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Investigation of Half-Bridge LLC Resonant DC-DC Converter for Photovoltaic Applications

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Abstract: This paper deals with the analysis and design of LLC resonant converter suited for photovoltaic applications. The proposed converter maximizes battery life without penalizing the volume of the charger. Theoretical values of turns ratio, resonant inductor, resonant capacitor, magnetizing inductor are calculated using design equations. Switching losses and voltage ripple are calculated. Also performance parameters such as efficiency and voltage gain are calculated and compared with LCC Resonant converters. Simulation studies are carried out using MATLAB / SIMULINK. A prototype of the proposed LLC resonant converter is built to validate the simulation results.

Keywords: LLC resonant converter, ripple, voltage gain and switching losses

I. INTRODUCTION

LLC resonant converter is gaining attention because of its ability to achieve higher frequencies and low switching losses .It consists of two inductors and one capacitor and the converter can regulate the output voltage against line and load variation over a wide range. Soft switching can be achieved over the entire operating range compared with LCC[1-3]. The resonant tank of LLC and LCC Resonant Converter is shown in Fig.1.

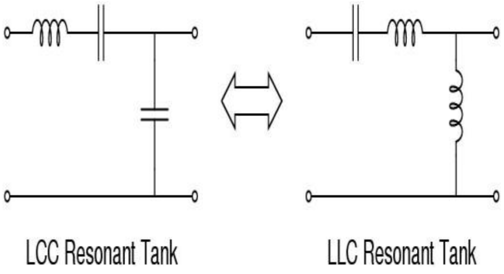


Fig.1 LCC and LLC resonant tank

In LLC configuration, the uncoupled inductor can be replaced by a coupled one so that the size of the converter can be reduced. This paper focuses on the design aspects of the proposed converter for photovoltaic applications. The design equations are presented [4-5] and the performance parameters such as output voltage ripple, switching losses, efficiency and voltage gain are computed. Simulation studies are carried out using MATLAB/SIMULINK. Hardware is built to validate the theoretical results.

Operation of LLC RESONANT DC-DC CONVERTER

Fig.2 shows the circuit diagram of a half-bridge LLC resonant converter which consists of two inductances transformer magnetising inductance Lm, resonant inductance Lr and resonant capacitance Cr. Transformer primary output is a square- wave and the transformer turns ratio decides the voltage gain. On the secondary side of the transformer, a full-wave rectifier is added at the output to get a regulated DC output.

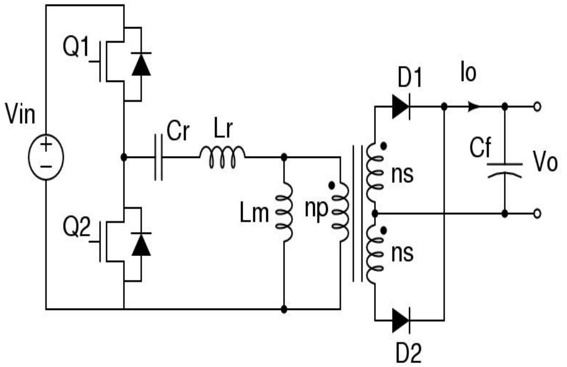


Fig. Circuit diagram of LLC resonant converter

The advantage of LLC is achievement of ZVS even under no-load condition and narrow switching frequency at light load [6-8]. The DC characteristics of LLC resonant converter could be divided into Zero Voltage Switching (ZVS) region and Zero Current Switching (ZCS) region. For this converter, there are two resonant frequencies. One is determined by the resonant components Lr and Cr. The other one is determined by magnetizing inductance (Lm), Cr and load condition. As load getting heavier, the resonant frequency will shift to higher frequency. The two resonant frequencies are

$$fr1 = \frac{1}{2\Pi\sqrt{L_r C_r}} \qquad (1)$$

$$fr2 = \frac{1}{2\Pi\sqrt{L_m + L_r C_r}} \qquad (2)$$

When LLC operates in ZVS condition, Lm never resonates with resonant capacitor Cr; it is clamped by output voltage and acts as the load of the series resonant tank. With this passive load, LLC resonant converter is able to operate at no load condition without the penalty of very high switching frequency.

Under ZCS operating region, the waveforms could be divided into two time intervals. In first time interval, Lr resonates with Cr. Lm is clamped by output voltage. When Lr current resonates back to same level as Lm current, the resonance of Lr and Cr is stopped, instead, now Lm will participate into the resonance and the second time interval begins. During this time interval, the resonant components will change to Cr and Lm in series with Lr.

