

Novel Design of LLC Resonant Converter with Peak Gain Adjustment

P. Kowstubha¹, K. Krishnaveni², K. Ramesh Reddy³

^{1,2}Department of Electrical and Electronics Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, India

³Department of Electrical and Electronics Engineering, G.Narayanamma Institute of Technology and Science, Hyderabad, India

*Corresponding author, e-mail: kowstubha.p@gmail.com¹, krishnaveni2k12.rvr@gmail.com², kollirameshreddy@yahoo.com³

Abstract

The main advantages of a half-bridge LLC resonant DC/DC converter having two inductors (LL) and a single capacitor (C) compared to the other load resonant converters are its less amount of circulating currents and large bandwidth for Zero Voltage Switching (ZVS). It also has the advantage of limited tuning of operating frequency to get the regulated output when variable frequency control method is implemented on the converter. This DC/DC converter is widely used in server and telecom applications due its higher efficiency and reliability. In this paper, a novel design using peak gain adjustment is proposed for a LLC resonant DC/DC converter with a design example of 400V/12V-5A used in server based applications. For the specifications of the converter mentioned, an experimental set up is built and evaluated with the Texas instruments power switch FSFR 2100 IC in closed loop configuration. The experimental results proved an improved efficiency of 94% for the converter with the novel design proposed.

Keywords: MOSFETS, LLC resonant DC/DC converter, fundamental harmonic approximation, zvs

Copyright © 2016 Universitas Ahmad Dahlan. All rights reserved.

1. Introduction

Higher efficiency and power density are the two important attributes required for any power converter. This can be achieved by forcing Pulse Width Modulated (PWM) converters to operate at high frequency. But, at high frequencies the occurrence of switching losses are huge. Therefore, a new topology called resonant converter topology has come in to existence. In these converters, since the power is processed in a sinusoidal way the switching devices undergo soft switching [1-2]. In these converters, the switching losses and the noise leading Electro Magnetic Interference (EMI) can be drastically reduced [3-8].

The main advantages of a half-bridge LLC resonant DC/DC converter compared to the other load resonant converters are its less amount of circulating currents and large bandwidth for ZVS. It also has the advantage of limited tuning of operating frequency to get the regulated output when variable frequency control method is implemented on the converter. This DC/DC converter is widely used in server and telecom applications due its higher efficiency and reliability. Figure 1 indicates the circuit diagram of half-bridge LLC resonant DC/DC converter with L_m , L_r as magnetizing and series resonant inductances and C_r as resonant capacitor. The principle of operation of the converter is explained with the help of Figure1 [9, 10]. It basically consists of a square wave generator stage, a resonant network stage and a diode rectifier network stage.

Square wave generation stage- On driving the switches S_1 and S_2 alternatively with 50% duty cycle, a square wave voltage (V_a) is produced at phase node. A small dead time is provided between the switching transitions of S_1 and S_2 .

Resonant network stage- Higher harmonic currents are filtered in this stage and only sinusoidal current is allowed to flow through the inductor L_r which is lagging the applied voltage (V_a). This stage also ensures the MOSFETs to be turned on with zvs causing the reduction of turn-on losses. Rectifier network stage- In this stage, a DC voltage is obtained on rectifying the AC current.

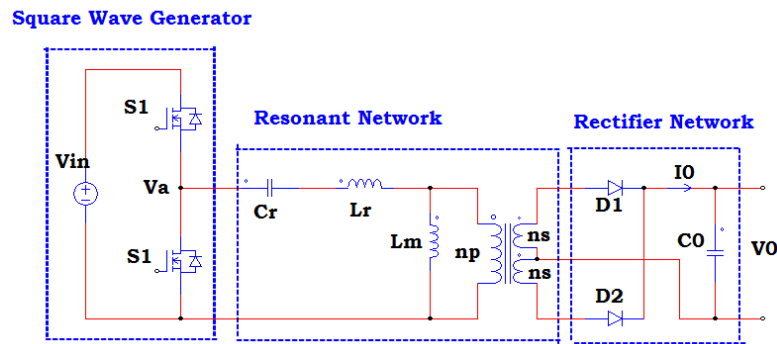


Figure 1. Circuit diagram of half-bridge LLC resonant DC/DC converter

The existing design procedures [11-14] in selecting resonant tank parameters provides boundaries or ranges of the values on trial and error basis. In this paper, a novel design using peak gain adjustment is proposed for a LLC resonant DC/DC converter with a design example of 400V/12V-5A used in server based applications. An analytical tool called Fundamental Harmonic Approximation (FHA) is used in the design. For the specifications of the converter mentioned, an experimental set up is built and evaluated with the Texas instruments power switch FSFR 2100 IC in closed loop configuration. The experimental results proved an improved efficiency of 94% for the converter with the novel design proposed.

