LLC Resonant Converter: Analysis and Design

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Abstract- Inductor Inductor Capacitor (LLC) resonant converter has gained attention of researchers and engineers these days High efficiency, power density and Reliability. LLC resonant converter is most suitable resonant converter for front end DC-DC applications. Integrated magnetic, ZVS and high frequency operation, make the converter more compact and efficient. In this paper brief analysis of the LLC resonant converter is discussed and the prototype of the converter is also developed.

Keywords—Full bridge LLC, FHA, Integrated magnetic, and ZVS;

I. Introduction

In today's highly competitive industrial environment designer always strive for highly efficient, reliable, and highly compact design. DC-DC converter technology has evolved from earlier lossy linear power converters to today's advanced resonant converters. Resonant converters present zero switching losses and hence the overall efficiency will increase considerably. Because of the zero switching losses operating frequency of the converter can be increased to higher values. In series resonant converter the resonant tank circuit is connected in series with load[1], hence the gain of the converter is always less than unity. At light-load or no-load condition to regulate output voltage we need to increase the switching frequency to very high value, ideally to infinity. But in parallel resonant converter since the load is connected in parallel with the resonant capacitor, it is quite easy to regulate the output voltage. But PRC suffers from high circulating energy losses. Hybrid LCC resonant converter came to existence to overcome the difficulties presented by conventional PRC and SRC. This topology is commonly known as SPRC. It combines both the properties PRC and SRC. Among all resonant converters LLC is the best with respect to all requirements listed above. LLC is formed by replacing all capacitor of resonant tank of SPRC with the inductor and inductor with the capacitor.

Several aspects of LLC resonant converter are discussed in many papers. High frequency operation results in reduced size of magnetic components. But in resonant converters the advantage gained with the high frequency operation is lost as it requires additional reactive elements [4]. With the integrated magnetics several magnetic components can be constructed in one magnetic core [4] [5]. Major advantage of LLC resonant converter is that the leakage inductance of the transformer can be used as resonant inductance and together with the resonant capacitor it participates in the energy transfer mechanism [5]. With the magnetic integration the number of components is reduced and the flux ripple cancellation is achieved so that core loss reduces [5]. But the integrated magnetic structure results in the inclusion of equal amount of leakage inductor on secondary side too. So that LLC with the center tapped secondary rectifier will experiences large voltage oscillation, due to the presence of secondary leakage inductance [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. 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.

In this paper full bridge LLC resonant converter is analyzed thoroughly, the prototype of the same is designed using first harmonic approximation method.

