DESIGN AND SIMULATION ANALYSIS OF RESONANT LLC CONVERTER FOR AUTOMOTIVE APPLICATIONS

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Abstract - *In this present scenario of the electric vehicles, there are lot of researches going on the various applications of the electric vehicle like the on board chargers, charge stations and other automotive applications in the vehicle which requires various voltage of supply for their application. One of those applications is where we use the resonant LLC converter. Inductor Inductor Capacitor(LLC) resonant converter has gained attention of researchers and engineers these days because of its advantages such as low switching losses due to ZVS turn on, possibility of high frequency operation, high power density over other existing resonant converters. In this paper LLC resonant converter is designed for a constant output voltage with the Ziegler-Nichols' PID tuning method. MATLAB/Simulink model of the DC/DC resonant LLC converter is built for the automotive application in which superiority of the outcome validated.*

Key Words: Full bridge LLC, ZVS, Ziegler-Nichols' PID tuning method, soft switching…

1. INTRODUCTION

The increasing demand for electric power in automobiles requires larger number of applications where DC-DC converters are used. To reduce the size of power supplies intended to use in modern electric power systems, it is desirable to raise the operating frequency to reduce the size of components. To decrease the higher switching losses resulting from higher frequency operation, resonant power conversion is receiving renewed interest. Generally speaking, DC-DC converters can be divided into two categories: pulse-width-modulation (PWM) converters and resonant converters. As most of the applications involve a regulated voltage output, therefore a feedback loop is incorporated into the control system to stabilize the output voltage. For optimal design purpose, small-signal equivalent circuit models are indispensable [1]-[2]. The resonant LLC topology has three stages, including input stage, resonant tank and output stage. Each stage contains three parts, input signals, control signals and output signals. The relationship between three parts of each stage is fully investigated and modeled. A FPGA-based HIL simulation experiment is conducted and a normal PSIM simulation is also conducted to verify the FPGA-based model [3].As switching frequency increases, the size of the resonant components will be inevitably reduced through proper design methods of the LLC resonant converter. Moreover, small capacitance and small ESR can reduce the size of the output capacitor [4]. Many authors discussed the various aspects of LLC resonant converter. Basic advantage of LLC resonant converter is we can use the leakage inductance of the transformer as resonant inductor. Together with capacitor this will form a resonant tank. With the magnetic integration the number of components is reduced and the flux ripple cancellation is achieved so that core loss reduces [5]. Most importantly it is possible to regulate the output voltage over wide line and load variations [10]. ZVS is possible over entire operating region, so the switching losses are very little.

The LLC with center-tapped secondary rectifier experiences large voltage oscillations, because of secondary leakage inductance [8], now a days engineer prefer full bridge secondary rectifier. Several aspects of rectifier voltage variations are discussed in [8]. Power losses in LLC are mainly due to the losses in the magnetic circuit and the conduction losses. Conduction loss model for half bridge LLC resonant converter is presented in [6]. Author of [6] found that the secondary conduction losses are dependent on the switching frequency for constant output power.

The modeling of full bridge LLC resonant converter using *Ziegler-Nichols' PID tuning method* is discussed in. This approach will help us to select initial parameters and component. In this paper the LLC resonant converter is designed and practically realized.

2. FULL BRIDGE LLC RESONANT CONVERTER

Fundamental circuit of LLC resonant Converter is shown in the fig 1. Switches Q1 through Q4 operated to obtain a square wave Vdc. The input bridge implemented here is of full bridge and half bridge can also be implemented based upon the power rating. For high and medium power application full bridge is preferred level. Square wave is applied to resonant tank consisting of two inductors, magnetizing inductance Lm and leakage inductance Lr, and a capacitor Cr as shown in Fig 1. The resonant tank circuit is designed such a way, that it will channel out all higher order harmonics. Just fundamental sinusoidal harmonics of the square wave will be permitted to stream through the resonant tank circuit. Then it is rectified and supplied to the load.