2. Research Method

As a part of research methodology, modeling of LLC resonant DC/DC converter is developed using FHA. Later a novel design using peak gain adjustment is discussed in this section for the converter.

2.1. Modeling of the Converter with FHA

It is vital for the converter to operate near the resonant frequency (f_o) so that the circulating current in resonant tank becomes sinusoidal in nature with single frequency. The fundamental harmonic component of the square wave could be considered at phase node (V_a) of Figure 1. The assumptions made in this Fundamental Harmonic Approximation (FHA) method are:

1. Represent input voltage and currents with their fundamental approximated values.
2. Neglect the effect of output capacitor.
3. Neglect the transformer's secondary-side leakage inductance.
4. Represent the transformer's equivalent circuit referring to primary.
5. Represent the secondary side voltage and currents with their fundamental components.

An equivalent circuit of Figure 1 with these assumptions can be obtained as a model of the converter as indicated in Figure 2 used in modeling and designing the converter. A nonlinear and non sinusoidal circuit of Figure 2(a) is transformed into a linear and sinusoidal circuit of Figure 2(b) where an effective sinusoidal input is driving resonant tank and an equivalent resistive load.

In Figure 2(b), both input (V_{ge}) and output (V_{oe}) are sinusoidal with a frequency equal to the fundamental component of square-wave (V_{sq}) voltage. Before going to the design of the converter, the electrical variables and their relationships are obtained by considering Figure 2(b) are presented as follows.

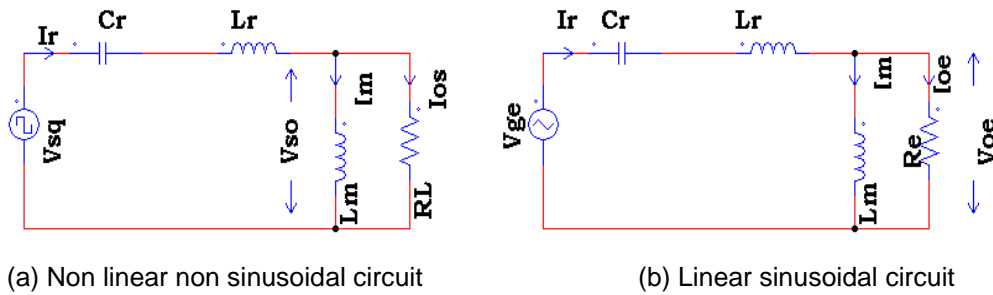


Figure 2. Model of half- bridge LLC resonant DC/DC converter

The fundamental voltage (V_{sq}) on the input side is

$$V_{ge}(t) = \frac{2}{\pi} \times V_{DC} \times \sin(2\pi f_{SW} t) \quad (1)$$

It's RMS value is given as:

$$V_{ge} = \frac{\sqrt{2}}{\pi} \times V_{DC} \quad (2)$$

Since V_{so} is referred as a square wave, the fundamental output voltage is

$$V_{oe}(t) = \frac{4}{\pi} \times n \times V_o \times \sin(2\pi f_{SW} t - \varphi_V) \quad (3)$$

Where φ_V is the phase difference between V_{oe} and V_{ge} , and its output RMS voltage is

$$V_{oe} = \frac{2\sqrt{2}}{\pi} \times n \times V_o \quad (4)$$

Fundamental component of current corresponding to V_{oe} .

$$i_{oe}(t) = \frac{\pi}{2} \times \frac{1}{n} \times I_o \times \sin(2\pi f_{SW} t - \varphi_i) \quad (5)$$

Where φ_i is the phase difference between i_{oe} and v_{oe} , and its output RMS current is

$$I_{oe} = \frac{\pi}{2\sqrt{2}} \times \frac{1}{n} \times I_o \quad (6)$$

The AC equivalent load resistance, R_e can be found as

$$R_e = \frac{V_{oe}}{I_{oe}} \times \frac{8 \times n^2}{\pi^2} \times \frac{V_o}{I_o} \times \frac{8 \times n^2}{\pi^2} \times R_L \quad (7)$$

The angular frequency is:

$$\omega_{SW} = 2\pi f_{SW} \quad (8)$$

And can be simplified as:

$$\omega = \omega_{SW} = 2\pi f_{SW} \quad (9)$$

The capacitive and inductive reactance of C_r , L_r , and L_m , respectively, are:

$$X_{C_r} = \frac{1}{\omega C_r}, X_{L_r} = \omega L_r, \text{ and } X_{L_m} = \omega L_m$$

The RMS magnetizing current is:

$$I_m = \frac{V_{oe}}{\omega L_m} = \frac{2\sqrt{2}}{\pi} \times \frac{n \times V_o}{\omega L_m} \quad (10)$$

The circulating current in resonant circuit is

$$I_r = \sqrt{I_m^2 + I_{oe}^2} \quad (11)$$

Now, voltage-gain function is developed by using this mathematical modeling of the converter.

