A INNOVATIVE HIGH RENOVATION EFFICIENCY AND POWER DENSITY LLC RESONANT CONVERTER

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Abstract LLC resonant converters in general attain a buck or boost gain with pulse frequency modulation and also exhibit a suitable topology for high power density. This LLC resonant converter has many advantages, such as wide soft switching range, high switching frequency capability, and low voltage stress of active devices; however, it also has range RMS current and circulating current. Thereby, the usage of LLC resonant converter had been limited to low voltage and high current output applications. In this paper, a new LLC resonant converter, which achieves high conversion efficiency while maintaining high power density, has been proposed. Since in the proposed converter the conduction loss and turn off loss could be reduced, it can achieve higher conversion to regulate the output voltage. The proposed converter changes the resonant frequency using the small size of the auxiliary circuit under hold-up time condition. Consequently, the proposed converter also has a topology that can satisfy both high conversion efficiency and high power density.

Keywords*: LLC resonant converter, conversion efficiency, power density, resonant topology, soft switching, switching frequency, voltage stress, conduction loss, turn off loss, hard switching, electromagnetic interference, ZVS,ZCS, MATLAB, Simulink*

I. INTRODUCTION

A great impact on power electronics has been made with the growing demand for delivering electric power in various forms with high performance and reliability. The demand for compact power supplies are grown significantly, as the rising energy intensity leads to a higher cost for delivering power. Thereby a need arises for power supplies with high efficiency, low profile and high power density. The increasing functionality of the consumer electronics also requires more power consumption and higher density requires compact size on the power supplies. Therefore, the power supplies are required to provide more power with small size and low cost.

Resonant power conversion technology offers many advantages in comparison with PWM. Resonant converters are desirable for power conversion due to their comparatively smaller size and lower power losses resulting from high-frequency operation and inherent soft switching. Among all the topologies of the resonant converters, the series–parallel resonant converter (SPRC) shares the advantages of both the pure series converter and pure parallel converter [1, 3]. To regulate the output of an SPRC, frequency control or phase control are usually used. The frequency control used in a half-bridge configuration is proposed in this paper.

Also in this converter, the current carried by the power FET's and resonant components is relatively independent of load. The series parallel resonant converter combines the above said advantages [5].

In an SMPS a rectification stage can be found on the secondary side of the converter. Typically this rectification is done with power diodes [8]. But due to the forward voltage drop of the diodes (0.5 V and higher) combined with the high output currents, these devices produce high conduction losses and therefore have a major contribution to the efficiency of the whole converter. To minimize these rectification losses, the diodes can be replaced with modern power MOSFETs, which tremendously reduces conduction losses especially at high output currents [6, 9, 10]. Here, the switching losses are considerably higher compared to those using diodes.

1.1 LLC Resonant Converter

A well designed LLC resonant converter can realize ZVS for the main switches from no-load to full load. Besides, ZCS can also be realized for the rectifier switches of the converter. So that the voltage stress on them can be minimized. By applying frequency control, the LLC converter can operate well with extra wide input voltage range [2, 3, 4]. For telecommunication and computing system applications, power supplies require increasing current level while the supply voltage keeps decreasing [7].

