Analysis of LLC Resonant Converter for constant voltage applications

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Abstract - With the development of power electronics devices, resonant converter is proved to be more efficient than conventional converter as it employs soft switching technique. Among the three basic configuration of resonant converter, Series Resonant Converter (SRC), Parallel Resonant Converter (PRC) and Series Parallel Resonant Converter (SPRC), the LLC configuration under SPRC is proved to be most efficient providing narrow switching frequency range for wide range of load variation, improved efficiency and provides ZVS capability even with no load. In the proposed system, an hysteresis controller is used along with LLC converter to provide constant output voltage despite wide input voltage variation. The simulation and analysis has been done for full bridge configuration of LLC converter for both open loop and closed loop operation and the results are presented.

Index Terms—LLC converter, hysteresis controller, converter, Open loop , closed loop control.

I. INTRODUCTION

Resonant converter is switching converter that includes a tank circuit which actively participates in determining the input and output power flow. In resonant converter, the switch network drives the resonant tank symmetrically in both voltage and time and thus acts as a voltage source. Resonant converters are preferred over PWM converter due to advantages like high frequency operation, high efficiency, smaller size, light weight ,low component stress and reduced EM interference. To control the output voltage of the LLC converter, a relatively narrow variation of switching frequency is required[1]–[5].

Figure 1 gives the block diagram for resonant converter which illustrates that the input DC voltage is first transformed to AC and then rectified back to DC. The difference from other conventions lies in the resonant tank circuit that is introduced before the rectification stage. With inductor (L) and capacitor (C) comprising the resonant tank, eight configurations are possible among which four are practically applicable with voltage source input. These are categorized into three as SRC, PRC and SPRC. SPRC is further sub divided into two , LLC configuration and LCC configuration.

In all types of resonant converter topologies, a square pulse of voltage or current generated by the power switches is applied to a resonant circuit. Energy circulates in the resonant circuit, and some or all of it is then tapped off to supply the output. Among resonant converters, two basic types are the series resonant converter (SRC), shown in Fig. 2, and the parallel resonant converter (PRC),shown in Fig. 3. Both of these converters regulate their output voltage by changing the frequency of the driving voltage such that the impedance of the resonant circuit changes.

The input voltage is split between this impedance and the load. Since the SRC works as a voltage divider between the input and the load, the DC gain of an SRC is always lower than 1. Under light-load conditions, the impedance of the load is very large compared to the impedance of the resonant circuit. Hence it becomes difficult to regulate the output, since this requires the frequency to approach infinity as the load approaches zero. Even at nominal loads, wide frequency variation is required to regulate the output when there is a large input-voltage range. In the PRC shown in Fig. 3, the load is connected in parallel with the resonant circuit, inevitability requiring large amounts of circulating current. This makes it difficult to apply parallel resonant topologies in applications with high power density or large load variations.

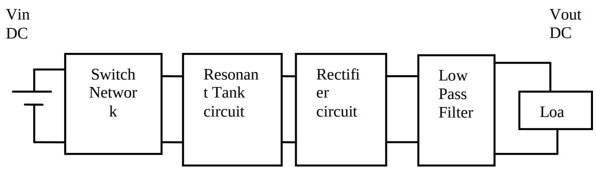

Fig.1 Block Diagram of Resonant Converter

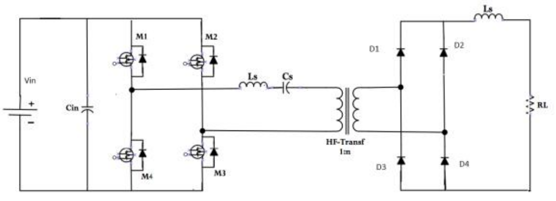

Fig.2 Schematic circuit of SRC

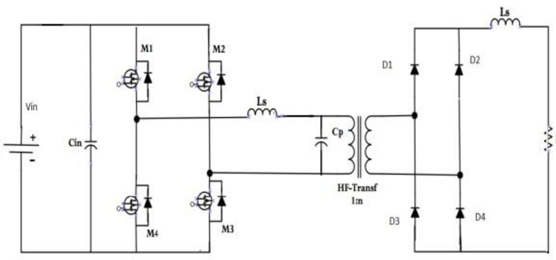

Fig.3.Schematic circuit of PRC

To solve these limitations, a converter combining the series and parallel configurations, called a series-parallel resonant converter (SPRC),has been proposed. One version of this structure uses one inductor and two capacitors, or an LCC configuration, as shown in Fig. 4.