2.1.1. Voltage-Gain Function

Gain gives the relationship between input and output voltages and is given by

$$M_{g-DC} = \frac{n \times V_o}{V_{in}/2} = \frac{n \times V_o}{V_{DC}/2} \quad (12)$$

As mentioned earlier, Equation (12) is approximated as the ratio of bipolar (V_{so}) to unipolar (V_{sq}) square-wave voltages.

$$M_{g-DC} \approx M_{g-SW} = \frac{V_{SO}}{V_{sq}} \quad (13)$$

M_{g-AC} , AC voltage ratio is approximated by using V_{ge} and V_{oe} to respectively

$$\begin{aligned} M_{g-DC} &= \frac{n \times V_o}{V_{in}/2} \approx M_{g-SW} \\ &= \frac{V_{SO}}{V_{sq}} \approx M_{g-AC} = \frac{V_{oe}}{V_{ge}} \end{aligned} \quad (14)$$

To simplify the notation, M_g is used in place of M_{g-AC} . From Figure 2(b), voltage-transfer function becomes:

$$\begin{aligned} M_g &= \frac{V_{oe}}{V_{ge}} = \left| \frac{jX_{Lm} || R_e}{(jX_{Lm} || R_e) + j(X_{Lr} - X_{Cr})} \right| \\ &= \left| \frac{(j\omega L_m) || R_e}{j\omega L_m || R_e + j\omega L_r + \frac{1}{j\omega C_r}} \right| \end{aligned} \quad (15)$$

Where $j = \sqrt{-1}$.

Equation (15) gives the relation between input (V_{in}) and output (V_o) voltages established in connection with M_g for LLC-circuit parameters. Further on simplification, Equation (15) can be written as:

$$V_o = M_g \times \frac{1}{n} \times \frac{V_{in}}{2} \quad (16)$$

Therefore, the output voltage is determined after knowing the values of M_g , n , and V_{in} .

2.1.2. Normalized Expression of Voltage-Gain Function

Equation (15) gives the voltage-gain expression with absolute values. It could be convenient to express this equation in a normalized format so as to design the converter parameters. Therefore, series resonant frequency (f_0) is selected as the reference base for normalization and the converter normalized frequency is taken as

$$f_n = \frac{f_{sw}}{f_0} \quad (17)$$

Further, an inductance ratio can be defined as:

$$\beta = \frac{L_m}{L_r} \quad (18)$$

The quality factor is defined as:

$$Q_e = \sqrt{\frac{L_r}{C_r} \frac{1}{R_e}} \quad (19)$$

Notice that f_n , β , and Q_e are constants. The normalized voltage-gain function can be given as:

$$M_g = \left| \frac{\beta \times f_n^2}{[(\beta+1) \times f_n^2 - 1] + j[(f_n^2 - 1) \times f_n \times Q_e \times \beta]} \right| \quad (20)$$

Equation (21) gives the output voltage expression in terms of input voltage.

$$V_o = M_g \times \frac{1}{n} \times \frac{V_{in}}{2} = M_g(f_n, \beta, Q_e) \times \frac{1}{n} \times \frac{V_{DC}}{2} \quad (21)$$

Where, $V_{in} = V_{DC}$

2.1.3. DC Characteristics

The voltage gain (M), obtained through (FHA) [15] as in Equation (21) can be rewritten as:

$$M = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{f_{sw}}{f_0}\right)^2 (\beta-1)}{\left(\frac{f_{sw}^2}{f_p^2} - 1\right) + j \frac{f_{sw}}{f_0} \left(\frac{f_{sw}^2}{f_0^2} - 1\right) (\beta-1) Q} \quad (22)$$

Where,

$$\begin{aligned} R_e &= \frac{8n^2}{\pi^2} R_L & \beta &= \frac{L_m}{L_r} \\ Q_e &= \sqrt{\frac{L_r}{C_r} \frac{1}{R_e}} \\ f_0 &= \frac{1}{2\pi\sqrt{L_r C_r}} & f_p &= \frac{1}{2\pi\sqrt{L_p C_r}} \quad (\text{Usually less than } f_0) \end{aligned}$$