II. Full Bridge LLC Resonant Converter

The power circuit of LLC resonant converter is shown in the fig 1. The switches Q1, Q2 and Q3, Q4 are switched in such a way that the square wave of magnitude VDC is produced at the output of the bridge. The square produced is applied to the resonant tank formed by Lr, Cr, and Lm. Then it is rectified and applied across the load.
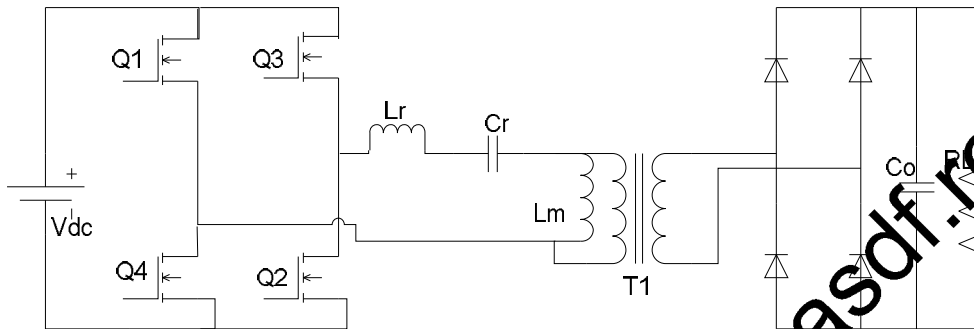
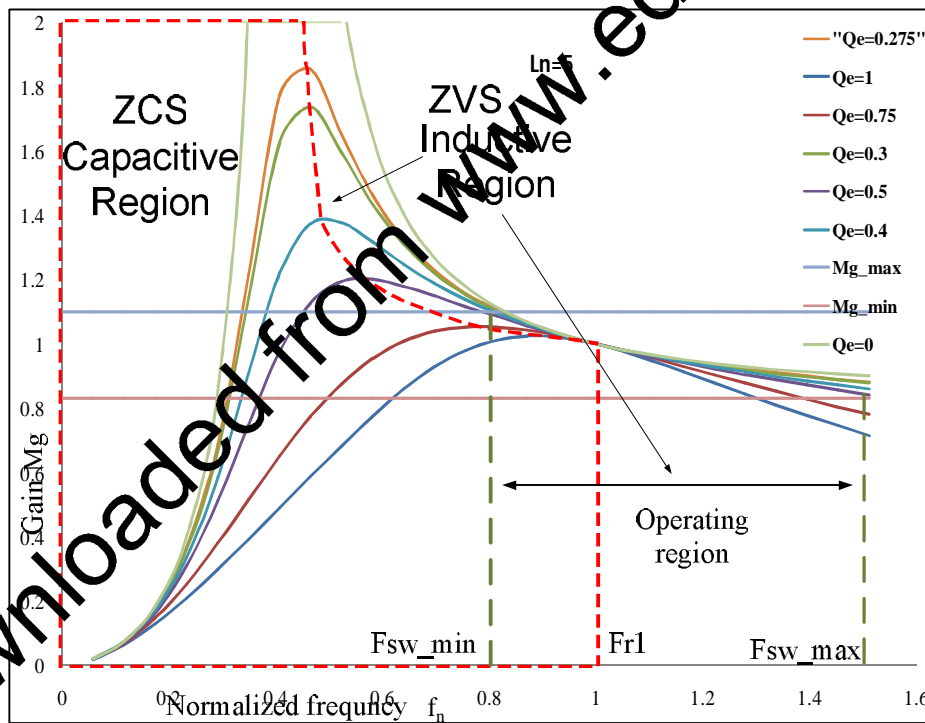Fig.1. Power Circuit of LLC resonant converter

Fig.2. DC Characteristics and operating regions of LLC

The DC characteristics of LLC resonant converter is shown in the figure. The DC characteristics of the LLC can be divided into two regions, ZVS region and ZCS region. The converter is characterized by two resonant frequencies. One resonant frequency corresponds to C_r, L_r, other one can be determined by L_m, C_r. As load increases the resonant frequency will shift to the higher resonant frequency. The two resonant frequencies can be given by

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

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

Above the resonant frequency fr1 the converter exhibits the same properties as that of SRC but below fr1the properties of both SRC and PRC trying to dominate. At heavy load condition SRC will dominate but at light load condition the PRC will dominate. In order to have high efficiency the converter is designed so that it should operate near the fr1.

Typical waveforms of LLC resonant converter is shown in the figure. Basically the operation of the LLC resonant converter depends upon the relationship between the frequency at which the switches are operated and the series resonant frequency (fr1) of the converter. Operation of converter at different conditions results in different characteristics Converter can be basically operated in three different conditions;

- ➢ Operation at resonant frequency(when $f_{r1} = f_{sw}$)
- ➢ Operation below resonant frequency(when $f_{r1} > f_{sw}$)
- ➢ Operation above resonant frequency(when $f_{r1} < f_{sw}$)

