Closed Loop Controlled LLC Half Bridge Isolated Series Resonant Converter

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***Abstract*—LLC series resonant converter is the most suitable converter for medium power applications due to its high efficiency and wide input range. This paper presents the closed loop controlled LLC half bridge series-resonant converter with isolated load. LLC resonant converters display many advantages over the conventional LC series resonant converter, such as narrow frequency variation over wide range of load, input variation and zero voltage switching even under no load conditions. High switching frequency operation reduces switching losses. Resonant transition converters are characterized by low switching losses and low conduction losses. Power factor improvement and high efficiency is achieved with a constant output voltage and is regulated by using closed loop control and the simulation results for the converter is presented.**

***Index Terms*—DC-DC High frequency Converter; zero voltage soft-switching converter (ZVS); LLC resonant tank circuit.**

I. Introduction

Nowadays the trend of power supply market is more inclined to high switching frequency, high efficiency and high power density. To meet this trend, resonant power supply holds more attraction, because it can be operated in high switching frequency with high efficiency. There are many resonant power supplies such as Series-Resonant Converter (SRC), Parallel-Resonant Converter (PRC) and Series-Parallel Resonant Converter (SPRC). All the switching devices are hard-switched with abrupt changes of currents and voltages, which results in severe switching losses and noises. Meanwhile, the resonant technique process power in a sinusoidal form and the switching devices are softly commutated. Therefore, the switching losses and noises can be dramatically reduced. For this reason, resonant converters have drawn a lot of attentions in various applications [1]-[2].

In isolated zero-current-switched (ZCS) quasi-resonant converters (QRC's), the leakage inductance of the transformer can be utilized as a part of the resonant switch to achieve zero-current turn off [3]. High efficiency DC-DC converter for wide load ranges is necessary for the applications which are battery-powered and have energy consumption constrains [4]. For a high efficiency DC-DC converter, the LLC series-resonant half-bridge (SRHB) converter is gaining its popularity [5].

The main advantages of this soft-switching bidirectional converter with PWM are minimum inductor size, zero turn-on loss, low EMI without diode reverse recovery, and ease of controller implementation [6]. The trend in power converters is towards increasing power densities. In order to achieve this goal, it is necessary to reduce power losses, overall system size and weight by increasing the switching frequency [7]. Output voltage regulation is achieved by switching-frequency modulation [8]. However, switching frequency increases, as the output load decreases. Power efficiency decreases because switching losses dominate at light load condition.

In recent decades, research on AC-DC converters with power factor correction and low total harmonic distortion (THD) is consistently enjoying increasing interests [9]. Soft switching technique is one of the most effective solutions to reduce the switching loss in high-frequency operations, which is an approach made by researches and engineers in the field of power electronics circuits and systems [10]. Various types of soft switching circuits have been proposed and applied to the power converters, operated at a high switching frequency, leading to a great reduction of the switching loss as well as mitigation of electromagnetic noise.

Resonant converter topology has been used for telecommunications and aerospace applications and it has been recently proposed for electric vehicles. Secondary batteries are widely used in the application of residential, industrial, and commercial energy storage systems to store electricity and supply the load for various types of electronic equipment [11]. On the other hand, introducing power devices with a low on state voltage/resistance is the only way to reduce the on-state losses. Super junction structures make it possible to decrease the on-state voltage and/or resistance drastically, which has been introduced to MOSFETs and insulated gate bipolar transistors (IGBTs) [12].

Analysis and Design of a Half-Bridge Parallel Resonant Converter Operating Above Resonance was given by Young-Goo Kang et al, [13]. Analysis and Design of High-Frequency Isolated Dual-Bridge Series Resonant DC/DC Converter was given by Xiaodong Li and and Ashoka K. S. Bhat, [14]. Analysis and Design of a Double-Output Series-Resonant DC–DC Converter was presented by Yu-Kang Lo et al, [15].

In the present work open loop operation and closed loop controlled LLC half bridge isolated series resonant converter are simulated and the results are presented.