Where R_e is equivalent value of resistance considering load and rectifier stage. The converter's two resonant frequencies are taken as f_0 and f_p . Figure 3 indicates the DC characteristics of LLC resonant DC/DC converter. In this figure, for different values of quality factor a graph is plotted between DC voltage gains and the normalized switching frequencies. The two resonant frequencies are found with components L_r , C_r , L_m , and load. In Figure 3, it is evident that as load increases, the resonant frequency shifts towards higher frequency. ZVS is preferred as MOSFETs are used for the converter. The operating range where converter is to be operated is between f_p and f_0 frequencies.

The inferences made from the DC characteristics are:

1. Maximum gain changes along with the changes of load.
2. Regulation can be achieved around resonant frequency. Operating zone can be divided as zero current and zero voltage switching regions.

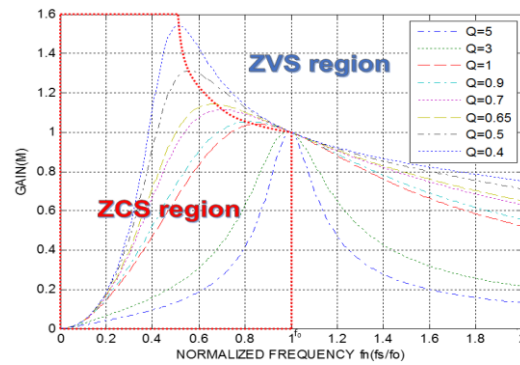


Figure 3. DC Characteristics of LLC resonant DC/DC converter.

2.2. Design Procedure

To design the parameter values of LLC resonant DC/DC converter, a voltage-transfer function as given in Equation (22) and the DC Characteristics as shown in Figure 3 are considered. A novel design method based on peak gain adjustment provides the optimal set of L, L and C parameters is proposed in this paper. This design procedure ensures the minimization of power losses and also gives the gain requirement for the converter. In the design of the converter, peak gain point is considered as the key parameter. This point is a measure of max gain capability and lower limit of switching frequency. In the design of LLC, set the peak gain so that the converter has its peak gain at full load and minimum operating frequency position. This set value of peak point should also be the required gain at minimum input voltage. From Figure 3, it is clear that the peak gain point comes under below-resonance region.

Now from Equation (22) it is clear that there are two resonant frequencies that are existing in the converter. One is found by L_r and C_r , and the other is found by L_r , L_m and C_r . Now once again by considering Figure 3 as well as the gain Equation (22) for different values of Q with $\beta=4$, $f_o=100\text{kHz}$. The following observations are made.

1. At resonant frequency f_o , gain characteristics are independent of load.
2. The bandwidth of the converter is limited by the peak gain that exists between f_p and f_o .
3. As quality factor decreases, the peak gain point moves towards f_p and higher peak gain is obtained. On the other hand, as quality factor increases, the peak gain point moves towards f_o and the peak gain drops. Therefore full load condition is the worst case for the designing resonant tank.

As per the observations made, a novel design procedure is demonstrated with an example having following design specifications are provided in Table 1 used for server based applications. The input to the converter is taken from Power Factor Correction (PFC).

Table 1. Design Specifications of LLC resonant DC/DC converter	
Specifications and Parameters	Values
DC-Bus voltage(V_{DC}) range	300V-400V(output of PFC stage)
Output voltage(V_o) and current(I_o)	12V and 5A
Hold-up time	20ms
DC link capacitor of PFC output	100 μ F
Resonant frequency	100kHz
Turns ratio of transformer	18:1
Maximum required voltage gain	1.25
Equivalent load resistor	630 Ω

The different procedural steps carried out to determine the circuit parameters are given below.

Step-1:

With estimated efficiency (η) 92%, the maximum input power is

$$P_{in} = \frac{P_o}{\eta}$$

As the maximum input voltage is same as nominal PFC output voltage, the minimum input voltage considering the hold-up time is

$$V_{in}^{min} = \sqrt{V_{0PFC}^2 - \frac{2P_{in}T_{HU}}{C_{DL}}}$$

Where V_{0PFC} = nominal PFC output voltage, T_{HU} = hold-up time, and C_{DL} = DC link bulk capacitor.