II. LITERATURE SURVEY

The switched mode DC-DC converters are some of the simplest power electronic circuits which have received an increasing deal of interest in many areas. Shih-Yu Chen, Zhu Rong Li, Chern-Lin Chen proposed that the pulse charging and discharging instances are controlled by the user, and hence can be applicable to pulse width modulation schemes as well as resonant converters [2]. Xiaodong Li proposed a number of soft switching techniques aiming at combining the desirable features of both the conventional PWM and resonant converters while avoiding their respective limitations [1]. Yu Fang, Dehong Xu, Yanjun Zhang, Fengchuan Gao, Lihong Zhu proposed generated amplitude modulated square wave train to control the output resulting in simple configuration and inherent ZVS characteristics [3].Sung-Soo Hong, Sang-Ho Cho, Chung-Wook Roh, and Sang-Kyoo Han concluded that resonant derived topologies are simple compared with the other topologies used in low power applications. With the Incorporation of the active clamp circuit, the LLC topology serves to recycle the transformer leakage energy while minimizing the switch voltage stress [4].A. K. S. Bhat proposed a modification in the asymmetrical zero voltage switched half bridge DC-DC LLC resonant converter topology to be optimized for higher efficiency and power density that substantially changes the static transfer function and the voltage stress distribution within the converter power mesh[5]. C. Kim, K. B. Park, C. E. Kim, B. H. Lee, and G. W. Moon presented a simple clamping circuit for the ZVS PWM asymmetrical half bridge DC-DC resonant converter. This clamping circuit reduces the oscillations caused by the reverse recovery of the output diodes thereby increasing the efficiency of the converter [6]. S.Selvaperumal, C. Christober Asir Rajan, S.Muralidharan proposed a model that recognizes that a resonant converter's power switch has a finite resistance in its ON state. If MOSFET is used, then this resistance will be variable and can be utilized to change the time taken by the switch voltage to reach the inverter threshold voltage. This changes the ON time and provides a regulation mechanism for variable output power and input voltage [9]. J. Alvarez-Ramirez, I. Cervantes, G. Espinosa-Perez, P. Maya, and A. Morales proposed a family of DC-DC LLC converters which employs an innovative interleaving concept by using series primary windings and interleaved parallel secondary sides. The advantages of their converters include reduced filter size, improved transient response and increased efficiency [10]. Juergen Biela, Member, IEEE, Uwe Badstuebner analyzed the detailed circuit behavior of the asymmetrical half bridge LLC converter. Several practical issues including the specific relationships between the duty cycle and the different types of energy in the energy storage elements and the zero voltage switching conditions of the power switches were examined [11]. Chen Zhao, Min Chen, Guoxing Zhang, Xinke Wu proved that the current driven synchronous rectifier with current sensing energy recovery are suitable for high frequency switching topologies. The synchronous rectifier can be driven ON and OFF automatically according to the current direction. It can be taken as an active diode with very low power dissipation [12].Joe C.P.Liu, N.K.Poon, Bryan and M.H.Pong designed a low power DC-DC LLC converter with wide input voltage range. They analyzed several topologies and selected the flyback with active clamp converter circuit because it presents a good tradeoff between simplicity and efficiency. Their topology provides a wide regulation capability even at no load, ZVS capability and soft turn off in the rectifier diode [13].

III. LLC RESONANT CONVERTER

LLC resonant converter has two resonant frequencies. Low resonant frequency is determined by series resonant tank L_r, C_r and high resonant frequency is determined by C_r and equivalent inductance of L_r and L_m in series. For resonant converter, it is normally true that the converter could reach high efficiency at resonant frequency. The LLC resonant converter is shown in Figure 1.

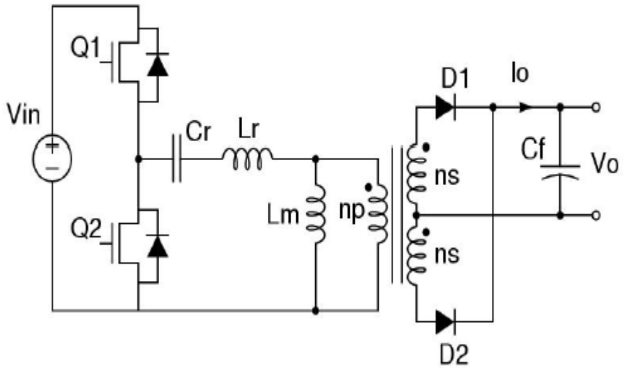


Figure 1 Half bridge LLC resonant converter

For LLC resonant converter although it has two resonant frequencies, unfortunately, the lower resonant frequency is in ZCS region. Now the higher resonant frequency is in the ZVS region .With all this criteria the converter could be designed to operate around this frequency. It is designed to operate at a switching frequency higher than resonant frequency of the series resonant tank of L_r and C_r.

IV. THE PROPOSED LLC DC-DC RESONANT CONVERTER

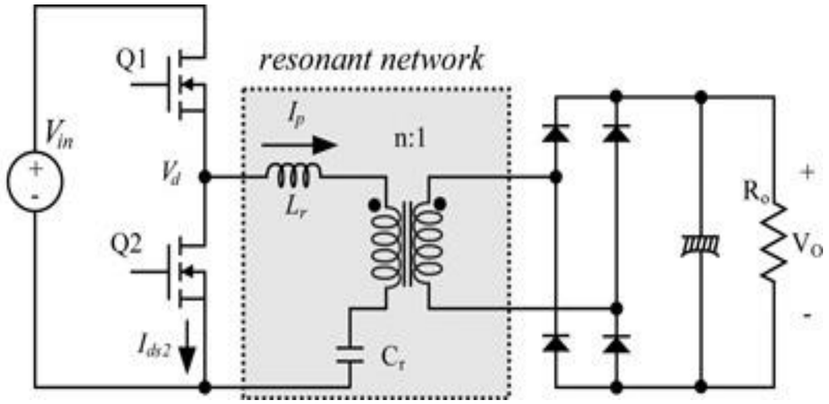


Figure.2 Proposed concept of LLC resonant converter with current tripler topology.