II. Half Bridge Resonant Converter

The circuit diagram of a half bridge Series Resonant Converter is shown in Fig.1. The resonant inductor L_r and

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resonant capacitor C_r are in series. They form a series resonant tank circuit. The resonant inductor L_m is connected across the primary of the transformer. The resonant tank will then in series with the load. From this configuration, the resonant tank and the load act as a voltage divider. The circuit consists of two switches Q_1 and Q_2. The converter circuit switching losses and noises are very high due to hard switching with abrupt changes of currents and voltages, the switching losses and noises can be dramatically reduced. For this reason, resonant converters have drawn a lot of attentions in various applications.

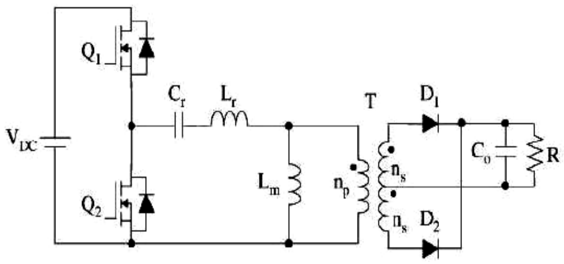

Fig. 1.Half bridge resonant converter

By changing the frequency of input voltage, the impedance of resonant tank will change. This impedance will divide the input voltage with load. Since it is a voltage divider, the DC gain of SRC is always lesser than 1. At resonant frequency, the impedance of series resonant tank will be very small and all the input voltage will drop on the load. So, for series resonant converter, the maximum gain happens at resonant frequency.

III. Half Bridge Resonant Converter Operation

A. Mode 1

Fig. 2 shows the mode 1 operation of half bridge resonant converter. This mode begins when Q_2 is turned off. Immediately, resonant inductor Lr current is reverses and it will flow through the diode which is connected anti-parallel to the MOSFET Q_1. This provides a ZVS condition for Q_1. Gate signal of Q_1 is applied during this mode. When resonant inductor Lr current flow through the diode of Q_1, begins to rise, this will force secondary diode D_1 conduct and the load current Io begin to increase. The inductor Lm is charged with constant voltage.

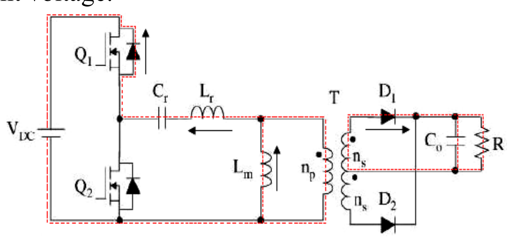

Fig. 2. Mode 1 operation of Half Bridge Resonant Converter

B. Mode 2

The MOSFET Q_1 is turned on during mode 1, current will flow through MOSFET Q_1. This mode begins when the resonant inductor L_r current becomes positive. Output rectifier diode D_1 conducts. The transformer voltage is clamped at Vo. The parallel inductor L_m is linearly charged with output voltage, and hence it is inactive with resonant circuit during this period. In this mode, the circuit works like a Series Resonant Converter with resonant inductor L_r and resonant capacitor C_r. When the current in both inductors L_r and L_m are same, this mode ends. Also the current in output reaches zero value. The operation of mode 2, for the half bridge resonant converter circuit is shown in Fig.3.

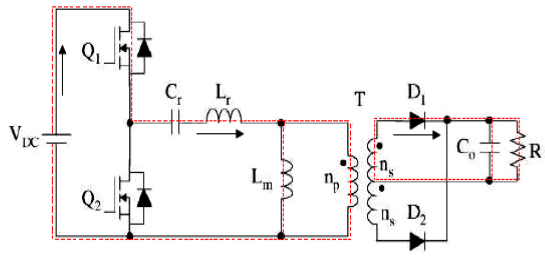

Fig. 3. Mode 2 operation of Half Bridge Resonant Converter

C. Mode 3

Mode 3 begins when the current in two inductors Lr and Lm are equal. At the same time the output current reaches zero value. The secondary side rectifier diodes D_1 and D_2 are in reverse biased. Transformer secondary voltage is lower than the output voltage. The inductor L_r, capacitor C_r and inductor L_m forms a resonant tank in series. The Fig.4 shows the operation of half bridge resonant converter in mode 3. When the MOSFET Q_1 is turned off, this mode ends.