The operation of LLC resonant converter is divided into three modes namely mode 1, mode 2, mode 3. Mode-1, begins when Q_2 is turned off at t0. At this moment, resonant inductor Lr current is negative; it will flow through body diode of Q_1, which creates a ZVS condition for Q1. Gate signal of Q1 should be applied during this mode. When resonant inductor Lr current flow through body diode of Q1, ILr begins to rise, this will force secondary diode D1 to conduct and Io begin to increase. Also, from this moment, transformer sees output voltage on the secondary side. Lm is charged with constant voltage.

Mode-2 begins when resonant inductor current ILr becomes positive. Since Q1 is turned on during mode 1, current will flow through MOSFET Q1. During this mode, output rectifier diode D1 conduct. The transformer voltage is clamped at Vo. Lm is linearly charged with output voltage, so it doesn't participate in the resonant during this period. In this mode, the circuit works like a SRC with resonant inductor Lr and resonant capacitor Cr. This mode ends when Lr current is the same as Lm current. Output current reach zero. In mode-3, the two inductor's currents are equal. Output current reach zero. Both output rectifier diodes D1 and D2 is reverse biased. Transformer secondary voltage is lower than output voltage. During this period, a resonant tank of Lm in series with Lr resonates with Cr. This mode ends when Q1 is turned off.

A. *Design Equations*

The design equations for turns ratio, resonant inductor, resonant capacitor, magnetizing inductor are as follows [9-10]:

A.1. Selecting Turns Ratio, Nn

The transformer turns ratio should be selected at the resonant frequency where the gain is unity and can be calculated using (3), where *Vd* represents the diode voltage drop of the output rectifier

$$N_n = \frac{V_{in(nom)}}{2(V_{o(\min)} + V_d)} \qquad (3)$$

A.2 Calculating Resonant Inductor, Lr

The minimum resonant inductor must be selected to limit the maximum output current in the short circuit condition and limit the converter to its maximum switching frequency.The minimum inductance is given by [11]

$$L_{r(scc)} = \frac{N_n . V_{in(nom)} . V_{o(nom)}}{8. f_{s\_\max} . P_o} \qquad (4)$$

A.3. Calculating Resonant Capacitor ,Cr:

Once the resonant inductor is selected, the resonant capacitor is given by:

$$C_{r(res)} = \frac{1}{(2.\Pi . f_o)^2 . L_{r(scc)}} \qquad (5)$$

A.4 Calculating Magnetizing Inductor, Lm:

The Magnetizing inductor is given by [12,13]

$$L_{m(zvs)} = \frac{t_{dead} . N_n . V_{o(\min)} . (\frac{1}{4. f_{s\_\max}} - \frac{t_{dead}}{2})}{C_{HB} . V_{in(\max)}} \qquad (6)$$

Using equations (3) to (6) , the following values are computed for the proposed DC-DC converter.

TABLE1
DESIGN PARAMETERS

Design parameters for LLC resonant converter		
Parameter	**Designator**	**Value**
Input Voltage	Vin	110V
Resonant Inductor	Lr	35μH
Resonant Capacitor	Cr	8.2nF
Magnetizing Inductor	Lm	105μH
Resonant frequency	fr	100KHz
Switching frequency	fsw	200KHz
Turns ratio	Nn	4:1:1

II. SIMULATION RESULTS

Simulation studies are carried out using MATLAB/SIMULINK and the simulation circuit is shown in Figs.2 & 3. Simulation results of LLC Resonant DC-DC Converter for an input of 60V are as follows:

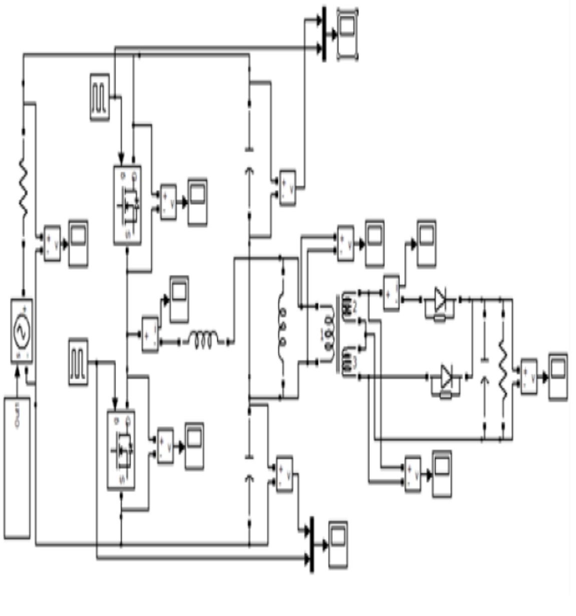


Fig.2. Simulation Circuit for LLC resonant converter

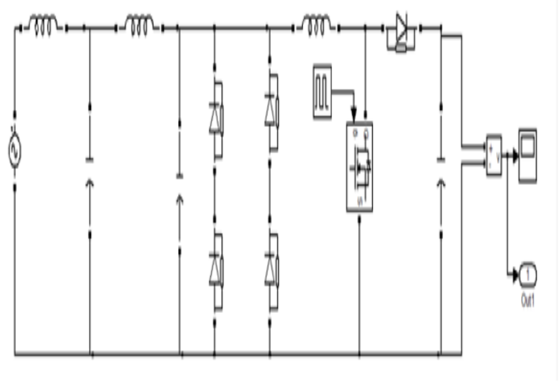


Fig.3 Sub-system of LLC resonant converter

The gating pattern of MOSFET 1 with switching frequency of 20 KHz and duty ratio of 0.5 is obtained. The voltage across the resonant capacitor and gating pulse of MOSFET-1 &2 is shown in Figs.4 &5.

