Analysis Of Soft Switching Characteristics Of LLC Resonant Converter for DC-DC Application.

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***Abstract*- This paper presents the control strategy applied to the half-bridge LLC Resonant Converter, applicable for the DC-DC applications. A closed-loop control is achieved by varying frequency through VCO and is analyzed with the help of PI Controller. Due to the Soft Switching (ZVS) technique the turn-on losses in both the switches(MOSFETs) of the circuit are reduced. ZVS method is used for the control of the closed-loop. Validity of the control circuit for the closed-loop is established with the help of PSIM simulation software and results for wide range of input and load. The converter's power rating is 300W. This circuit is simulated and analyzed for various tank circuits in detail and found that circuit works with very high efficiency when tank W network is used. The efficiency of the converter is 95%.**

***Index Terms*- LLC Resonant Converter, ZVS, VCO, closed-loop control.**

I. Introduction

The LLC resonant converter in half-bridge implementation with MOSFETs as power switches is very popular due to the negligible turn-on losses, soft switching, high efficiency. To design a control system and also to regulate or control the output voltage of the converter is a big task particularly in high power DC-DC applications.

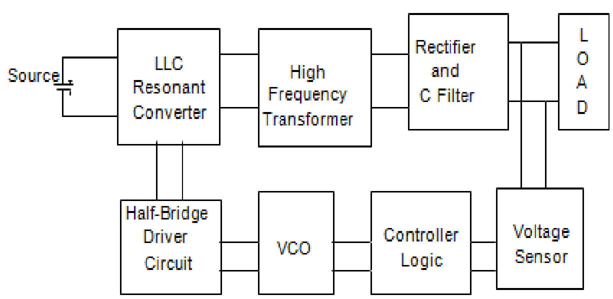

Fig.1. Basic block diagram of proposed closed-loop control system

Resonant converter is best suited for the very high power and high switching frequency applications due to their high power density. Their ability to operate at a very high switching frequency and thus reduces the size of passive components. Design of resonant elements, inductor L & capacitor C is same as that of the normal converters but the design of high frequency transformer is such a way that the value of the magnetizing inductance (Lm) of the transformer is considered to be less and hence it is connected in parallel with the LC tank circuit (Fig.2)

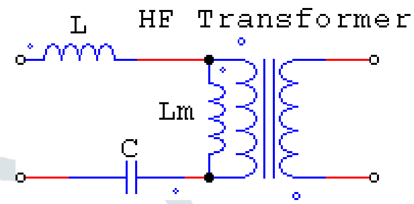

Fig.2. LLC tank with HF Transformer

According to the block diagram, the converter is operated at a very high frequency, half –bridge circuit and it is driven with the driver circuit. The output of the driver circuit is the square wave pulses with 0.5 as the duty ratio and dead time is also included between the two switching instants to avoid short circuit condition and to achieve ZVS. Due to resonating condition the current resonates in the form of pure sine wave as all the harmonics are filtered out with the help of the resonant tank. With this LLC resonant topology the operation of the converter with switching frequency (fs) greater than the resonant frequency (fo) is also possible to turn on the switches at the zero switching (ZVS). In this regard the turn on switching losses are eliminated.

The voltage sensor is used to sense the output voltage and as per the sensed output, the Voltage Controlled Oscillator (VCO) produces the square wave pulses of required frequency based on the error voltage which maintains the output voltage at desired level. Any variation in the output voltage due to the changes in load or source is taken care by the VCO.

II DESIGN CONSIDERATION FOR CLOSED-LOOP CONTROL

The specifications known for the design are as shown in the table below.

Table 1: Known parameters for the design

Parameter	Value
Output power	300W
Input voltage	400V
Output voltage	24V
Delay time	100us
Cstray	250pF

Assuming 95% efficiency,
Input power is calculated as follows

$P_{in} = P_{out}/\eta$

$P_{in} = 300/0.95 = 315.79W$

The range of input values that is given to the converter is calculated as

$V_{in(max)} = \sqrt{V_o * V_o - 2 P_{in} T_d C_s} = 158V$

$V_{in(max)} = V_o = 400V$

Calculation of gain

$\text{Max gain} = V_o/V_{in(max)}/2 = 1.14$

$\text{Min gain} = V_{in(max)}\ V_{in(min)}\ \text{Max(gain)} = 0.63$

$f_o = 250KHz$ and $f_s = 500KHz$

Table 2 . List of component values based on the design for the simulation

Component	Values
Lr	17.5uH
Lm	60uH
Cr	7.2nF
Co	4700uF
Cstray	250pF
Tdead	100ns
Transformer ratio	29:3
Duty ratio	0.5

III SIMULATION OF THE CIRCUIT

Open loop simulation of the circuit

The simulation of the circuit is done with the help of the values designed and is made to operate at 500kHz with the help of PSIM software and the open loop simulation is as shown in Fig. 3.