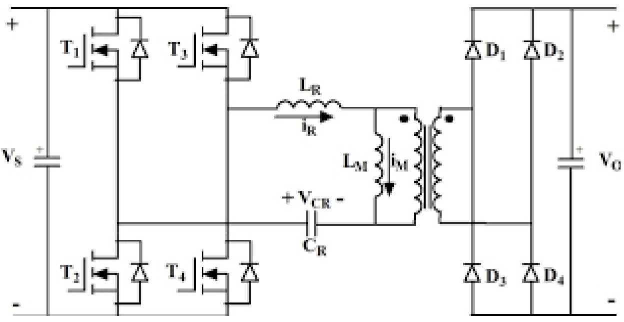

Fig.1. LLC Resonant Converter

Fig 2 shows the typical waveforms of LLC resonant converter. Here Vg_T1, T2 and Vg_Q3, Q4 are gating pulses for the switch pairs T1, T2 and T3, T4 respectively. The Im, Ir, and Is in the fig1 are magnetizing current, resonant current and secondary current flows separately. Vp is the square waveform. The current Ir can be approximated as sinusoidal wave. This is valid at resonant frequency fr. This estimation is utilized for demonstrating the converter. During first half cycle the resonant current Ir starts to increase and at the same time the output voltage of the first bridge is applied over the magnetizing inductor Lm. So that, magnetizing current increases straightly and arrives at its top toward the finish of its half cycle. Then another set switch is turned on with ZVS, Ir resonant and the output voltage is applied over the Lm in other direction. Specifically the voltage applied across Lm is a square wave[7] and the Im is triangular waveform.

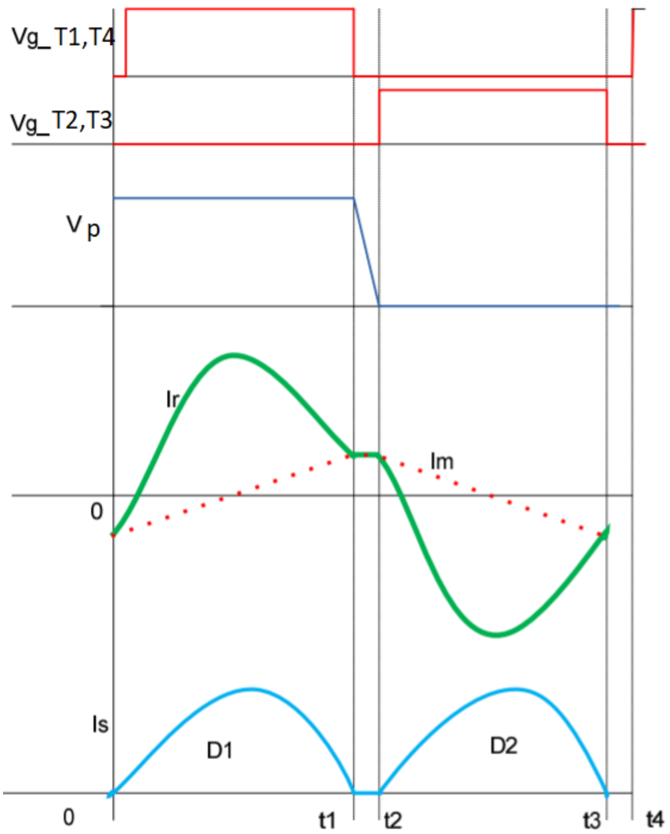

Fig.2.Typical waveforms of LLC

Utilizing LLC we can accomplish both buck and lift method of tasks. At resonant frequency the gain of this converter is always less than one and this converter works as series resonant converter[2], [7]. Working the converter at resonant frequency fr is constantly favored as it brings out high efficiency and the circulating energy is very little. Gain characteristics of the LLC resonant converter for different load condition are shown in the fig.3. Ln is the proportion of magnetizing inductance Lm, to leakage inductance Lr, of the transformer. From the fig 3 we can see that ZVS operation is possible only at inductive region and the ZCS is possible only at the capacitive region, however operating frequency of the converter is less. Under light–load condition the parallel resonant converter dominates the series resonant converter so regulation of output voltage is possible

2. DESIGN OF FULL BRIDGE LLC RESONANT CONVERTER

To design the LLC resonant converter Ziegler-Nichols' PID tuning method is used. It is assumed that all other higher order harmonics will be filtered by series resonant tank circuit. So the gain of the LLC can be expressed in terms of normalized frequency fn, quality factor Qe, and inductance ratio Ln as

Transformer Turns ratio,

$$\mathbf{n} = \text{Vin nom}/\text{Vout} \qquad (1)$$

In fig.3. The curve Mg vs. Qe is plotted for Ln =5 with different values of Qe. Increasing the Qe the curve starts shrinking, which results in narrow operating region, and in turn the magnitude of the gain also reduces. For a good design maximum and minimum values of gain are to be calculated. Using the gain values Ln and Qe are selected at full load condition at resonant frequency fr.

$$\text{Mg min} = n*(\text{Vo min} + \text{Vf})/\text{Vin max} \qquad (2)$$

$$\text{Mg max} = n*(\text{Vo max} + \text{Vf} + \text{Vloss})/\text{Vin min} \qquad (3)$$