Step-2:

From Equation (22), the voltage gain is a function of β ($\beta = L_m/L_r$) and is chosen as 4. This value of β results a voltage gain of 1.1~1.3 at f_0 . Voltage gain for the nominal PFC output is

$$M^{min} = \sqrt{\frac{\beta}{\beta-1}} @f = f_0$$

Now the maximum voltage gain is

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

Step-3:

The transformer turns ratio is

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{max}}{2(V_0 + V_F)} M^{min}$$

Where V_F is secondary-side diode voltage drop.

Step-4:

With turns ratio n , the equivalent load resistance is

$$R_e = \frac{8n^2}{\pi^2} R_0$$

Step-5:

From Figure 3 With the chosen value of β , get the value of Q from the peak gain curves. Once Q is found, the resonant tank parameters are found with

$$C_r = \frac{1}{2\pi Q f_0 R_e}$$

$$L_r = \frac{1}{(2\pi f_0)^2 C_r}$$

$$L_m = \beta L_r$$

Now all above mentioned procedural steps have been evaluated and final resonant tank values are given in Table 2.

Table 2. Designed Values of LLC Resonant DC/DC Converter

Parameter	Designed Values
L_m	1924 μ H
L_r	481 μ H
C_r	5.26nF
f_0	100kHz
B	4
Q	0.48
$M @f_0$	1.15
Minimum frequency	75kHz

3. Experimental Results and Analysis

For the proposed design, an experimental set up of LLC resonant DC/DC converter based on design specification provided in Table 1 has been built and evaluated in closed loop configuration. Figure 4 shows the experimental set up of LLC resonant DC/DC converter for a output power of 60W.

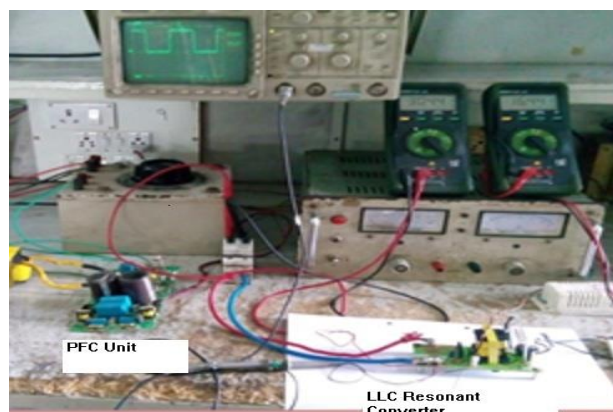


Figure 4. Experimental set up of a LLC resonant DC/DC converter

In the set up, FSFR2100IC(Texas make),a power switch is used. MUR160 power diodes are implemented in rectifier stage. Practically, on main input and output buses, high frequency capacitors with low ESR ratings are used. An integrated transformer is developed with EER 3542 core having a turns ratio of 18:1. This integrated transformer is built such that the leakage inductance is used as a series inductor (L_r) and the magnetizing inductance is used as a shunt inductor (L_m). Transformer turns are wounded with Litz wire. A small capacitor is connected in parallel with power MOSFETs^[16] to reduce turn-off losses. Load resistance is varied from 2.5Ω to infinite and the operating frequency is tuned between 60 kHz and 100 kHz to cover all modes of operation of the converter. The developed prototype is tested for different loads (0–5 A DC) and input voltage conditions (300–400V DC). The experimental results confirm high performance of designed wide-range converter.

Figure 5 indicates the primary side waveforms of LLC resonant DC/DC converter under no-load with maximum input voltage. Figure 6 indicates the secondary side waveforms of LLC resonant DC/DC converter under full-load with minimum input voltage. The probe of CRO is connected with $\times 10$ multiplier to measure drain to source voltage (V_{DS}) and capacitor voltage (V_{Cr}) as indicated in Figure 5(a, b) and Figure 6(a, b). The DC output voltage both on no load and full load conditions shown in Figure 5(c) and Figure 6(c). Primary side inductor current (i_{Lr}), is measured by connecting a low wattage resistor in series with the primary of the transformer. But practically this resistor will act like load to the converter. Switching current of MOSFET 2 is sensed through current sensing (CS) pin of FSFR2100 IC instead of measuring i_{Lr} . This can be sensed with 2W $R_{sensing}$ resistor (R8) as shown in the PCB layout of the converter given Figure 8 of Appendix. From Figure 5(a) and Figure 6(a), it is observed that switch current on no-load condition is negligible but switch current on full-load condition will be a reasonable value.

