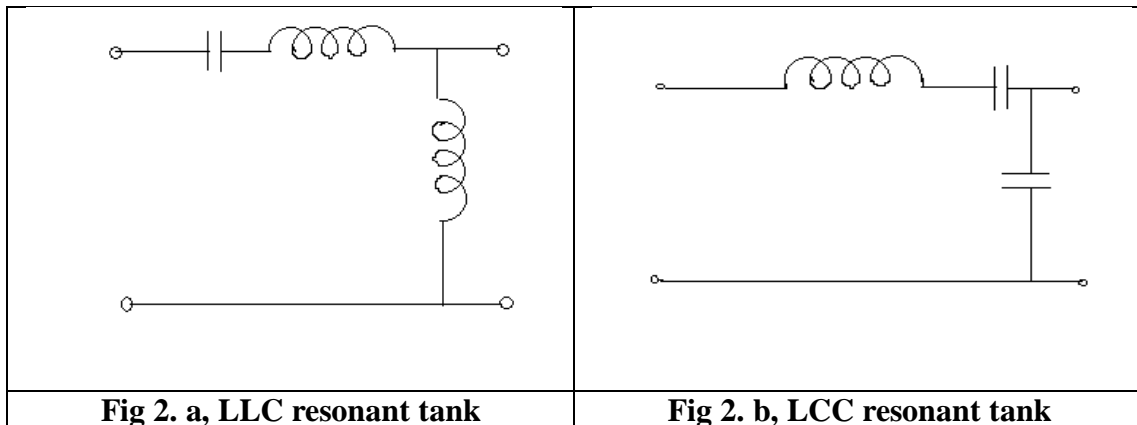
In this paper half bridge LLC converter is designed for the output voltage range of 15V-20V for a lead-acid battery with the input range of 30V. The circuit is simulated using PSIM software and the output voltage is regulated with the help of PI controller as a feedback path. In Section II operation of LLC resonant converter is discussed. In Section III circuit operation and in Section IV design procedure of the converter is discussed. Section V explains the simulation results.



**Fig 1. Block Diagram of Battery Charger.**

### LLC RESONANT CONVERTER

Generally the resonant converters can be in form LLC or LCC configurations. Fig 2. a, represents the LLC network where two inductors and capacitors are present. Fig 2. b, represents the LCC network where two capacitors and one inductor are used. LLC networks are capable of obtaining the soft switching over wide range of operations when compared with the LCC network. The size of the converters can be reduced in LLC network by combining inductors as transformer.



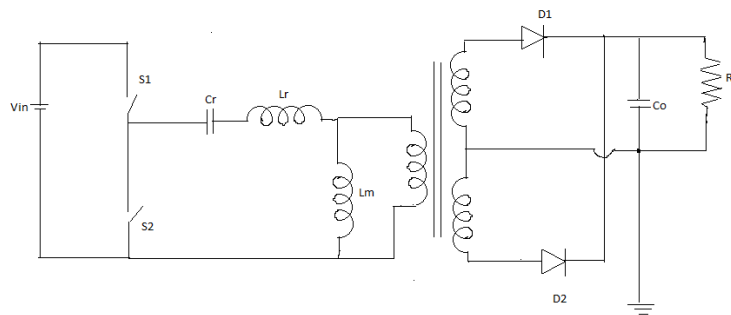
**A. LLC Series Resonant Converter.**

Fig 3, represents the proposed half series resonant LLC converter, which is a high efficiency DC-DC converter. The main parts of this converter are (i) Switching Network (ii) Resonant tank and Transformer (iii) Rectifier and Filter.

*Switching Network:* The switching network which controls the frequency of the network acts as a square wave input DC with a duty cycle of 50% for each switch. The switch used to control the frequency is MOSFETs. Some dead time are introduced between the switches in order to obtain zero voltage switching. When the dc input is given to the switching network it converts the input signal into square wave with a fixed duty ratio of amplitude equal to input voltage.