The resonant tank consisting of three reactive energy storage elements (LLC) has overcome the conventional resonant converter with two elements. The first stage converts a DC voltage to high frequency AC voltage. The second stage converts AC power to DC power by suitable high frequency rectifier and filter circuit. The well designed LLC resonant converter can realize from no load to full load the ZVS for the main switches. Besides, ZCS can also be realized for the rectifier switches so that the voltage stress on them can be minimized. The proposed converter can operate with extra wide input voltage range by applying frequency control.

V. AC ANALYSIS OF THE PROPOSED LLC SERIES PARALLEL RESONANT CONVERTER

In the ac analysis, the output rectifier and filter are replaced by the equivalent AC resistance and the square-wave input voltage source is replaced by its fundamental sinusoidal equivalent [2]. The power transfer from input to output is assumed to be only via the fundamental component and the contribution of all the harmonics is neglected. The equivalent circuit for LLC series parallel resonant converter is shown in Figure 3.The output power is associated to the output load resistance R_o. The load resistance reflected to the transformer primary side is R_{ac}.

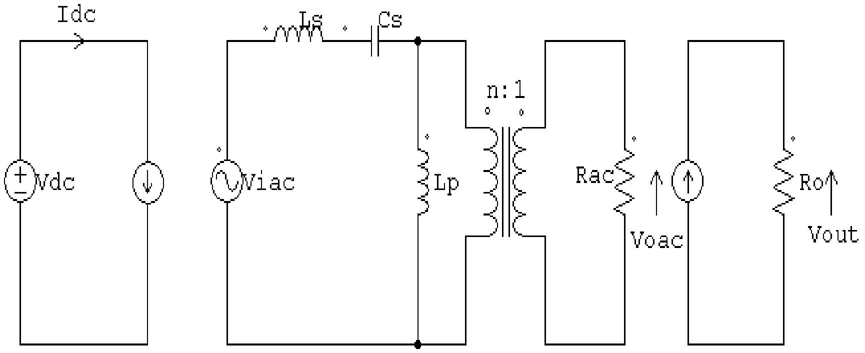


Figure 3 Equivalent circuit for LLC series parallel resonant converter

5.1 Transfer Function:

The ac resonant tank can be defined by the following transfer function H(s).

$$H(s) = \frac{1}{n}\frac{\left(R_{ac} // sL_m\right)}{\left(sC_s\right)^{-1} + sL_s + R_{ac} // sL_p} \qquad (1)$$

$$R_{ac} = n^2 \frac{8}{\pi^2} R_L \qquad (2)$$

5.2 Voltage gain:

$$G_{dc} = \frac{1}{n}\frac{1}{1+\left(\frac{1}{k}\right)\left(1-\frac{f_s^2}{f^2}\right)+j\left(\frac{f}{f_s}-\frac{f_s}{f}\right)Q} \qquad (3)$$

Where inductor ratio

$$k = \frac{L_p}{L_s}$$

Quality factor

$$Q = \sqrt{\frac{L_s}{L_p}}\frac{1}{R_{ac}}$$

Series resonant frequency

$$f_s = \frac{1}{2\pi\sqrt{L_s C_s}}$$

Series parallel resonant frequency

$$f_m = \frac{1}{2\pi\sqrt{(L_s + L_p)C_s}} < f_s$$

The switching frequency is higher than series parallel resonant frequency and lower than series resonant frequency, so that zero voltage switching turn-on and low current turn-off can be achieved.

Design of transformer turns ratio should satisfy,

$$G_{dc} \leq \frac{V_o}{V_{in(Max-dc)}}(@\, f = f_s) \qquad (4)$$

$$n \geq \frac{V_{in(Max-dc)}}{V_o} \qquad (5)$$

In case of minimum input voltage, the determination of Q, k, n and fs must meet the requirement of DC voltage gain for the full load. After the determination of Q, k, n and fs, the values of Ls, Cs and Lp can be calculated.