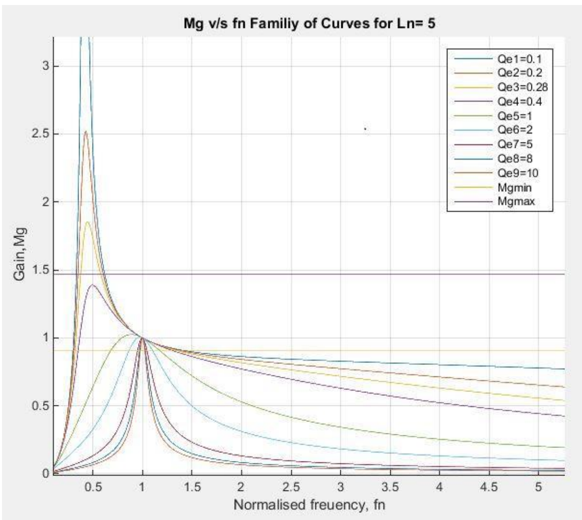

Fig.3.Gain characteristics of LLC

Selection of Qe and Ln is actually a very critical task as it decides the value of all reactive components. The equivalent load resistance Rac is calculated.

Re= (8*n^2/pi^2)*(Vo/Io) (4)

Resonant circuit parameters are found as follows,

Cr=1/(2*pi*Qe*fo*Re) (5)

Lr=1/((2*pi*fo)^2*Cr) (6)

Lm=Ln*Lr (7)

The Lm value is selected based on a condition that the magnetizing current is 20% less than that of primary current. Smaller the Lm values, higher are the magnetizing current and the circulating energy. Once the final component selection is done the transformer is to be designed.

- Turns ratio, n = 11
- Primary terminal Voltage in V = 201.35 V
- Primary winding rated current in A = 43.47 A
- Secondary terminal voltage = 18.33
- Secondary winding rated current in A = 211.39 A
- Frequency at no load in Hz = 60554.1 Hz
- Frequency at full load in Hz = 120040.94 Hz

Table -1: Design Parameter of Resonant LLC Converter

Design Parameters	Min	Type	Max
Input Voltage	120V	153.6 V	175 V
Output Power		3300W	
Output Voltage	13.8V	14.1V	14.4V
Output Current	229.17A	234.04A	239.13A
Output Ripple	0.69	0.705	0.72
Resonant Inductor		2.90E-06 H	
Resonant Capacitor		9.62E-07 F	
Magnetizing Inductance		1.16E-05 H	
Filter Capacitance		4.09E-04 F	
Switching frequency		100kHz	
Ln		4	
Qe		0.48	

To achieve the ZVS operation in the system, MOSFET is tuned when its drain to source voltage Vds is zero. This is achieved by allowing the body diode of the MOSFET to conduct the magnetizing current just before turning on the switch. This ZVS operation is shown in fig 4. And for a successful ZVS we need to ensure the availability of sufficient inductive energy. Selected Lm should provide required amount of magnetizing current such that ZVS is possible.

Fig.4. ZVS operation in switch

4. SIMULATION RESULTS

The design details of the LLC resonant converter with the specification Po=3.3KW, Vo=14.1V, Vin=120-175V efficiency 90% is developed as shown in the fig.5. Input to the converter is battery. Integrated transformer is used here and a resonant inductor is connected in series with the transformer primary. The schematic of the modeled Resonant LLC converter maintaining an output voltage of 14V and connected to a resistive load of 0.12Ω. The converter has a nominal output of 14V and 234.04A.

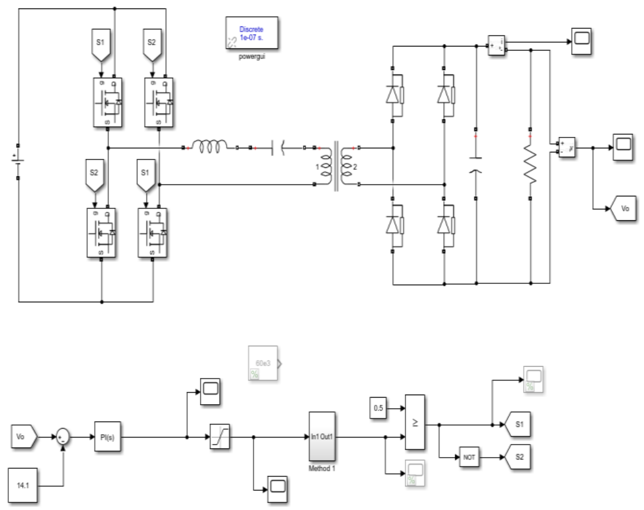

Fig.5. Schematic of Modeled Resonant LLC Converter

The pwm signals are generated from the closed to maintain the required output voltage is shown in fig 6.