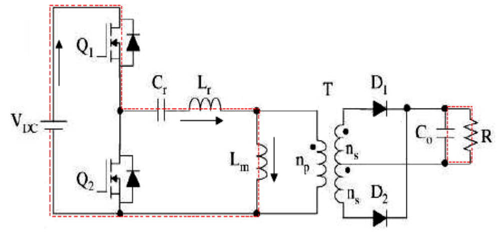

Fig. 4. Mode 3 operation of Half Bridge Resonant Converter

The next half cycle repeats the same set of modes by conducting and disconnecting MOSFET Q_2.

IV. Half Bridge LC Series Resonant Inverter

Fig. 5 shows the half-bridge resonant inverter for the condition when M_1 is off and M_2 is ON.

Since $C_1 = C_2$, the load current will be shared equally by C_1 with the supply voltage. If the loop of V_1, C_1, R and L is considered, the load current can be obtained by the equation

$$L\frac{di}{dt}+Ri+\frac{1}{2C_1}\int idt+V_{c_1}\Big|_{t=0}=V_1 \qquad (1)$$

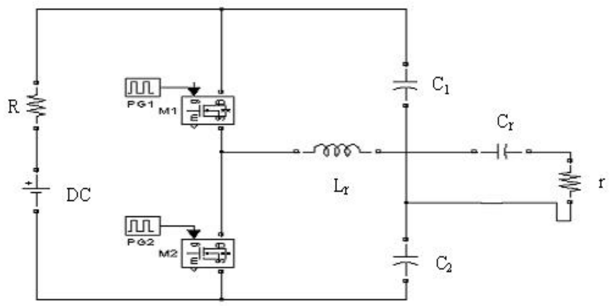

Fig. 5. Half Bridge LC Series Resonant Inverter

The equation of current in the resonant circuit for $C_1 = C_2 =$

C is given by,

$$i = \frac{V_1 + V_c}{\omega_r L} \sin \omega_r t e^{\frac{-Rt}{2L}} \qquad (2)$$

The peak MOSFET current is equal to the peak load current and is expressed as,

$$I_p = \frac{V_1 + V_c}{\omega_r L} \sin \omega_r t_p e^{\frac{-R}{2L} t_p} \qquad (3)$$

The rms load current I_L (rms) is

$$I_{L(rms)} = \sqrt{2}\, I_{rms(MOSFET)} \qquad (4)$$

The peak supply current is

$$I_{S(p)} = 0.5 \text{ peak load current} \qquad (5)$$

V. LLC Series Resonant Half Bridge Converter

Fig. 6 shows the LLC-SRHB DC-DC converter. The circuit consists of DC input source, half bridge inverter, LLC Resonant Converter, high frequency transformer, full bridge rectifier, filter and load. The DC input voltage is inverted by means of high frequency AC using MOSFET half bridge inverter. The primary of the transformer is connected to the inverter thro LLC resonant tank circuit. The transformer secondary voltage is rectified using diode bridge rectifier then filter circuit and load.

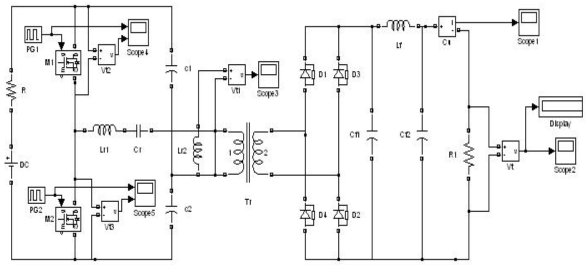

Fig. 6. LLC SRHB converter

The filter circuit consists of capacitor C_{f1}, Inductor L_f and capacitor C_{f2} forms a pi filter. Scopes are connected in the circuit to measure the pulses and voltage across MOSFET M_1 and M_2, output of the resonant inverter, output voltage, output current, etc. The resonant frequency f_r is determined a

$$f_r = \frac{1}{2\pi\sqrt{L_{lk} C_{eq}}} . \qquad (6)$$

VI. Simulation Results

The Half bridge LLC series resonant DC to DC converter is simulated using Matlab and the results are presented. The driving pulses and the voltage across the MOSFET M_1 are shown in Fig. 7 and MOSFET M_2 is in Fig.8. The results shows that, when the pulse applied to the MOSFET's are high the voltage across the MOSFETs are low and vice versa.