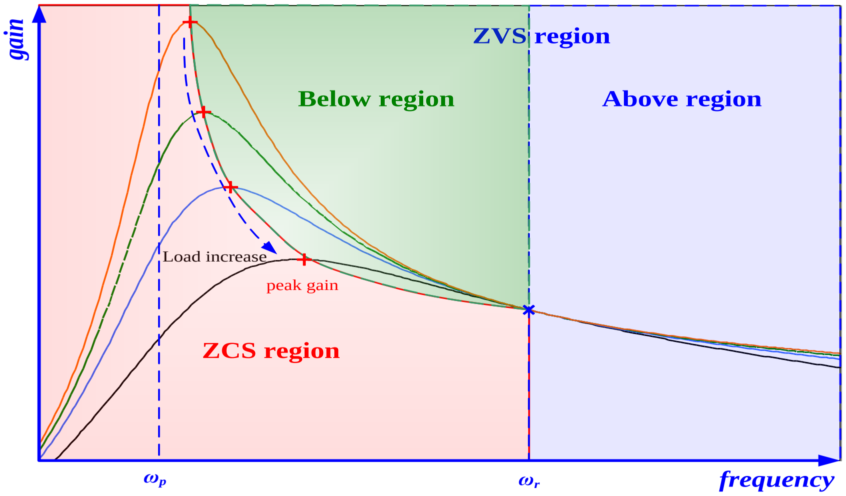
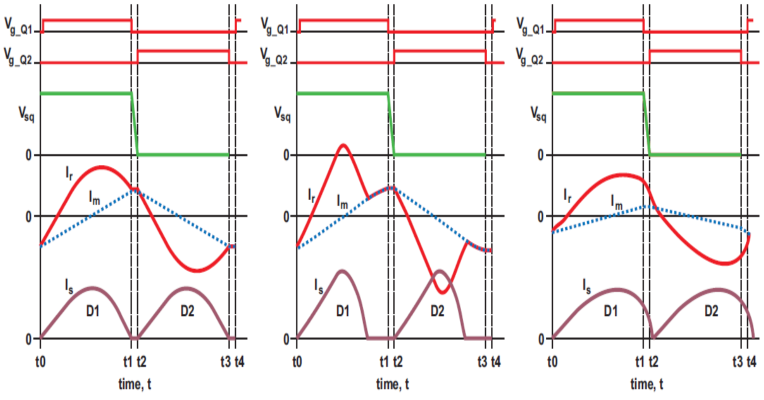


Figure 4 Conversion ratio of an LLC resonant converter according to the operating frequency & load variation

The highest value for each curve is called 'peak gain'. It is found in between two resonant frequencies, ω_p and ω_r. A value of the peak gain lessens and the position of peak gain moves to a higher frequency, as output load increases more and more. Meanwhile, it can be seen that the resonant gain at ω_r is fixed even though the output load varies. The gain curve demonstrates that the gain decreases and output voltage reduces as the operating frequency applied to the resonant network rises up in the ZVS region. Figure 5 shows the gain curve for at, below and above the resonant frequency.



a. At f_0. *b. Below f_0.* *c. Above f_0.*

Figure 5 Gain curve at, below and above the resonant frequency

VI. DESIGN

To assure resonance for almost different power ranges and also to limit the current and voltage peak values, the values of all elements were obtained using the design procedure. For an example, a DC/DC converter with 192W/24V output has been selected. The design specifications are as follows:

- Input voltage: 400V DC (output of PFC stage)
- Output: 12V/8A
- Hold-up time requirement: 20ms
- DC link capacitor of PFC output: 220µF

Estimated efficiency (E_{ff}): In order to calculate the maximum input power with a given maximum output power the power conversion efficiency must be predicted. Here we use efficiency E_{ff} = 0.92. With the expected efficiency, the maximum input power is given as:

$$P_{in}=\frac{P_o}{E_{ff}}=20 \qquad (6)$$

Input voltage range (V_{in}^{min} and V_{in}^{max}): The maximum input voltage is:

$$V_{in}^{max}=V_{o.PFC}=4 \qquad (7)$$

The input voltage drops during the hold-up time, even though the input voltage is regulated as constant by PFC pre-regulator. The minimum input voltage is given as:

$$V_{in}^{max}=\sqrt{V_{o.PFC}^2-\frac{2P_{in}T_{HU}}{C_{DL}}}=34 \qquad (8)$$

Maximum and Minimum Voltage Gains of the Resonant Network

The LLC resonant converter is characteristically operated about the resonant frequency (f_o) to reduce switching frequency variation. Since, the input is supplied from the PFC output voltage, for the nominal PFC output voltage, the converter should be designed to operate at f_o. The gain at f_o is m ($m=L_p/L_r$). By choosing that value of m, the gain at f_o is calculated. A very small m value results in poor coupling of the transformer and decreases the efficiency, whereas a higher peak gain can obtained with a small m value,. Here m is set to 5, which gives voltage gain of 1.12~1.28.

$$M^{min} = \sqrt{\frac{m}{m-1}} = 1 \tag{19}$$

which would be the minimum gain because the nominal PFC output voltage is the maximum input voltage (V_i). The maximum voltage gain is given as:

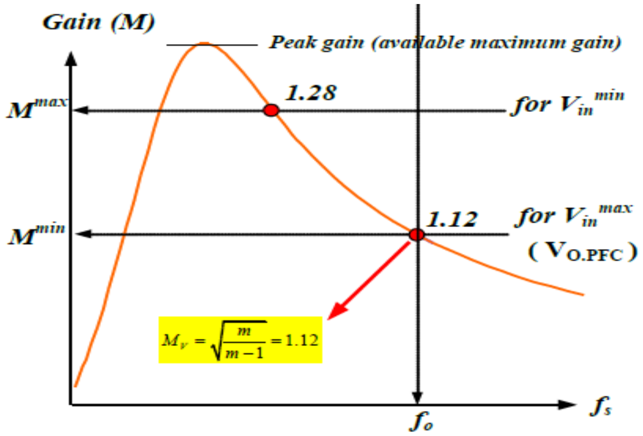


Figure 6. Maximum Gain/ Minimum Gain

$$M^{max} = \frac{V_{in}^{max}}{V_{in}^{min}} M^{min} = \tag{10}$$

Transformer Turns Ratio (n=N$_p$/N$_s$)

With the minimum gain (M$_{min}$) obtained in previous step, the transformer turns ratio is given as:

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{max}}{2(V_o+V_f)} M^{mi} \tag{11}$$

where V$_F$ is the secondary-side rectifier diode voltage drop(0.6V).

Equivalent Load Resistance

With the transformer turns ratio calculated, the equivalent load resistance is obtained as:

$$R_{ac} = \frac{8n^2V_o^2}{\pi^2 P_o} = 1 \tag{12}$$

Resonant Network

Choosing *m* value, read proper *Q* value from the peak gain curves in the figure below, which allows enough peak gain. Taking into consideration the load transient and stable zero-voltage-switching (ZVS) operation, 15% margin should be introduced on the maximum gain and the peak gain is determined as 1.47. The *Q* value finally obtained is 0.4 and the resonant parameters are obtained as:

$$C_r = \frac{1}{2\pi Q f_o R_{ac}} = 20. \tag{13}$$

$$L_r = \frac{1}{(2\pi f_o)^2 C_r} = 12 \tag{14}$$

$$L_p = m.L_r = 63 \tag{15}$$

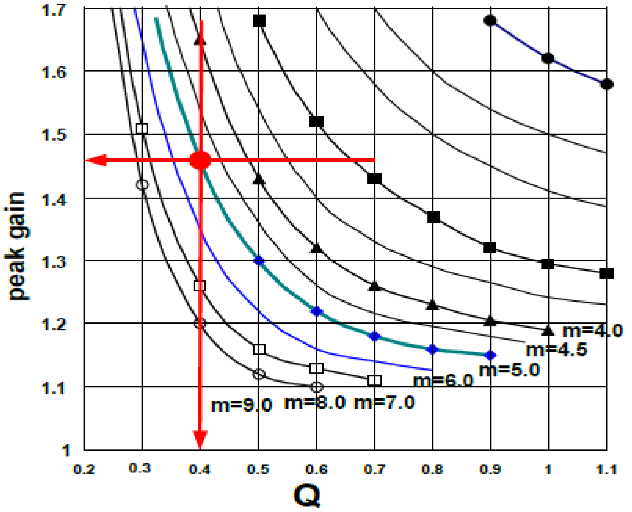


Figure 7. Resonant network Design Using the peak gain

Design the Transformer

In the minimum switching frequency state, the transformer design is done, and this state occurs at the minimum input voltage and full-load condition. Plot the gain curve and read the minimum switching frequency to obtain the minimum switching frequency. On the transformer's primary-side the minimum number of turns is obtained as:

$$N_p^{min} = \frac{n(V_o+V_F)}{2 f_s^{min} . M_v . \Delta B . A_e} = 30.4 \text{ tı} \tag{16}$$

where, A_e is the cross-sectional area of the transformer core in m^2 and ΔB is the maximum flux density swing in Tesla. We use $\Delta B = 0.4$ T. A virtual gain M_V caused by the secondary-side leakage inductance is introduced, which is equal to the minimum gain. Choose the proper number of turns for the secondary side that result in primary-side turns larger than N as:

$$N_p = n.N_s > N_p^{min} \tag{17}$$

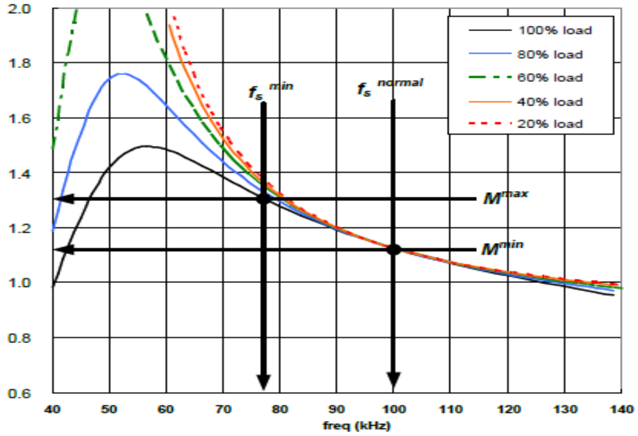


Figure 8.Gain Curve

Resonant Network Design Parameters

Table 1 shows the Design Parameters used in the resonant network.