*Resonant Tank and Transformer:* The inductor  $L_r$ , capacitor  $C_r$  forms a resonant converter. The energy is transferred to the load with the help of transformers when the resonant converter allows the current to circulate. When the switching network is combined with resonant tank it forms a resonant inverter. The output of the resonant converter will be a sinusoidal voltage which is fed as an input for the transformers. Depending upon the turn's ratio of the transformer gain is determined and electrical isolation is provided.

*Rectifier and Filter:* As the output of the transformer is a sinusoidal voltage, they are rectified by full wave rectifier. The diodes D1, D2 with center tapped transformer forms a full wave rectifier[2]. Now the AC input will be rectified as a constant DC output voltage with the help of the filter circuits at the secondary side of the transformer.



**Fig 3, Proposed resonant LLC resonant converter**

### III. OPERATION OF LLC SERIES RESONANT CONVERTER

The energy delivered to the load is controlled by the impedance of the resonant tank by varying the switching frequency. LLC resonant converter operates in two frequencies. First frequency involves  $L_r$ ,  $C_r$  and second frequency involves  $L_r$ ,  $C_r$ , and  $L_m$ .

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (1)$$

$$f_{r2} = \frac{1}{2\sqrt{L_r C_r L_m}} \quad (2)$$

Equation 1 represents the frequency at no load condition. And equation 2 represents the frequency with load conditions. But the LLC converters are designed in such a way that  $f_{r1} > f_{r2}$ . The frequency depends upon the gain of the transformer. The power flow from the input to the load side is controlled by the switching frequency. Depending upon the range of frequencies LLC converter has three modes of operation. They are

- (i) Below resonance
- (ii) At resonance
- (iii) Above resonance

*At Resonance:* When the switching frequency is equal to the resonant frequency the converter said to be operated in resonance condition. During this period when the switch S1 is turned off, the resonant current will be equal to magnetizing current where there will be no power transfer between the source and the load. Zero current switching is obtained due to the dead time switching between the switches.

*Below Resonance:* When the switching frequency is greater than resonant frequency, then the converter is in below resonant mode. Here the resonant current will be equal to the magnetizing current before the switch turns off and the power is delivered to the load. If the  $f_{r1}$  frequency is less than switching frequency zero voltage switching can be obtained through out the operation, if  $f_{r2}$  is greater than switching frequency then zero voltage switching may be lost due to high switching losses.

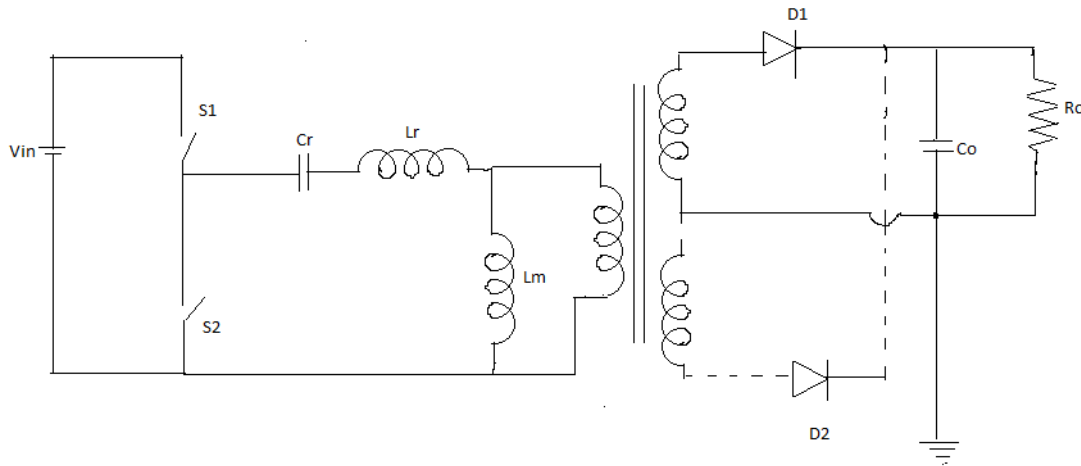
*Above Resonance:* When the switching frequency is lower than resonant frequency, the converter is in above resonance mode. Due to increase in switching frequency the conduction losses will be reduced as the circuit operates in continuous conduction mode[3]. As the  $f_{r1}$  is greater than the switching frequency the ZVS can be easily obtained even in light load conditions.