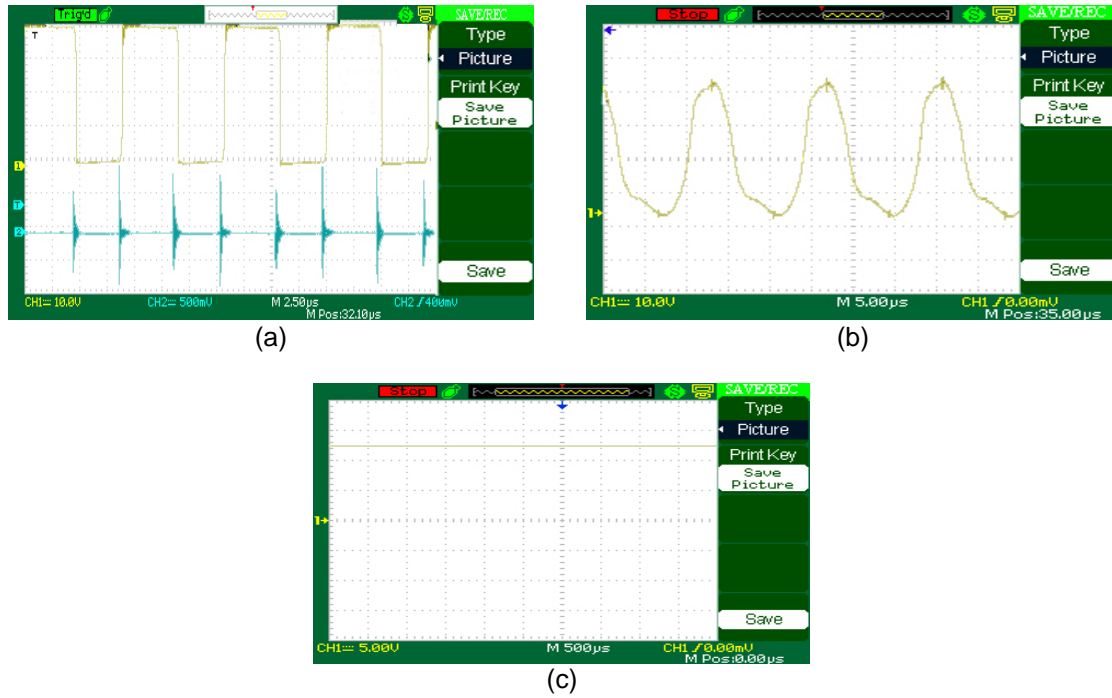


Figure 5. LLC resonant DC/DC converter waveforms under no-load condition $I_o = 10\mu A$, $V_o = 12V$ when $V_{in} = 400V$ (a) Primary-side V_{DS} voltage and Switching current through MOSFET 2, (b) Primary-side resonant capacitor voltage(V_{Cr}), (c) Secondary load voltage(V_o)waveforms