Table 1 Resonant Network Design Parameter

Parameters	Design values
Normal Input AC voltage	280V
Normal DC bulk voltage	400V
Normal output full load	12V/8A
Switching frequency	100kHz
Minimum frequency	78KHz
L_p	630μH
L_r	126μH
C_r	20nH
f_o	100KHz
M	5
Q	0.4
M@f_o	1.12

VIII.VISIMULATION AND RESULTS

Simulation Circuit

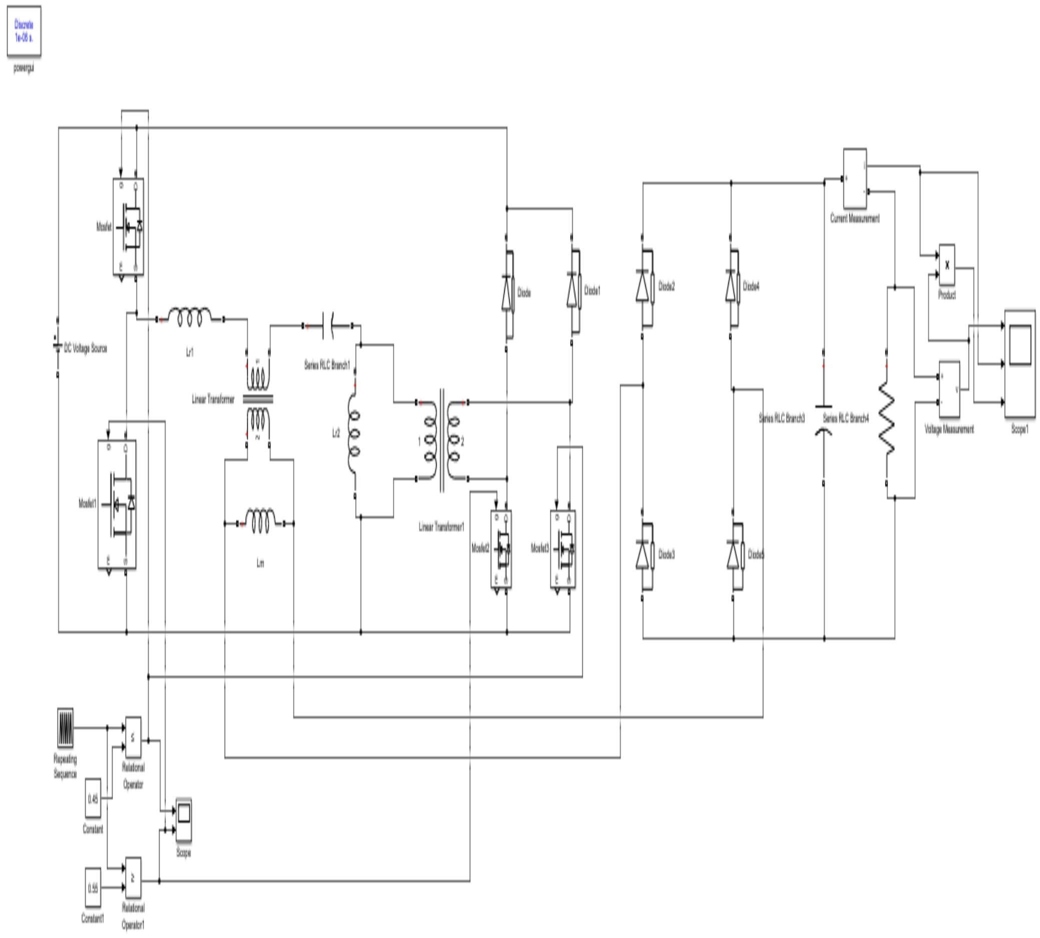


Figure 9 Simulation circuit

Detailed simulation studies are carried out on MATLAB/Simulink platform and the results obtained for various operating conditions are presented in this section [14]. The figure 9 shows the simulation circuit for the proposed LLC resonant converter circuit.

11.2 Input Voltage

The input voltage, and current from LLC resonant converter has been obtained as shown in figure 10.