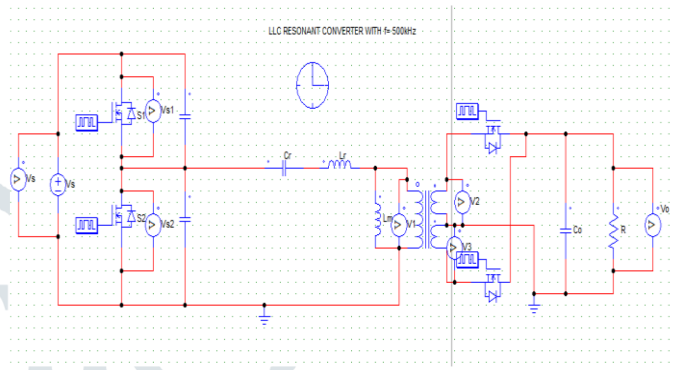

Fig. 3. Open loop simulation circuit.

Open loop simulation results are as shown below. The circuit is made to operate in ZVS mode, so the switching losses are reduced and that is depicted in Fig. 4. it is observed that the current is at its maximum the pulse voltage is low and so if the power loss is calculated during switching, the power loss is very low.

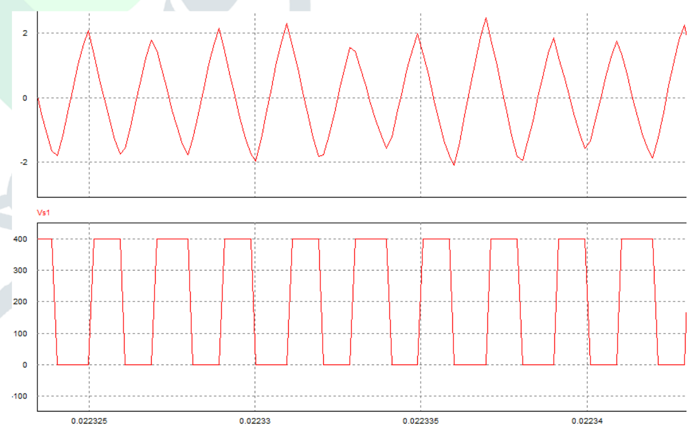

Fig. 4. Waveforms of resonant inductor current and gate pulses to represent ZVS operation.

The current through the magnetizing inductor as shown in Fig. 5 is continuous as the operating frequency is greater than the resonating frequency.

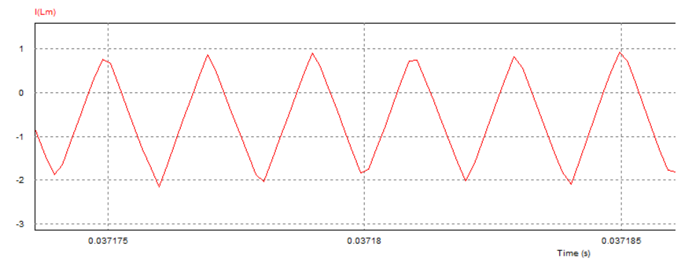

Fig. 5. The current through the magnetizing inductor

The waveforms of input voltage as in Fig. 6, output voltage as in Fig. 7 is as shown in the respective waveforms.