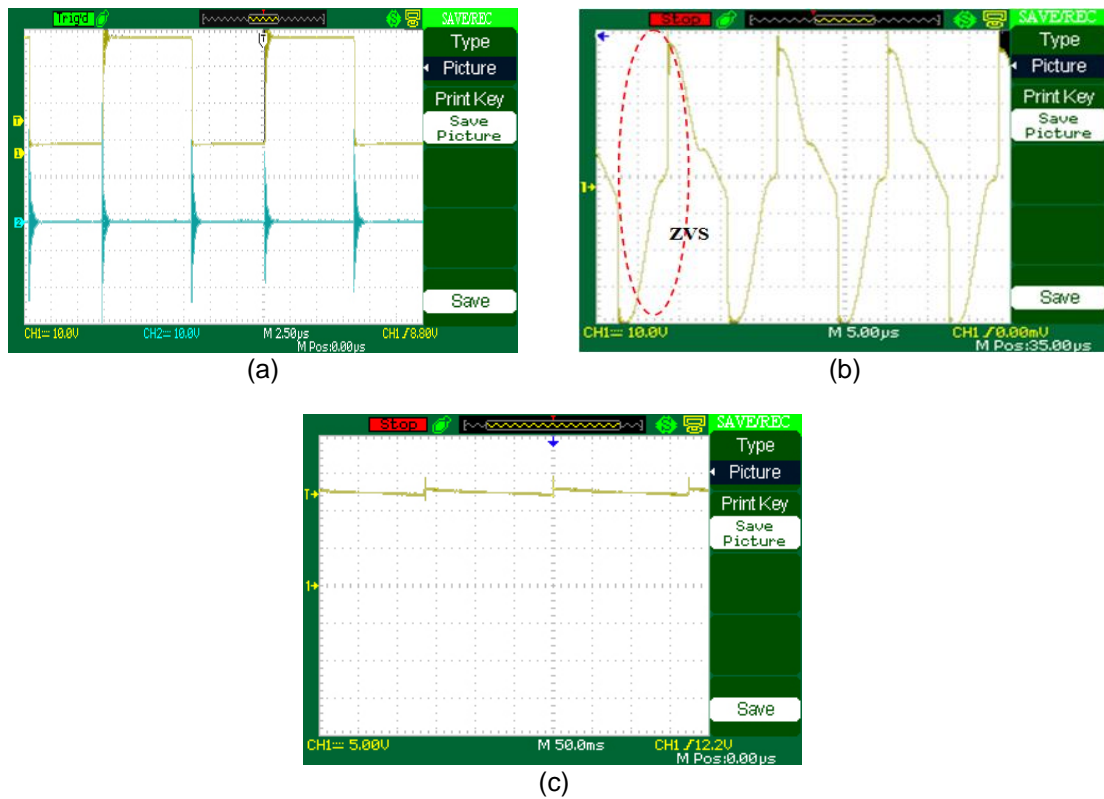


Figure 6. LLC resonant DC/DC converter waveforms under full-load condition $I_o = 5A$, $V_o = 12V$ when $V_{in} = 300V$ (a) Primary-side V_{DS} voltage and Switching current through MOSFET 2, (b) Primary-side resonant capacitor voltage(V_{Cr}), (c) Secondary load voltage(V_o)waveforms

From Figure 6(a), it is understood that the MOSFETs turn on losses are almost zero on full-load condition for wide input voltage and wide load variation ranges. Soft commutation(zvs) is witnessed through Figure 6(a). It is also observed that during hold-up time, to boost up voltage gain the converter has to reduce switching frequency to 66 kHz. In the experimental set up, frequenc modulation is done by FSFR 2100IC. This IC is enabled through an isolation opto-coupler for load/line variations so as to control output voltage during hold up time. An efficiency of 94% is observed at full load condition. Figure7 indicates a flat efficiency curve at $V_{in}=400V$ and $V_{in}=300V$ for different load conditions.

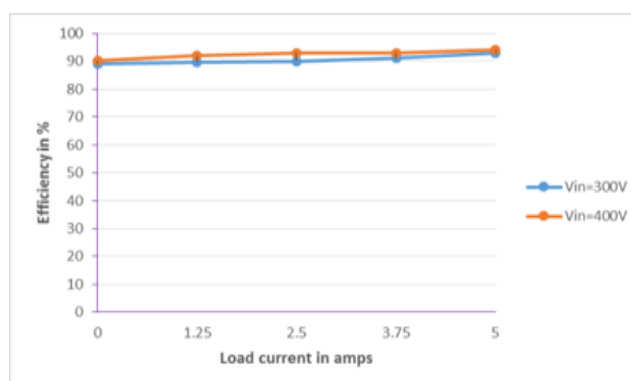


Figure 7. Measured efficiency graphs at different input voltages for different load conditions

From Figure 7, it is understood that at light loads, the efficiency is reduced, due to the increase of switching frequency and reactive power, occurred in the constant output voltage applications of the LLC resonant DC/DC converter.

4. Conclusion

A unique analytical tool- Fundamental Harmonic Approximation (FHA) is discussed for the mathematical modeling and design of half-bridge LLC resonant DC/DC converter. A novel design procedure using peak gain adjustment is proposed by considering a design example of 400V/12V-5A converter operating at 75 kHz used in server based applications. A prototype model of the converter for the mentioned specifications is built with FSFR 2100 IC power switch (Texas make) in closed loop configuration.

Acknowledgements

The authors wish to thank Chaitanya Bharathi Institute of Technology and G.Narayanamma Institute of Technology and Science authorities for permitting to publish.

References

- [1] Muhammad H Rashid. Power Electronics-Circuits, Devices, and Application. 3rd edition. Pearson Education. 2004.
- [2] Ned Mohan, Tore M Underland, William P Robbins. Power Electronics-Converters, Application and Design. 3rd edition. John Wiley & Sons. 2003.
- [3] Younghoon Cho. A Low Cost Single-Switch Bridgeless Boost PFC Converter. *International Journal of Power Electronics and Drive System*. 2014; 4(2): 256-264.
- [4] M Facta, T Sutikno, Z Salam. The Application of FPGA in PWM Controlled Resonant Converter for an Ozone Generator. *International Journal of Power Electronics and Drive System*. 2013; 3(3): 336-343.
- [5] WY Choi, JM Kwon. *High-performance front-end rectifier system for telecommunication power supplies*. Proc. Inst. Elect. Eng. 2006; 153(4): 473-482.