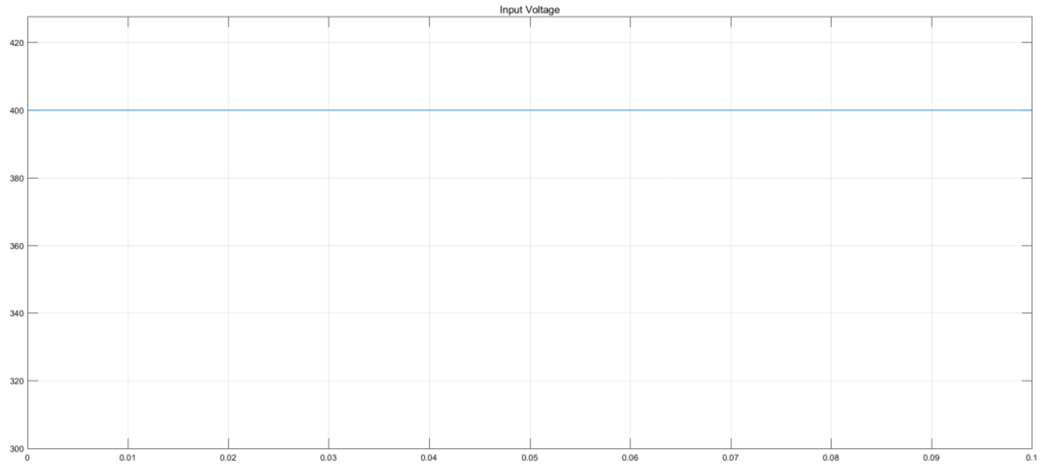


Figure10. Input voltage, and current from LLC resonant converter

Gate pulse

Figure 11 shows the gate pulses 1 and 2 applied to the LLC resonant converter.

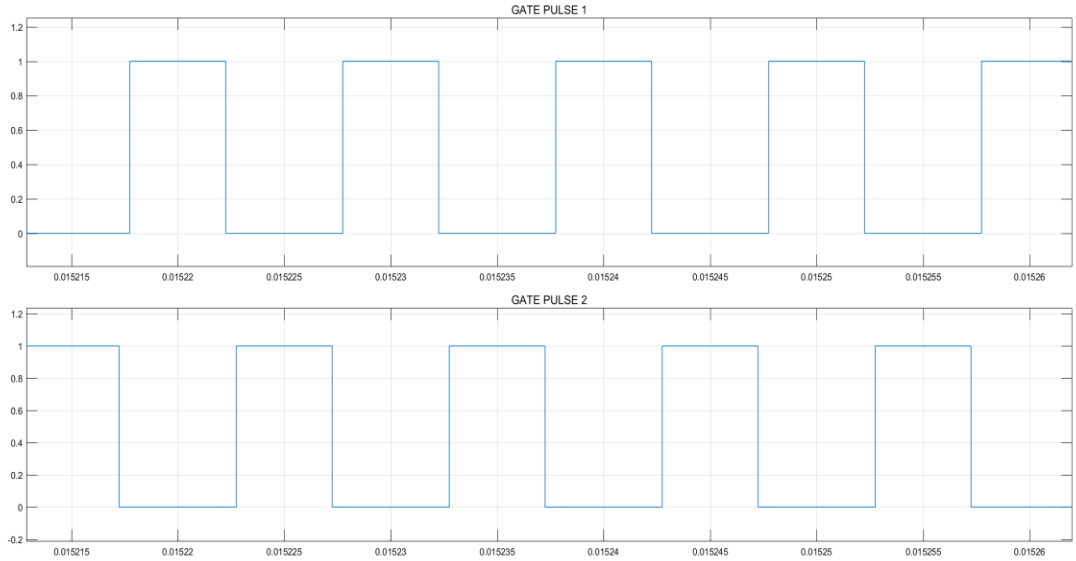


Figure 11. Gate pulse 1 and gate pulse 2 on LLC resonant converter

Resonant Current and Voltage

Figure 12 shows the resonant current and voltage waveforms for the particular design parameters.