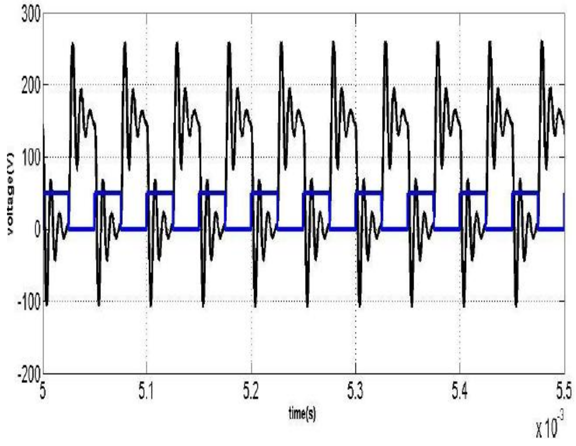


Fig.4 The voltage across the resonant capacitor-1 and gating pulse of MOSFET-1

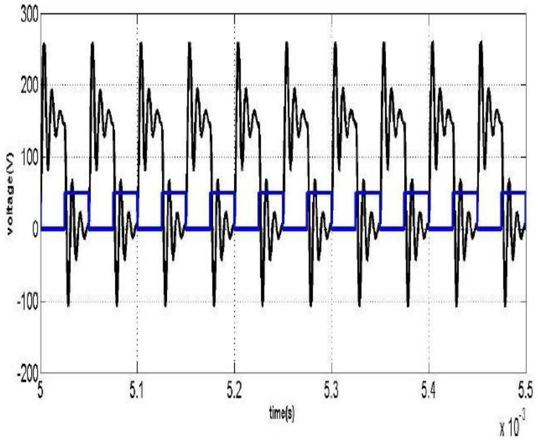


Fig.5 The voltage across the resonant capacitor-1 and gating pulse of MOSFET-1

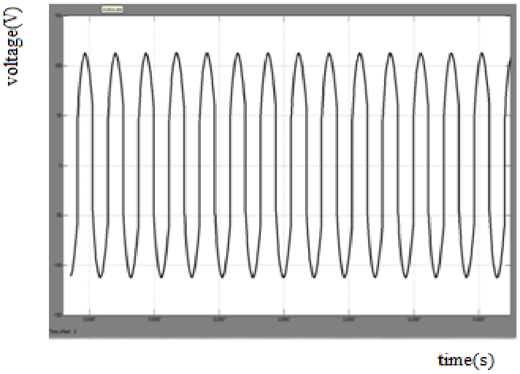


Fig.6 Primary voltage waveform of the transformer

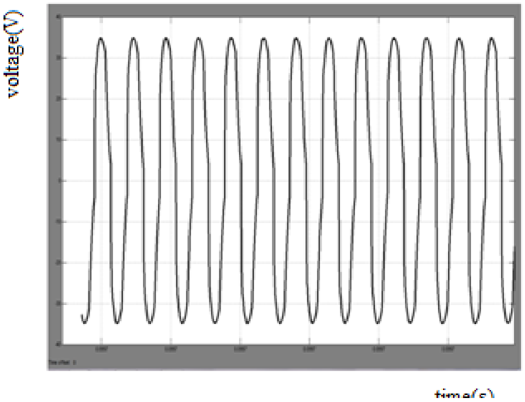


Fig.7 Secondary voltage waveform of the transformer

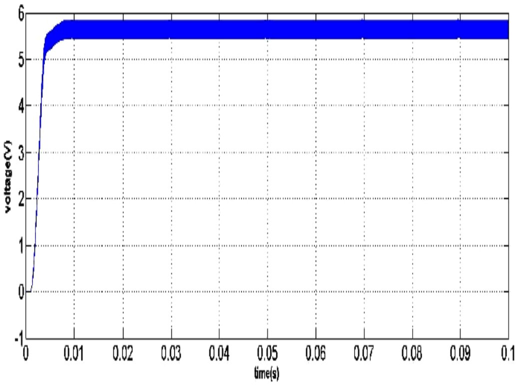
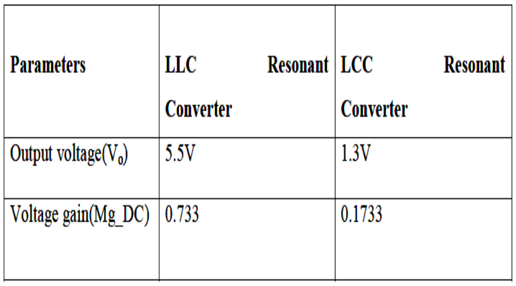


Fig.8 Output Voltage of LLC resonant converter

III. **EVALUATION OF PERFORMANCE PARAMETERSFOR LLC CONVERTER**

The performance of LLC resonant converter is investigated by calculating the voltage gain and losses [14-16]. The voltage gain of LLC is compared with LCC converter and it is shown in table II [17-18]. The switching loss and voltage ripple of LLC resonant DC-DC Converter is calculated using equations (7) to (9).Power loss includes conduction and switching losses and it is calculated as follows:

Table II Comparison of voltage gain



Parameters	LLC Resonant Converter	LCC Resonant Converter
Output voltage(V_0)	5.5V	1.3V
Voltage gain(Mg_DC)	0.733	0.1733

Conduction losses are given by

$$P_{cond} = I^2_{on} R_{ds,on} \qquad (7)$$

where I_{on} is the drain current when the MOSFET is ON and $R_{ds,on}$ is the drain source resistance when the MOSFET is ON.Switching loss is given by [19]

$$P_{sw}=(C_{oss}+ C_p)V^2 f_{sw} \qquad (8)$$

where C_{oss} is the output capacitance of MOSFET, Cp is the parasitic winding capacitance of MOSFET, V is the input voltage of the MOSFET, f_{sw} is the switching frequency of LLC Resonant Converter. The values of $R_{ds,on}$, C_{oss} , C_p are taken from datasheet values. The total power losses are given by the sum of conduction losses and switching losses as shown in table III.

Table III : Loss calculation

Parameter	**Values**
Input Voltage	60 V
Output Voltage	5.65 V
Conduction Loss	1.21 W
Switching loss	00115 W
Total loss	1.225 W

The output voltage ripple is calculated as

$$V_{ripple} = V_{\max} - V_{\min} / V_{avg} \qquad (9)$$

where V_{avg} is the average value of maximum and minimum voltage from voltage ripple waveform. The voltage ripple waveform is shown in Fig.9 and it is around 0.053V.

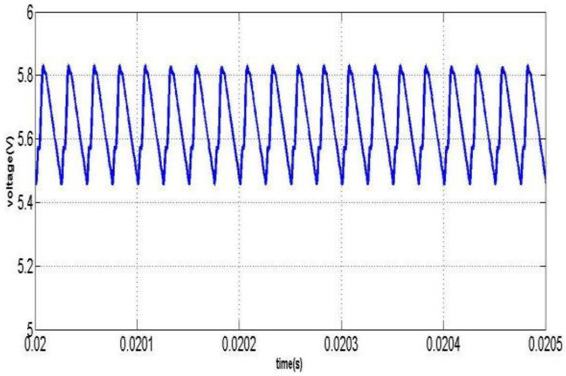


Fig. 9 Output ripple voltage of LLC converter

IV. EXPERIMENTAL RESULTS

A prototype of LLC resonant converter is built using MOSFET with an input voltage of 7V and an output of 1.5V is obtained as shown in Figs. 10, 11, 12 &13. PIC microcontroller is used to generate gating pulses. For isolation of the control signals, MCT2E optocoupler is used and a high frequency transformer is employed for the proposed converter. The pulses are shown in Fig.10