- [6] H de Groot, E Janseen, R Pagano, K Schetters. Design of a 1-MHz LLC resonant converter based on a DSP-Driven SOI Half-Bridge power MOS module. *IEEE Trans. Power Electron.* 2007; 22(6): 2307-2320.
- [7] X Fang, H Hu, J Shen, I Batarseh. Operation mode analysis and peak gain approximation of the LLC resonant converter. *IEEE Trans. Power Electron.* 2012; 27(4): 1985-1995.
- [8] JF Lazar, R Martinelli. *Steady-state analysis of the LLC series resonant converter.* In Proc. IEEE Appl. Power Electron. Conf. Expo. 2001; 2: 728-735.
- [9] B Yang, FC Lee, AJ Zhang, G Huang. *LLC resonant converter for front end DC/DC conversion.* In Proc. IEEE Appl. Power Elec. Conf. and Expo. 2002; 2: 1108-1112.
- [10] Y Ye, C Yan, J Zeng, J Ying. *A Novel Light Load Solution for LLC Series Resonant Converter.* In Proc. IEEE Telecommunications Energy Conf. 2007: 61-64.
- [11] C Zhao, X Wu, Z Qian. *Design and comparison of two front end DC/DC converters: LLC resonant converter and soft-switched phase-shifted full-bridge converter with primary-side energy storage inductor.* In Proc. 24th Annu. IEEE Appl. Power Electron. Conf. Expo. 2009: 1073-1077.
- [12] MP Foster, CR Gould, AJ Gilbert, DA Stone, CM Bingham. Analysis of CLL voltage-output resonant converters using describing functions. *IEEE Trans. Power Electron.* 2008; 23(4): 1772-1781.
- [13] X Xie, J Zhang, C Zhao, Z Qian. Analysis and optimization of LLC resonant converter with a novel over-current protection circuit. *IEEE Trans. Power Electron.* 2007; 22(2): 435-443.
- [14] CM Bingham, YA Ang, MP Foster, DA Stone. Analysis and control of dual-output LCLC resonant converters with significant leakage inductance. *IEEE Trans. Power Electron.* 2008; 23(4): 1724-1732.
- [15] B Yang, FC Lee, AJ Zhang, G Huang. *LLC resonant converter for front end DC/DC conversion.* In Proc. IEEE Appl. Power Elec. Conf. and Expo. 2002; 2: 1108-1112.
- [16] RW Erickson, D Maksimovic. *Resonant converters.* In *Fundamentals of Power Electronics*. 2nd edition. Norwell, MA, Kluwer. 2001; 19: 705-759.

Appendix

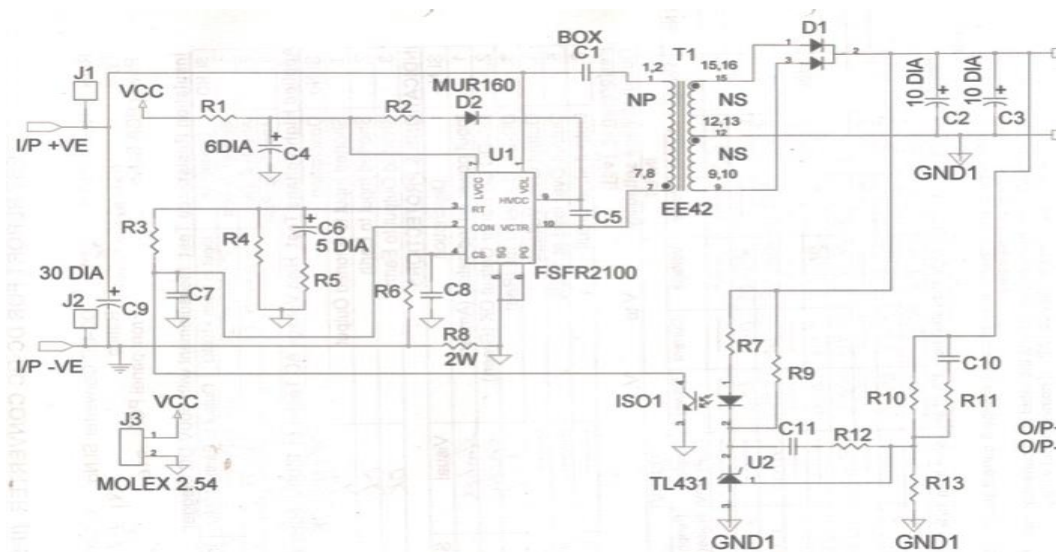


Figure 8. PCB set up of LLC resonant converter