#### A. Circuit Operation

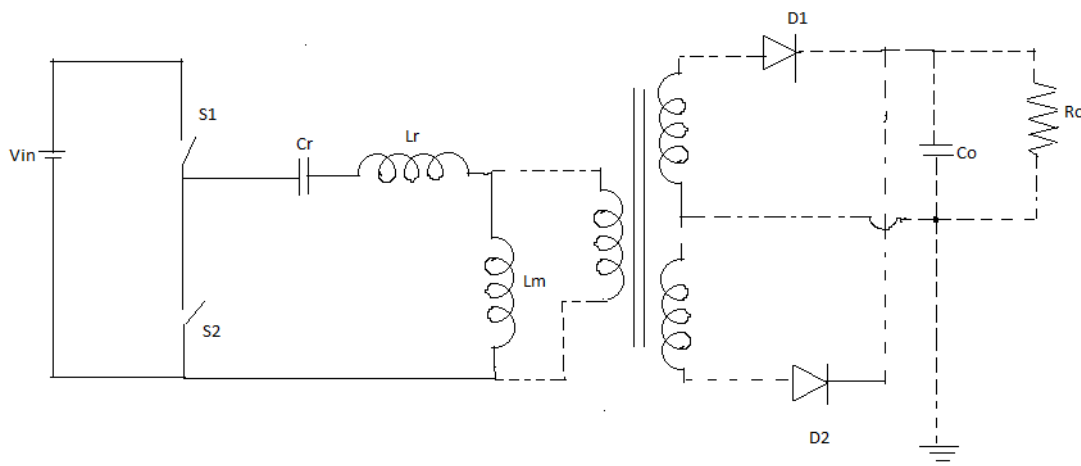
For one switching cycle the resonant converter operates in four different modes. For each half cycle two modes of operation takes place.

**Mode 1:** Before turning ON the MOSFET switch the voltage across the switch should be equal to zero. When the switch S1 is ON, the resonant current starts to increase across the inductor  $L_r$ . The magnetizing inductance which is coupled to the load side will also get charged but it does not participate in resonance. Hence the diode D1 on secondary side will be ON and energy is delivered to the load[4]. When the resonant current becomes equal with the magnetizing current this mode ends.

**Mode2:** During mode 2 S1 will be ON, the resonant current will be equal to the magnetizing current. In this mode magnetizing inductor will be connected in series with the resonant circuits where the output load will be disconnected from the input. Hence no power will be delivered to the output and current will be circulating only in primary side of the transformer. When the switch S1 is turned OFF this mode ends. For the next cycle mode 1 and mode 2 will be repeated as mode 3 and mode 4, when the MOSFET switch S2 in ON condition.



**Fig 4. a S1 ON-mode1**



**Fig 4 b. S1 ON-Mode2**

**IV. DESIGN PROCEDURE**

The design procedure for the proposed converter is summarized in following steps.

**STEP 1: System Specifications:**

To calculate the input power the efficiency of the system should be determined. If efficiency data are not provided then assuming the efficiency to be 0.88~0.92 for low voltage and 0.92~0.96 for high voltage. The power input is

$$P_{in} = \frac{P_o}{E_{ff}} \quad (3)$$

**STEP 2:** Determining the maximum and minimum voltage of the resonant converter. The gain value is set to be in the range of 2~5. Now the minimum resonant voltage is given by,

$$M_{min} = \frac{k}{k+1} \quad (4)$$

$$M_{max} = \frac{V_{in}^{max}}{V_{in}^{min}} M_{min} \quad (5)$$

Where k is the gain of converter which is obtained from the frequency response plot.

**STEP 3:** Determine the transformer turns ratio:

As the full wave rectifier is connected with the secondary side of the transformer the turns ratio is calculated as,

$$n = \frac{V_{in}}{(V_o + V_f)2} \quad (6)$$

Where  $V_f = 0.6$

**STEP 4:** Calculation of load resistance:

The resistance at the load is calculated by,

$$R_{ac} = \frac{8n^2 V_o^2 E_{ff}}{n^2 V_o} \quad (7)$$

Where, n is the turns ratio of the transformer

$V_o$  is the output voltage

$E_{ff}$  is the efficiency.