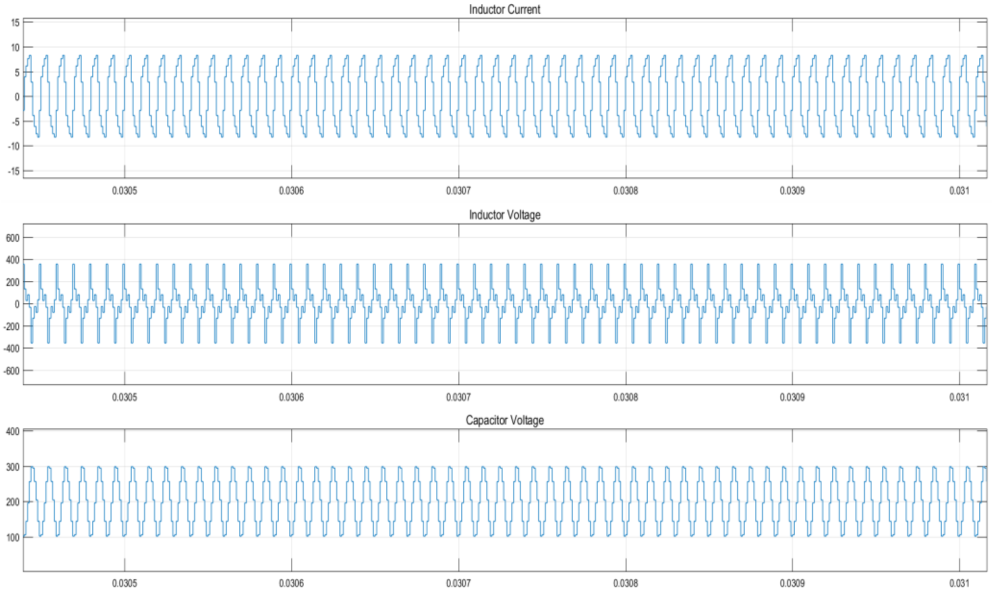


Figure 12 Resonant current and voltage waveforms

Output

The final output waveform for the proposed LLC resonant converter has been shown in figure 13.

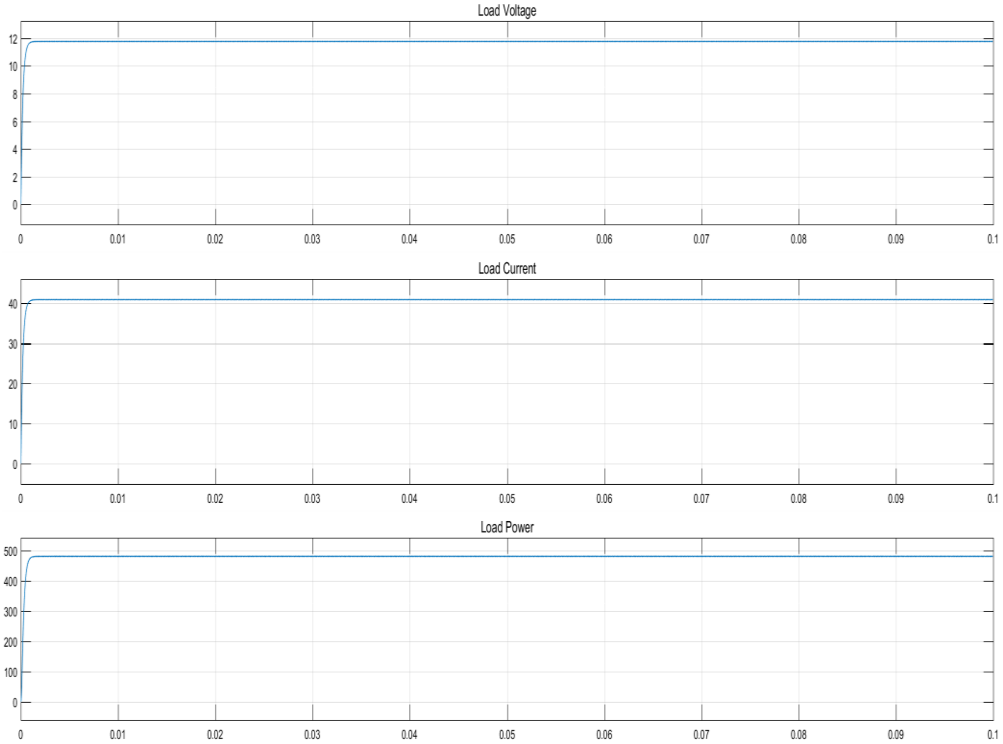


Figure 13 Output waveforms for the proposed LLC resonant converter

IX. CONCLUSION

In this paper, the design of the components has been presented, based on a theoretical analysis of circuit operation at the peak gain point. It is possible to optimize LLC resonant converter by using the developed precise analytical solution for the peak gain, it is possible to optimize LLC resonant converter, which during wide range of loads can control the output voltage. With a proper design based on the FHA analysis results, with variation of output voltage for the whole range of load level, this converter keeps up the ZVS operation for all switches. In this paper irrespective of the load, the effects of controller in regulating load voltage, has been demonstrated. Therefore, with a wide range of load, the proposed LLC resonant converter is a good choice for low voltage applications.

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