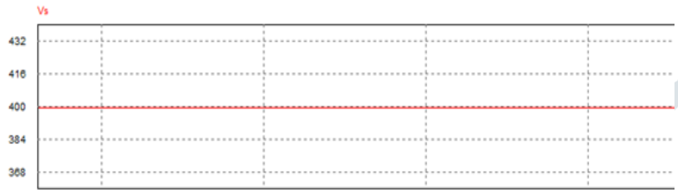

Fig. 6 Input voltage to the converter

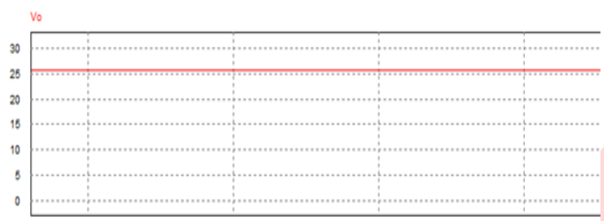

Fig.7 Output voltage of the converter

Analysis of the circuit in three different modes of operation is as follows based on the relationship between the switching and resonant frequency.

Mode 1, Analysis for fs > fo

The waveforms of the current through the resonating inductor as shown in Fig. 8, the pulses given to the switch are as shown in Fig. 9. The FFT analysis is as shown in Fig. 10 when the switching frequency is greater than resonating frequency.

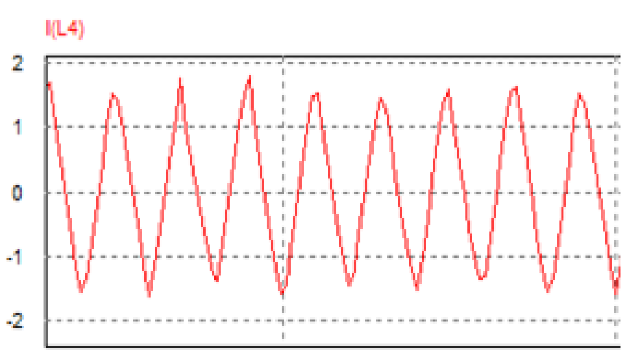

Fig. 8 The waveforms of the current through the resonating inductor

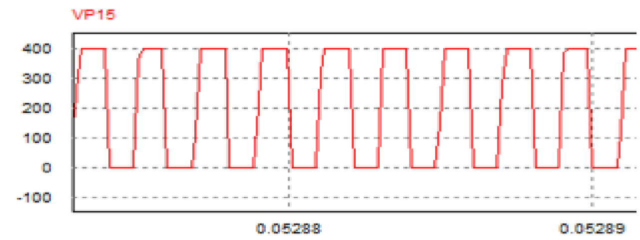

Fig. 9. The pulses given to the switch

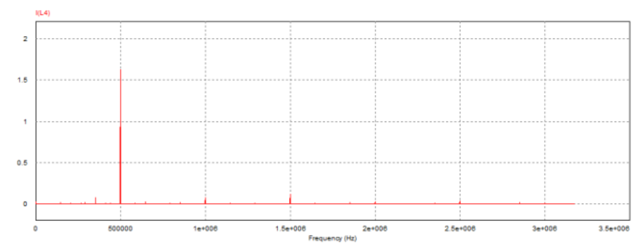

Fig. 10. The FFT analysis of the resonant inductor current

The various conclusions are made based on the waveforms.

1. Current through the resonant inductor is continuous.
2. Current through the resonant inductor varies sinusoidal with the frequency equal to fs.
3. The current in the switch is turned on at zero voltage and off at non zero current.
4. The harmonic content in the resonant inductor current is neglected.

Mode 2, Analysis for fo/2 < fs < fo

The waveforms of the current through the resonating inductor as shown in Fig. 11, the pulses given to the switch are as shown in Fig. 12. The FFT analysis is as shown in Fig. 13 when the switching frequency lies between fo/2 and f0.

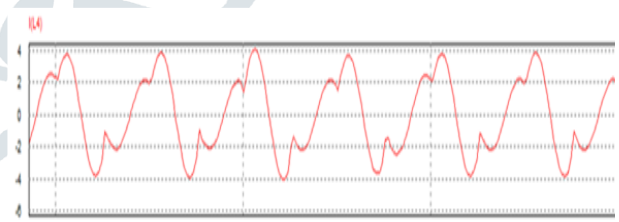

Fig. 11 The waveforms of the current through the resonating inductor

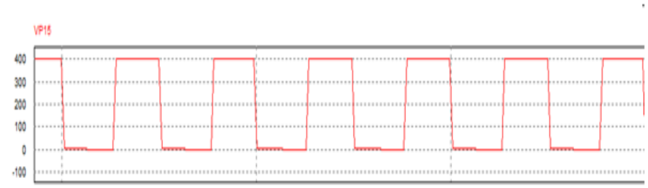

Fig. 12 The pulses given to the switch

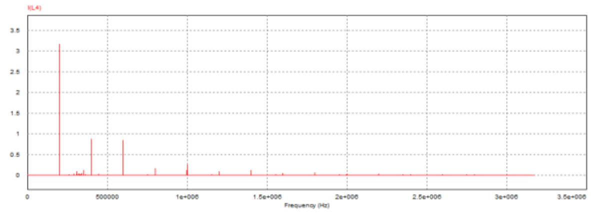

Fig. 13. The FFT analysis of the inductor current

The various conclusions are made based on the waveforms.