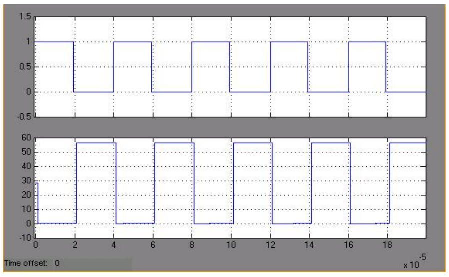

Fig. 7. Driving Pulse and Voltage across MOSFET M_1

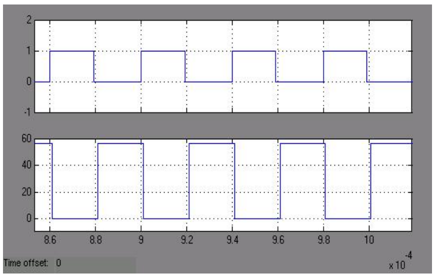

Fig. 8. Driving pulse and Voltage across MOSFET M_2

Output voltage and current waveforms are shown in Fig.9 and Fig.10 respectively. From the results, it is clear that the output voltage and current waveforms are smooth and ripple free.

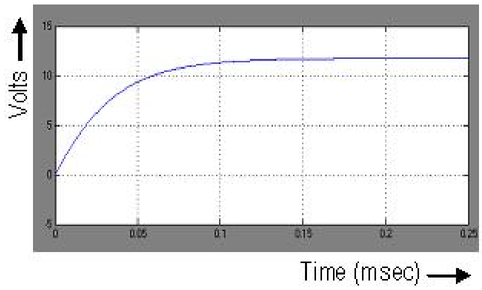

Fig. 9. Output voltage

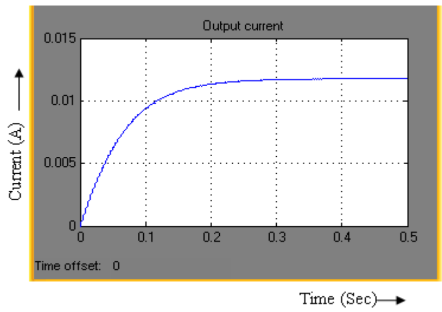

Fig. 10. Output current

VII. Open Loop System

Fig.11 shows LLC half bridge converter with step input. A disturbance is introduced at the input by using two switches.The input DC voltage is changed by introducing a step input. Due to this disturbance, the input voltage is increased. The voltage at the inverter and hence the output voltage increases. This gives an error voltage at the output. In order to get the desired output voltage and to reduce the error signal, closed loop performance is essential.

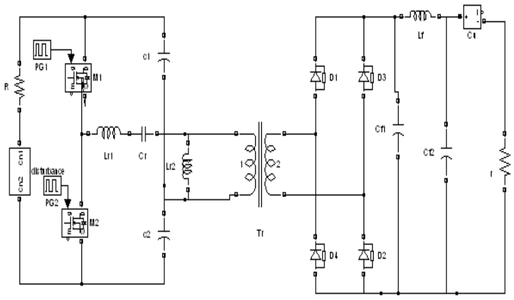

Fig. 11. LLC Half Bridge Resonant converter with step input

A. Circuit Description for Step Input

Fig.12 shows the circuit for step input. It consists of two DC source, one for normal voltage and the other for error voltage which is to be added with the normal rated voltage source. The step variation of input voltage can be introduced by two switches and two timers. If the switch one is closed the normal voltage is being applied to the circuit. When the switch two is closed the two DC sources are get connected in series and the input voltage is increased.

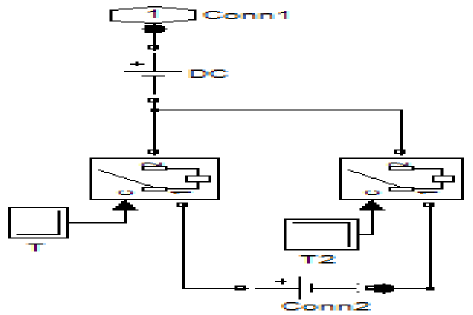

Fig.12. Circuit for step input

VIII. Simulation Results For Open Loop System

Input DC voltage waveform with step input variation is shown in Fig. 13. Peak value of pulse and output of the MOSFET M_1 with step variation at input DC waveforms are shown in Fig. 14.