**STEP 5:** Calculation of resonant parameters:

To obtain a soft switching in a proposed converter the selection of resonant parameters are very important[5].

$$C_r = \frac{1}{2\pi Q f_o R_{ac}} \quad (8)$$

$$L_r = \frac{1}{4\pi^2 f_o^2 C_r} \quad (9)$$

$$L_m = k L_r \quad (10)$$

**Table 1: Values used for simulation**

S. NO	PARAMETERS	VALUES
1	$V_{in}$	30V
2	$V_{out}$	15-20V
3	$f_s$	20kHz
4	$f_o$	25kHz
5	$L_r$	190.09uH
6	$C_r$	0.21uF
7	Gain(k)	0.5
8	Mmin	0.33
9	Mmax	0.528

## V. SIMULATION RESULTS

The proposed converter is simulated using PSIM software and PI controller is used to obtain a constant output voltage. The PWM is created with the help of sinusoidal signal and reference signal. The pulses generated are adjusted by the PI controller which drives the secondary of the transformer where the constant output voltage is obtained as 13 V.

The main aim of this topology is to obtain soft switching to reduce the switching losses. Fig 5 infers that, as the current through the switch is zero the voltage across the switch starts to increase where soft switching is obtained.

From fig 6 it is inferred that the current through the inductor is sinusoidal because of the resonant capacitor  $C_r$ . Since the current through the inductor is sinusoidal the voltage across the capacitor should also be sinusoidal.

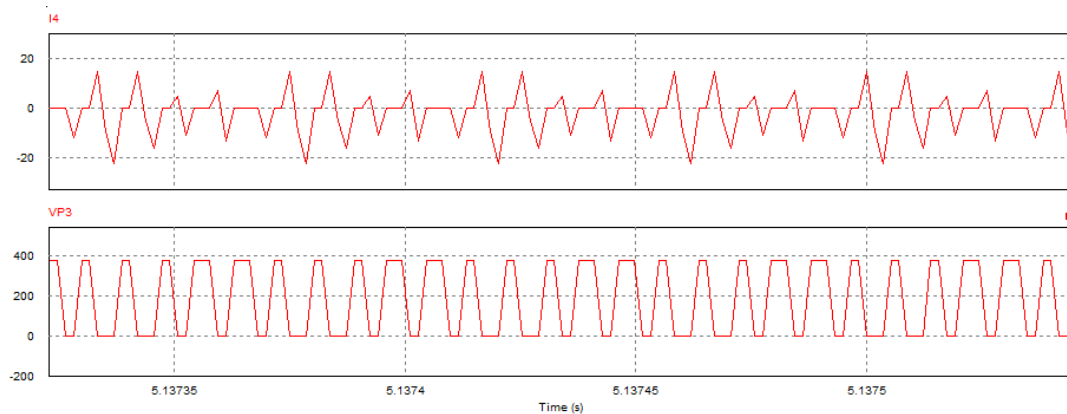
As the resonant tank forms a sinusoidal signal the input given to the transformer should be in sinusoidal. Fig 7 shows the primary voltage of the transformer.

The proposed converter is a DC-DC converter. So the input and output should be in a constant DC voltage. Fig 8 shows the constant output voltage of the converter with 13V and the current of about 1.09 amps.