1. Current through the resonant inductor is continuous.
2. Current through the resonant inductor does not vary sinusoidal.
3. The current in the switch is turned on at positive voltage and off at zero current. So turn on switching losses occur.
4. The harmonic content in the resonant inductor current is present.

Mode 3, Analysis for fs < fo/2

The waveforms of the current through the resonating inductor as shown in Fig. 14, the pulses given to the switch are as shown in Fig. 15. The FFT analysis is as shown in Fig. 16. when the switching frequency is less than resonating frequency.

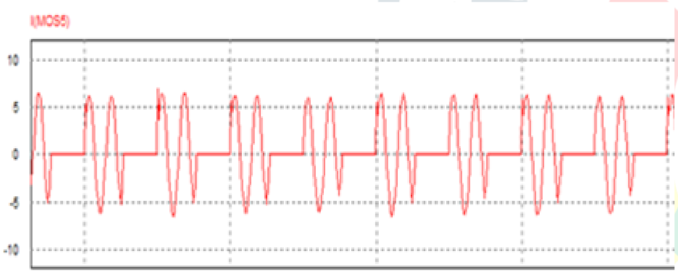

Fig.14. The waveforms of the current through the resonating inductor

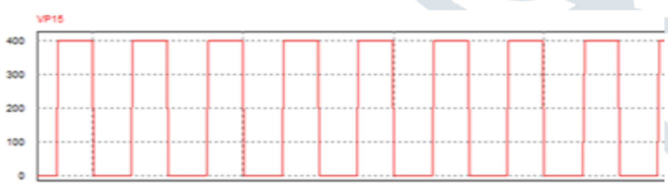

Fig. 15. The pulses given to the switch

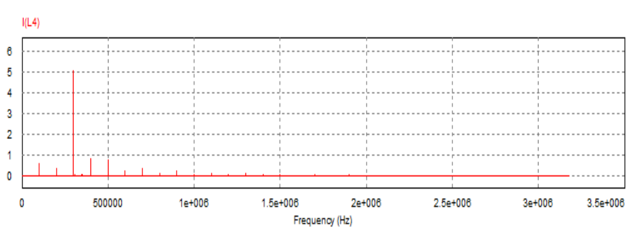

Fig. 16. FFT analysis of the resonant inductor current

The various conclusions are made based on the waveforms.

1. Current through the resonant inductor is dis-continuous.
2. Current through the resonant inductor oscillates.
3. Turn on and turn off switching losses occur.
4. The harmonic content in the resonant inductor current is present.

Closed loop simulation of the circuit

Fig.16 shows the closed loop simulation of the overall circuit. The DC input (Vdc) of 400V is given to the half-bridge LLC converter. The output of the DC-DC converter is given to the HF transformer. The High frequency transformer provides isolation. 27V DC output is obtained at the output. In order to regulate the output voltage, the closed loop control is designed with the help of Voltage controlled oscillator. The output voltage is sensed by a voltage sensor and it is given to the comparator. Comparator compares the output voltage with the reference value of 27V. the error voltage is given to the voltage controlled oscillator (VCO). VCO produces square pulses based on the error signals. The generated square pulses are given to the gate of MOSFETs along with the dead time. Thus any change in the output voltage is controlled by controlling the switching frequency. By changing the value of reference voltage the output voltage of the converter is regulated.