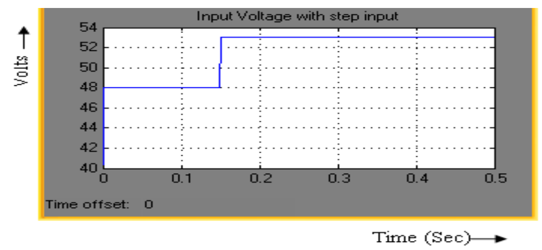

Fig. 13. Input DC voltage with step input

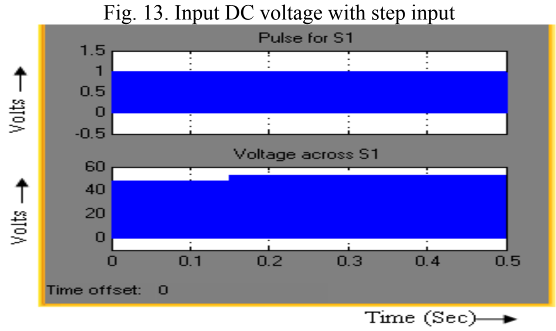

Fig. 14. Peak value of Pulse and output of MOSFET M_1 with step input

Fig. 15 shows the transformer primary and secondary amplitude waveforms with step variation at input for the open loop system. Fig.16 shows the input and output voltage waveforms for the open loop system. A step input voltage is introduced at 0.15 sec. Due to this, the input voltage increased at 0.15 sec onwards. The voltage across the inverter and hence both primary and secondary voltages are also increases at 0.15 sec. Results in output voltage increased at the same time.

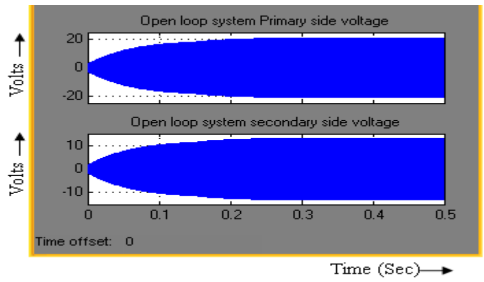

Fig. 15. Transformer primary and secondary side amplitude waveforms with step variation at input DC of open loop system

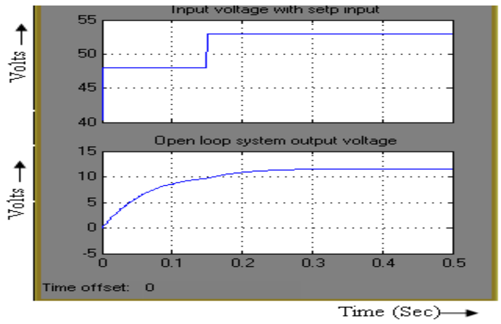

Fig. 16. Input voltage and output voltage of open loop system

IX. Closed Loop Controlled Converter

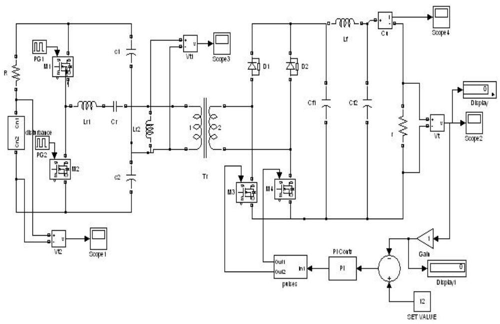

Fig. 17. Closed loop control of LLC SRHB converter

The closed-loop circuit model of the LLC Series-Resonant Half-Bridge DC-DC Converter is shown in Fig.17. The closed loop system consists of comparator and PI controller. The output voltage is sensed and it is compared with the reference voltage. The error signal is sent to the PI controller. The output of the PI controller is given to the MOSFET. The output of the PI controller controls the dependent source. The steady state error signal is reduced by properly turning the PI controller. Scopes and displays are connected to measure the input voltage, output voltage, etc.

X. Simulation Results For Closed Loop Controlled Converter

Transformer primary and secondary side peak to peak voltage waveforms for the closed loop system are shown in Fig.18. From the results, as the input voltage increases at 0.15

sec due to the step input, the amplitude of transformer primary and secondary side voltage would increases at 0.15 sec. This error voltage is reduced in steps from 0.2 sec onwards.