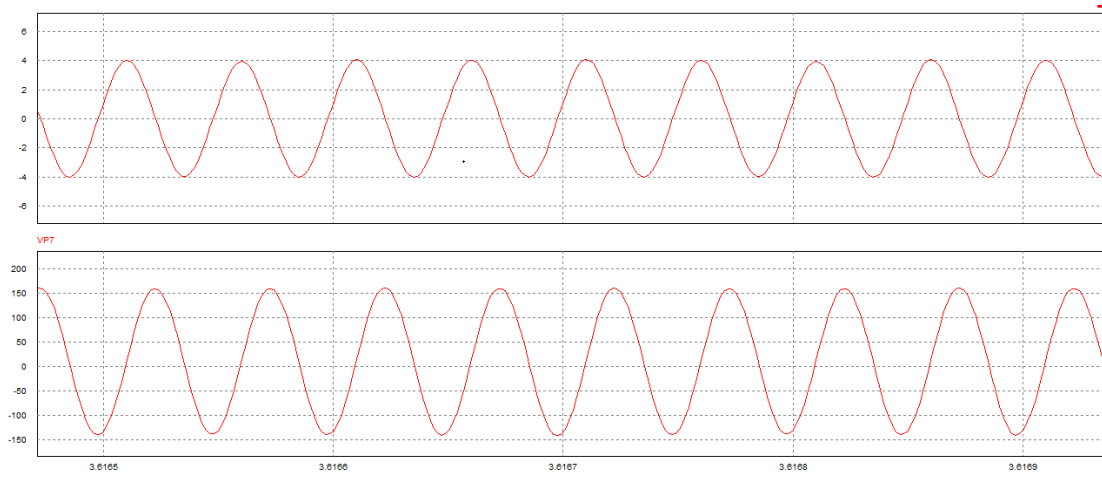
Fig 9, represents the general block diagram of closed loop system for the proposed converter. Where the output from the open loop is compared with the error signal and given to the PI controller then to converter to obtain required value.

The reference value of the controller is compared with the output from the open loop of the system and the error signals are sent to PI controller which adjusts the error value. With the help of PWM signal pulses are generated and a constant voltage of about 16 V is obtained which is shown in fig 10.

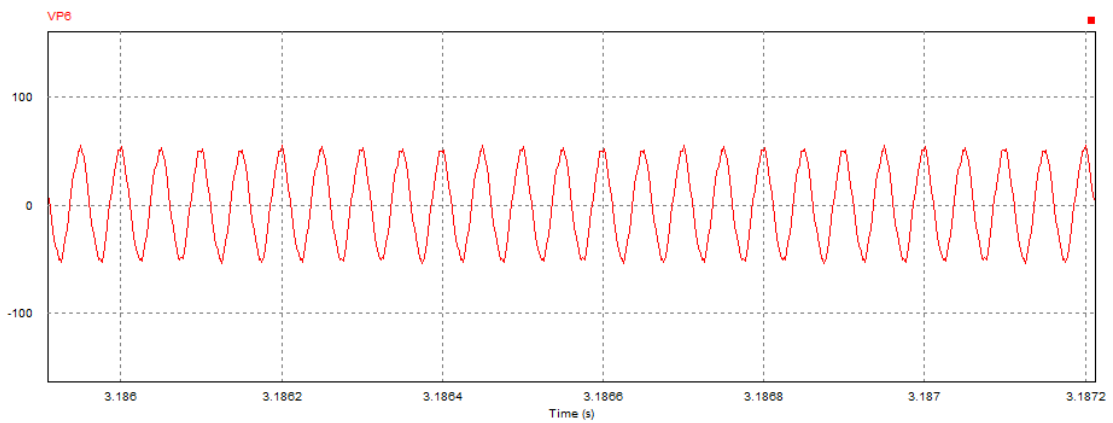
Comparing fig, 8 and fig, 10 the output voltage of the converter is efficient in closed loop system than the open loop system.



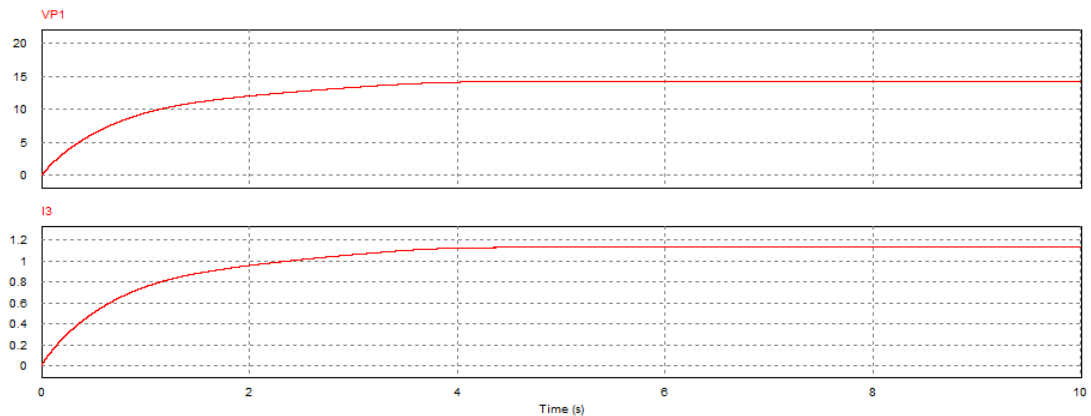
**Fig 5, Soft switching (ZCS) of the converter.**