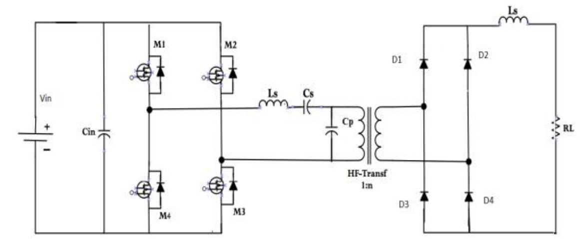

Fig4.Schematic circuit of SPRC (LCC)

Although this combination overcomes the drawbacks of a simple SRC or PRC by embedding more resonant frequencies, it requires two independent physical capacitors that are both large and expensive because of the high AC currents. To get similar characteristics without changing the physical component count, the SPRC can be altered to use two inductors and one capacitor, forming an LLC resonant converter as shown in Fig. 5. An advantage of the LLC over the LCC topology is that the two physical inductors can often be integrated into one physical

component, including both the series resonant inductance, Lr, and the transformer's magnetizing inductance, Lm. The LLC resonant converter has many additional benefits over conventional resonant converters. For example, it can regulate the output over wide line and load variations with a relatively

small variation of switching frequency, while maintaining excellent efficiency. It can also achieve zero voltage switching (ZVS) over the entire operating range.Even though efficient than regular converters due to the operation at ZCS region, among all the configuration, LLC is considered to be the best due to features like narrow frequency variation over wide range of load or input variation and ZVS supposedly taking place at higher resonant frequency and even also at the no load condition.

Analysis of a LLC converter in open loop condition for varying input voltage conditions is carried out using Matlab.

In the proposed scheme, closed loop control of the LLC converter is achieved using an hysteresis controller in the feedback path. The output voltage for the LLC converter is maintained constant because of the introduction of an hysteresis controller in the feedback path.

A comparative analysis is done for the open loop and closed loop operation of the LLC converter.

The half and full bridge configuration of LLC is dealt in [6], [7] and how the circuit is designed for the same [8], [9], [10]. The control strategies like closed loop control of LLC is understood [11], and how it can be implemented for dual output at the same time [12], or for applications like solar array simulator [13]. The optimization technique using a mode solver technique [14] or by introducing an extra LC circuit in the resonant tank [15] is understood and implemented.

II. LLC SERIES PARALLEL RESONANT CONVERTER

The ideal LLC resonant converter comprises of a resonant tank with a series inductance (L_r) and capacitance (C_r) which are in series with one more inductance (L_m) across which the load is connected in parallel. Actually L_m is connected to primary of a transformer and the secondary side of the transformer has the rectifier circuit and then the load.

The operation of LLC depends on parameters like; transformer turns ratio (n), series resonant inductor (L_r), series resonant capacitor (C_r) and resonant inductor ratio ($A=L_m/L_r$). The schematic diagram of LLC Converter is given as in Fig.5.