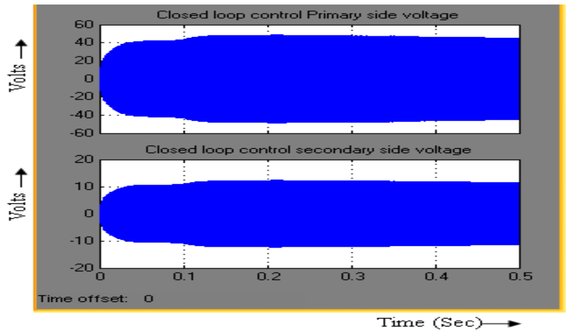

Fig. 18. Transformer primary and secondary side peak to peak voltage waveforms for closed loop system

Output voltage and current waveforms for the closed loop converter are shown in Fig.19 and Fig. 20. The results shows that the output voltage and current increases from 0.15 sec, due to the step input variation. The same are reduced step by step due to the closed loop control operation.

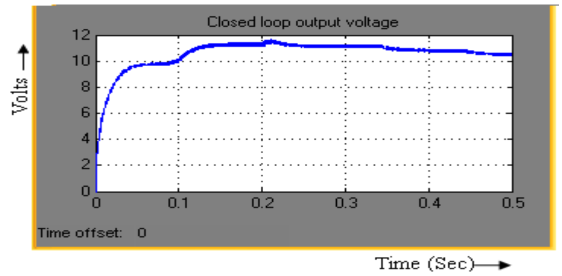

Fig. 19. Output voltage for closed loop system

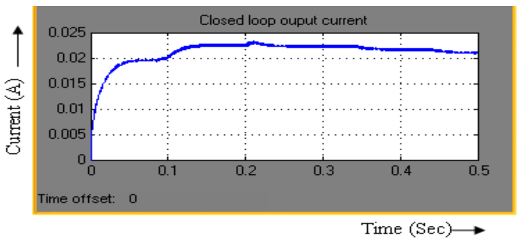

Fig. 20.Output current for closed loop system

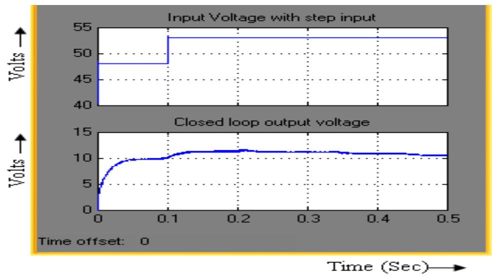

Fig. 21. Input voltage for open loop system and closed loop output voltage

Fig.21 shows the input voltage for the open loop system and closed loop output voltage. From the results we observed that, open-loop system has steady state error. For closed-loop system, the control circuit takes proper action to reduce the amplitude to the set value. The settling time is negligible. From the wave forms it is clear that the smooth DC output is obtained with LC filter. Thus, the closed-loop system reduces the steady state error.

Inverter output voltage and current wave forms are shown in Fig.22. From the wave form it is clear that when the voltage crosses zero, the current also crosses zero point. The voltage is in phase with current waveform. This results in improved power factor.

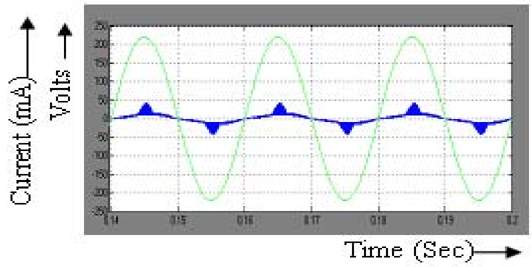

Fig. 22. Inverter output voltage and current waveform

XI. Conclusion

In this paper, ZVS based LLC SRHB DC-DC converter has with isolated load circuit, for both open loop operation and the closed loop controlled converter are simulated using MATLAB simulink and the results are presented. The results shows that the output voltage wave form is smooth without ripple. The closed-loop system reduces the steady state error. High efficiency is achieved with a constant output voltage. Resonant converter topologies can be used to increase circuit switching speeds, improved power factor and reduced switching losses.

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