Operating the converter at resonant frequency fr1 is always preferred as it results in high efficiency and the resonant current can be approximated as sin-wave. Major drawback of operating the converter below fr1 is that the circulating current is very high since the secondary diodes are in discontinuous mode. This requires the resonant circuit to supply more circulating energy in order to supply the load with the same amount of energy.
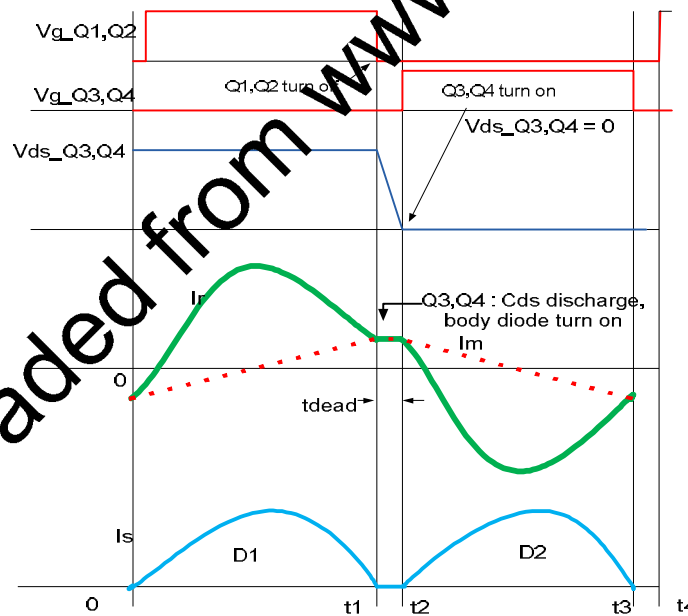

Fig.3. Typical waveforms of LLC

This additional circulating energy results in high conduction losses. But operating the converter above its series resonant frequency will results in very little circulating energy and hence very low losses. But the natural turn off of the secondary diodes is not possible and reverse recovery losses will be high. But the ZVS of primary operation is still possible but . operation above f_{r1} may cause significant increase in the switching frequency. The above analysis shows that operating the converter at series resonant frequency is always preferred.

III. Variable Frequency control of LLC Resonant Converter

From the figure 3.3 we can observe that during light load conditions the gain will be less than one and to maintain the output regulation we need to increase the switching frequency above the series resonant frequency. During normal full load conditions the converter operates near its series resonant frequency f_{r1}. Considering these facts frequency shifting technique is developed. This control system allows the converter to operate between frequency limit f_{sw_min} and f_{sw_max}, corresponding to 10% over load and no-load condition respectively. When the load gets heavier the controller is designed to decrease the switching frequency for supplying the required large power. In contrast to this when there is a light load condition the controller has to increase the switching frequency in order to supply the required power and to regulate the output voltage. Controller should be designed such that the frequency will never cross the lower and higher frequency limits fsw_min and fsw_max.

IV. Prototype Development

Prototype of LLC resonant converter is developed with the design values given in the table. To design the converter we used first harmonic approximation method. In this method the resonant current is assumed to be sinusoidal. This is true at least at series resonant frequency fr1. According to this method the gain equation is developed which is given by

$$M_{gn} = \left| \frac{L_n f_n^2}{[(L_n+1)f_n^2 - 1] + j[(f_n^2-1)*f_n*Q_e*L_n]} \right| \qquad (3)$$

Where,

$$f_n = \frac{f_{sw}}{f_r} \qquad L_n = \frac{L_m}{L_r} \qquad Q_e = \frac{\sqrt{L_r/C_r}}{R_{ac}}$$

The gain function described by the equation (4) depends on three variable Ln, fn, and Qe. For a particular design the value of Ln and Qe are fixed. Gain can be varied only by varying the switching frequency i.e. fn. Hence we can consider Ln, Qe as dummy variables and the only control variable is fn. Family of curves are plotted as shown in the fig.2. As we can see from the gain curve we observe that as the value of the quality factor Qe increases with Ln fixed the curve becomes narrower results in narrow frequency control band. This is expected since Cr and Ln are fixed and Qe depends only on load. As a matter of interest we shall consider two important conditions:

➢ If the load is open circuited then the value of Qe = 0 and the switching frequency $f_{sw} = f_{r2}$. Theoretically the corresponding peak value of gain function is ∞.

Table.1, Design Values

Parameters	Initial Design	Final Design
Input V_{in_nom}	72V	72V
Output V_{out}	400V	400V
P_o	2.4Kw	2.4Kw
L_m	8.15µH	8.5µH
L_r	1.31µH	1.51µH
C_r	2.51µF	2.62µF
Qe	0.42	0.42
Ln	6	6
f_r	86000Hz	82400Hz

➢ If the load is short-circuited then the value of Qe is ∞ and the switching frequency $f_{sw} = f_{r1}$. Theoretically the corresponding peak value of gain function is zero.