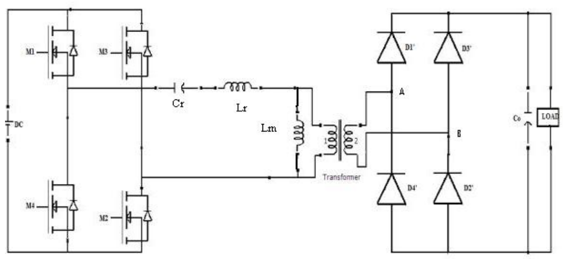

Fig.5.Schematic circuit of SPRC (LLC)

The resonant tank gives rise to two resonant frequencies as; one (ω_h) due to the series L_r and C_r, and the other (ω_L) due to (L_m+L_r) and C_r. The load on the secondary side is represented as R_i referred to the primary side. The transfer function for the same has been derived and found to be

$$\left|\frac{V_0}{V_i}\right| = \frac{1}{2n.\sqrt{(1+A)^2.(1-(\frac{\omega_L}{\omega})^2)^2+(\frac{1}{Q_L})^2.((\frac{\omega}{\omega_L})(\frac{A}{1+A})-(\frac{\omega_L}{\omega}))^2}} \quad ...(1)$$

Where, V_o is the output DC voltage, V_i is the input DC voltage, ω is the switching frequency, Q_L is the quality factor given by;

$$Q_L = R_i . \sqrt{\frac{C_r}{L_r + L_m}} \qquad \ldots\ldots (2)$$

III. DESIGN OF LLC CONVERTER

The three basic design requirements for a typical design of a power-supply converter are i)line regulation(ii)load regulation, and efficiency.

(i)Line regulation is defined as the maximum output-voltage variation caused by an input voltage variation over a specified range, at a given output load current

(ii)Load regulation is defined as the maximum output-voltage variation caused by a change in load over a stated range, usually from no load to maximum. These two types of regulation are actually achieved through the voltage-gain adjustment and in an LLC converter, the gain adjustment is made through frequency modulation.

(iii)Efficiency is one big benefit of using an LLC converter. The converter's switching losses can be reduced significantly by ensuring that primary side ZVS is maintained over the whole operating range.

A major benefit of the LLC converter topology is its potential for significantly reduced switching losses, primarily achieved through primary-side ZVS. To achieve ZVS, a MOSFET is turned on only after its source voltage, has been reduced to

zero by external means. One way of ensuring this is to force a reversal of the current flowing through the MOSFET's body diode while a gate-drive turn-on signal is applied .When M1 turns off ,the M2 gate's turn-on drive signal is not applied immediately but after a dead time. During dead time, the current in the resonant circuit (I_r) is diverted from M1 to M2 first discharging M2's drain-to-source capacitance, to make its voltage zero, and then forward biasing M2's body diode. The same conditions are necessary for a M1 ZVS turn-on.

The design is carried out to applications with constant output voltage power supplies used in computers and servers, where energy conservation is important.

The parameters considered for the design are(i) Transformer turns ratio: n(ii) Series resonant inductor: Lr(iii) Resonant capacitor: Cr and (iv) Resonant inductor ratio: Lm/Lr

The specifications for the design are(i)Input voltage range: 200V to 410V(ii)Output voltage: 30V(iii)Maximum load: 100 Ohms and (iv)Maximum switching frequency: 100kHz

For front-end application, the target is to optimize the performance at high input voltage. From the analysis results, the optimal operating point for this converter is when switching frequency equals to the resonant frequency of Lr and Cr. At this point, the voltage gain of LLC resonant converter is 1. Based on this,the transformer turns ratio is chosen to be 1.

For designing the resonant tank inductors , the ratio of two resonant inductors is chosen as 1, which means the two resonant inductors are with same value. The characteristic and operating region for this design are shown in Fig. 6. The region of Q is from 1(Full load) to 0(no load). Here Q is defined as: Q=Zo/Rl.For the proposed scheme,Resonant inductor Lr is chosen as 650μH, resonant inductor Lm as 650μH and Cr as 3.9nF.