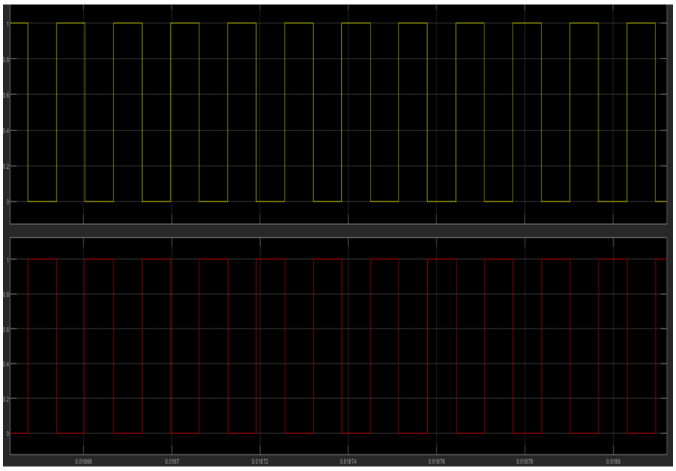

Fig.6. Gate signals to the switches

Voltage across the switch is as shown in the Figure 7.

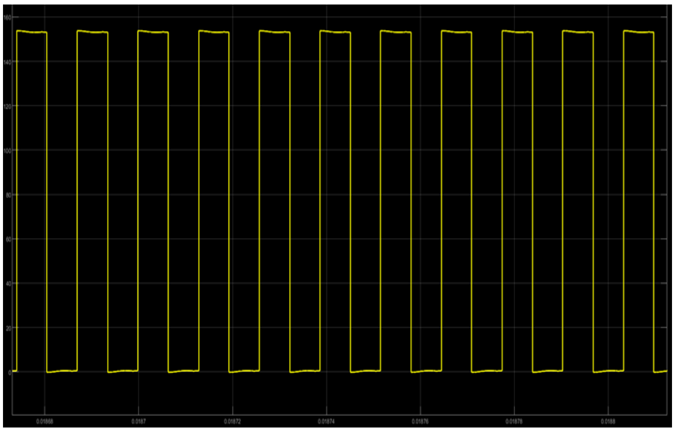

Fig.7. Voltage across the switch

The output voltage of the proposed converter for the input voltage of 153.6 V, and the duty ratio of 50% is 14.1 V. The simulation output voltage is as shown below in Figure 8. The output current through load is as shown in Figure 9. The current as calculated in previously is 234.04A

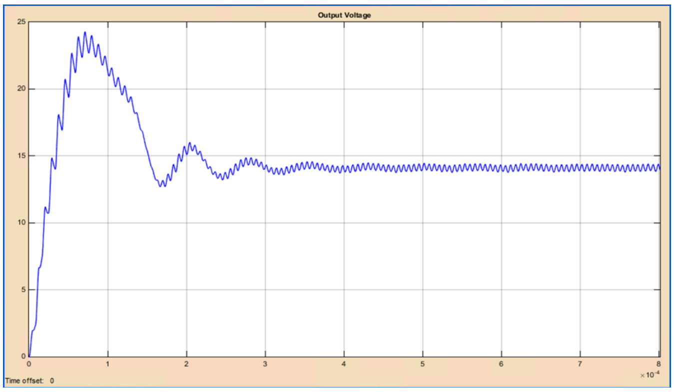

Fig.8. Simulation Result of Output Voltage.

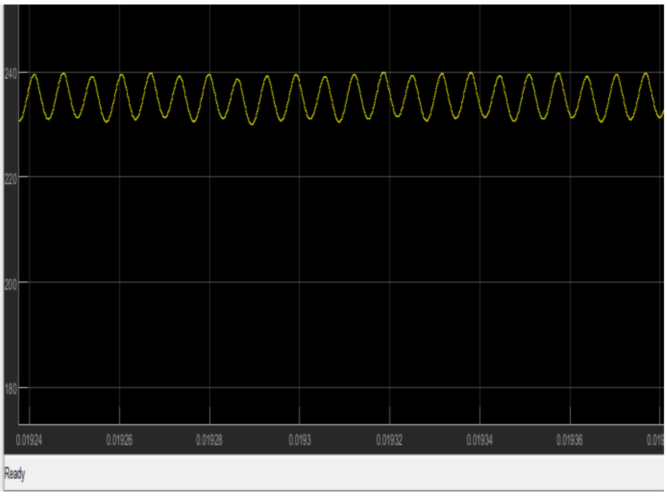

Fig.9. simulation results of output current

5. CONCLUSIONS

The full bridge resonant LLC converter topology is designed and simulation results are obtained. Based on the simulation results the different characteristics of LLC resonant topology were contemplated. It is observed that at low input voltages both efficiency and operating frequencies decrease. Due to increase in copper losses efficiency decreases. Working the LLC converter at arrangement full recurrence is the best working point as the productivity of the converter is most noteworthy now. So to overcome this efficiency problem the resonant LLC converters are always preferred to operate in series resonant frequency.

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