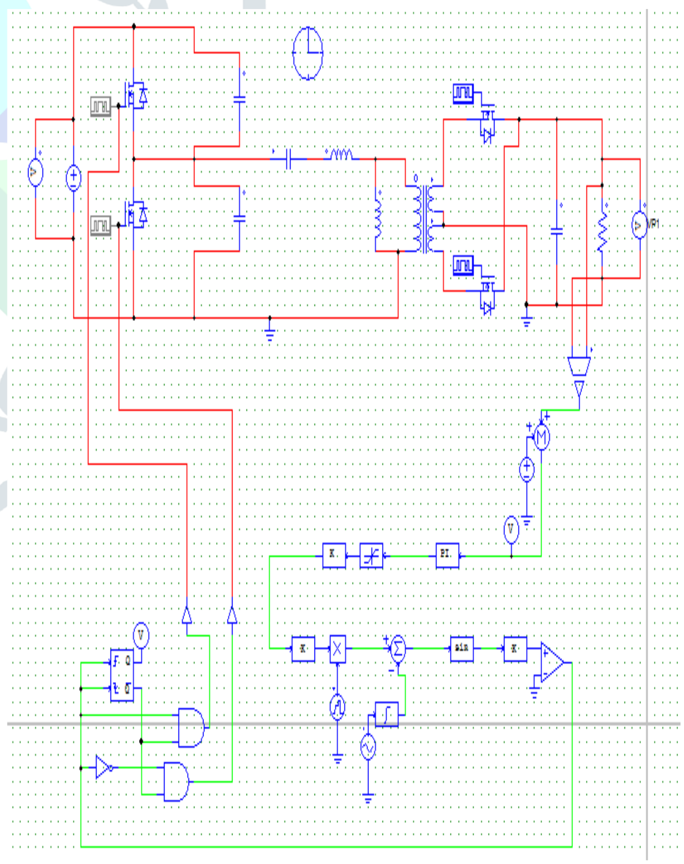

Fig. 17. Closed loop simulation circuit

The closed loop simulation circuit is as shown below. The 27V reference voltage is given to the comparator as shown in Fig. 18. And the output voltage is obtained as shown in Fig. 19.

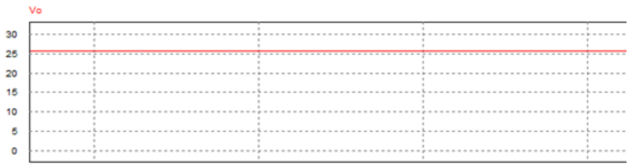

Fig. 18. Reference voltage of27V

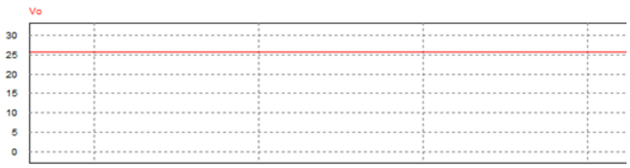

Fig. 19. Output voltage of 27V with the closed loop

Simulation of the circuit with different tank circuits.

There are various types of tank circuit namely tank U, Tank W and Tank G network. The simulation of the circuit is done with the same designed values and with the switching frequency is about 500kHz.

Table.3 represents the comparison of the circuit parameters with three different tank circuits.

Table 3 . The comparison of the circuit with three different tank circuits.

Parameter	With U network	With W network	With G network
Vs	400V	400V	400V
Vsw	400V	400V	400V
Ilr	64.9A	1.4A	1.26A
Vcr	0.22V	160.2V	184.09V
Ilm	64.84A	1.5A	2.95A
V1	700V	167.6V	219.3V
V2	112V	24.5V	52.8V
V3	129V	26V	57.29V
Vco	129.07V	24V	57.29V
Io	0.02A	12.5A	0.6A
Vo	129V	26V	57.29V

From the values obtained in the Table 3, it is clear that for the optimum design and implementation of the circuit it is necessary to use the Tank W network as the resonant tank.

IV. Conclusion and scope of future work

The high power system in closed-loop with half bridge LLC load resonant converter topology has been successfully analysed with two power switches and for the reducing switching losses and overall system cost also. The complete closed-loop system is done to simulate. ZVS/ZCS turn on for the switches are achieved in entire control range and better performance of PI controller is proved with the simulation.

The design and the simulation of the circuit is done and various conclusions are made. These are as follows.

- These converters are used at a very high frequency.
- Reduced size of filter components and transformer.
- Converter is operated at zero voltage switching, switching losses are reduced.
- The switching frequency is needed to be greater than the resonant frequency for controlling the output.
- W resonant tank network is the best suited tank circuit for this converter.

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