**Fig 6 voltage across capacitor  $C_r$  and current through inductor  $L_r$ .**

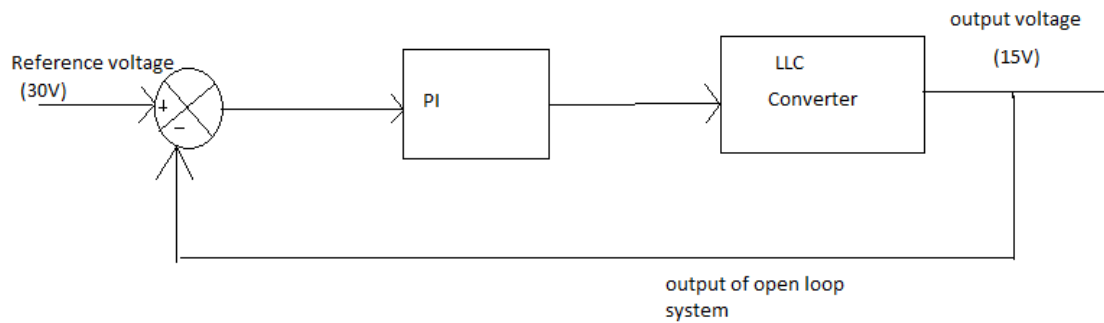


**Fig 7, Voltage across the primary side of the transformer.**

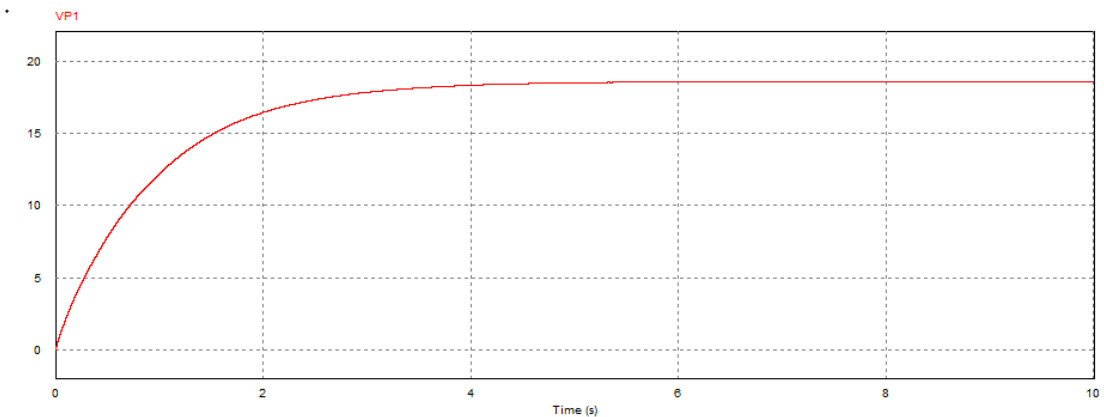


**Fig 8, Voltage and current waveforms for the open loop system.**





**Fig 9, General block diagram of closed loop system.**



**Fig 10, output voltage for closed loop system**

**VI. CONCLUSION**

In this paper ZCS based LLC resonant converter is designed for both open loop and closed loop system are simulated using PSIM software and the results are discussed. From the waveforms it is inferred that a constant output voltage is obtained without any distortion because of the filter capacitor used across the load. The steady state error is reduced in close loop system. Hence resonant converters can be used for battery applications because of their constant output voltage with reduced switching losses.

**VII. FUTURE WORK**

To implement the hardware for the proposed system this can be used for real time application and to do the research work of the system further for better performance.

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