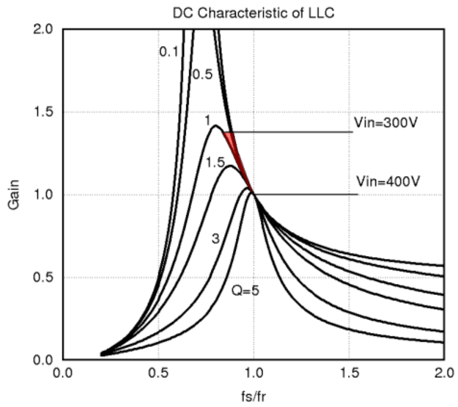

Fig.6 Characteristic of LLC Converter for the ratio Lm/Lr = 1

IV. OPEN LOOP CONTROL OF LLC CONVERTER

The full bridge configuration for LLC in open loop is simulated in Matlab. The simulation is carried out for wide input DC voltage for resonant frequency of 100 kHz and resistive load of 100 ohms and transformer's turn ratio as unity. Depending on the parameters that the operation of converter depends, there are nine different cases, seeking switching frequency relation with resonant frequency (whether greater, less or equal) and the resonant inductance ratio (>, <, =) with respect to unity.

All the nine types of operation is carried out and observed that maximum efficiency is obtained when the converter's switching frequency is equal to resonant frequency for the inductance ratio equal to unity. The output voltage and gain plot are given as follows as in Fig. 7 and Fig. 8.

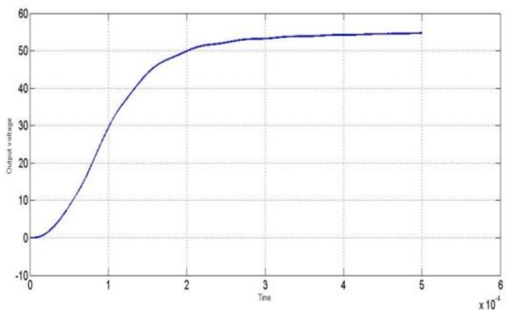

Fig. 7 Output Voltage for LLC converter

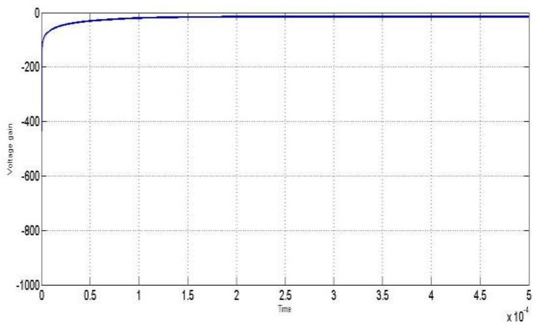

Fig. 8 Voltage gain for LLC Converter

V. CLOSED LOOP CONTROL OF LLC CONVERTER USING HYSTERISIS CONTROLLER

The Schematic diagram of closed loop control of LLC converter using Hysterisis controller is shown in Fig.9

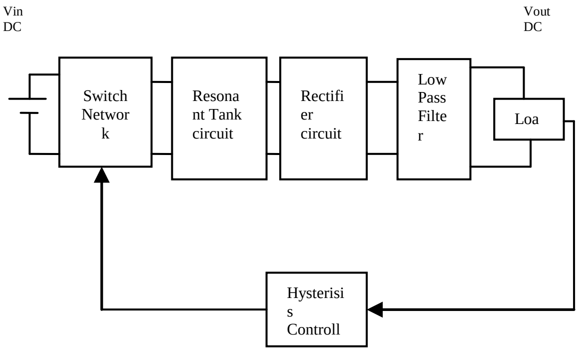

Fig.9.Closed loop control of LLC Converter

Similar to LLC, maximum efficiency is obtained at a switching frequency equal to resonant frequency for the resonant inductance ratio equal to unity. The output voltage of LLC Converter with hysteresis controller is shown in Fig.9. Gate pulses for the Mosfets, Voltage across resonant capacitor C_r and resonant Inductors L_m and L_r are shown in Fig.10.