Prototype built is shown in the fig 4. Switches used for primary full bridge were infenion MOSFETs having a part number IPP041N12N3 G. Secondary rectifier is a full bridge rectifier and diodes used were Fairchild Semiconductor's ultrafast diodes having part number RURG5060. To generate gating pulses we used a DSP PICCOLO320F28027 and FAN7390 was used as gate driver. Transformer and inductors were wound and fabricated at work place. Comparatively smaller heat sinks were required as the switching losses were very less.
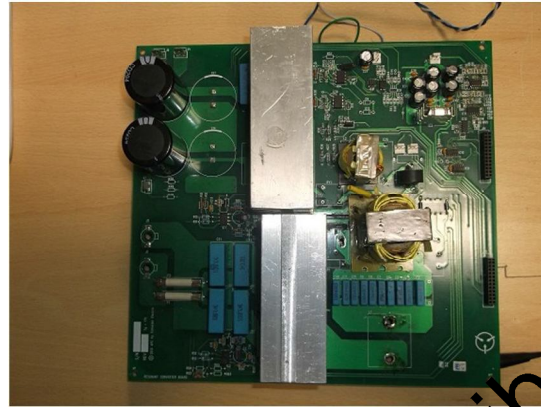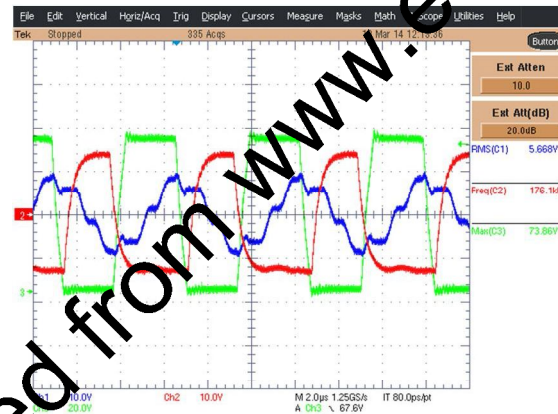

Fig.4. Prototype Developed.

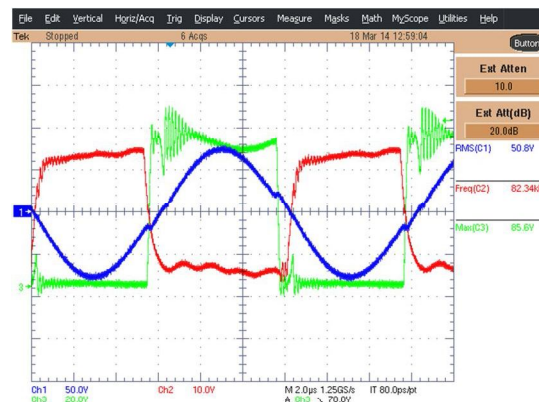Fig.5. Vgs of S1 (Red trace), Vds of S1 (green trace), I_Lr1 (blue trace) ,72 V, no-load.

Fig.4.6. Vgs of S1 (Red trace), Vds of S1 (green trace), I_Lr1 (blue trace), Pout = 2400W & 72 V.

Developed prototype is tested for various load conditions. Fig 6 shows the no-load test waveforms. Under no-load the resonant current is highly distorted and the switching frequency is very high. In the fig 7 full load test waveform is shown. The resonant current is almost sinusoidal and the switching frequency is almost equal to series resonant frequency.

V. Conclusion

In this paper full bridge LLC resonant converter is discussed and its design procedure also presented. In this project work we successfully designed full bridge LLC resonant converter with the specification P_o = 3.4 KW, V_o = 400V, V_{in} = 2V efficiency = 95%. Prototype of designed LLC resonant converter is realized. But due to the difficulties in adjusting the value of resonant inductor we did not use the principle of integrated magnetics. So in order to enjoy all the advantages of LLC resonant converter it is recommended to realize the integrated magnetic structure of the transformer. Various tests are conducted. From the test results various characteristics of LLC resonant converter were studied.

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