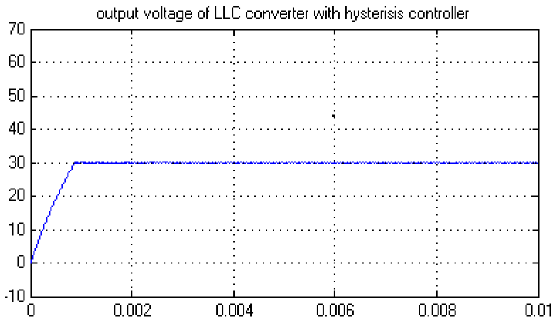

Fig.9.output voltage of LLC Converter with hysteresis controller

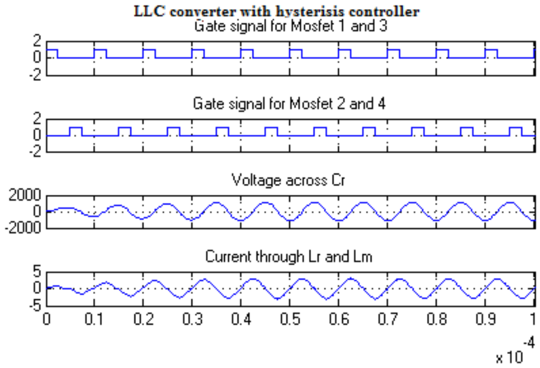

Fig.10 Gate pulses, Voltage across Cr,Lr and Lm

From the above plots, it can be observed that the output voltage of LLC converter under closed loop maintains a constant voltage for a wide input voltage variation. The performance of LLC converter under open loop and closed loop is tabulated in Table I and II respectively.

TABLE I
OUTPUT VOLTAGE OF LLC CONVERTER UNDER OPEN AND CLOSED LOOP OPERATION

S. No.	Vin	Vout(Open Loop)	Vout(Closed Loop)
1.	100	14.26	14.95
2.	150	21.87	22.69
3.	200	29	29.68
4.	250	36.84	29.8
5.	300	44.14	29.95
6	350	51.41	30.06
7	400	59.24	30.07

TABLE II
GAIN AND EFFICIENCY OF LLC PERFORMANCE PARAMETERS(CLOSED LOOP)

S. No.	Vin	Gain(Open Loop)	Gain(Closed Loop)	Efficiency (Open Loop)	Efficiency (Closed Loop)
1.	100	-16.99	-16.51	69.31	78.32
2.	200	-16.8	-16.4	75.23	80.78
3.	300	-16.73	-16.33	77.16	82.29
4.	400	-16.69	-16.25	79.8	86.45

Fig.11 shows the comparison between the open and closed loop performance of LLC Converter. For wide input variations the output voltage is maintained constant with the closed loop operation whereas the output voltage also increases with input voltage variation in open loop.

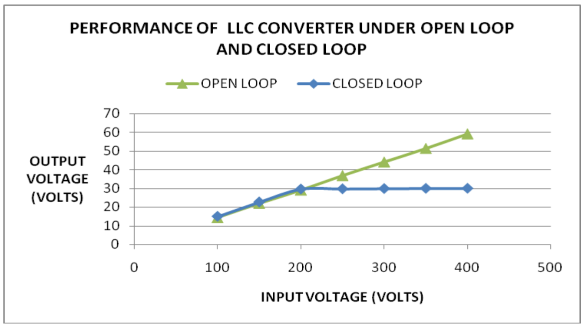

Fig.11 Performance of LLC Converter under open and Closed loop Operation

From the above tables, it can be seen that efficiency of the LLC converter under open Loop increases with increasing input voltage but the output voltage is not maintained constant which is unsuitable for constant voltage applications. But the closed loop control of LLC Converter using Hysterisis controller maintains a constant output voltage under varying input voltage conditions. Further it maintains good efficiency as well as voltage gain.

VI. CONCLUSION

The performance of the LLC converter under open loop and closed loop control is analysed for varying input voltage conditions. It can be concluded that the performance of LLC converter under closed loop control is better in comparison to LLC resonant converter under open loop giving better output voltage and efficiency.

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