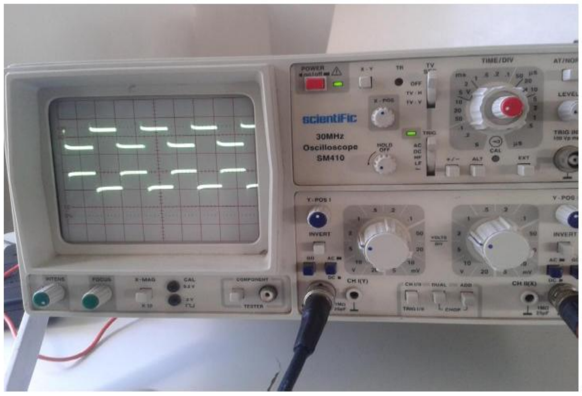


FIG.10 PULSE GENERATION FOR LLC RESONANT CONVERTER

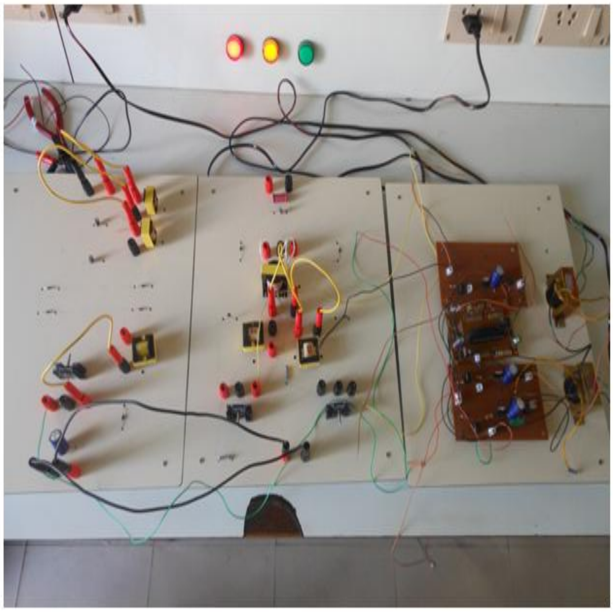


Fig.11 Gating and power circuit for LLC resonant converter

Fig.12 Primary winding voltage of LLC converter

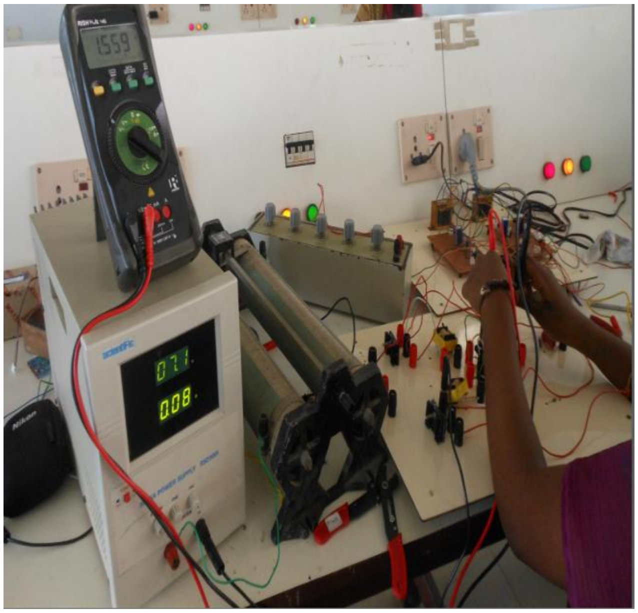


Fig.13 Output voltage of LLC converter

VI. CONCLUSION

The design procedure of LLC Resonant Converter is presented. Theoretical values are calculated using the design equations. Simulation results are provided for LLC Resonant converter for an input voltage of 60V. LLC resonant Converter is compared with LCC Resonant Converter. Performance parameters such as voltage gain and efficiency are calculated and compared. Also switching losses and voltage ripple of LLC resonant converter are calculated. Simulation studies are carried out using MATLAB/SIMULINK . It can be seen from comparison that LLC Resonant Converter has high efficiency, high voltage gain and reduced switching losses and voltage gain compared with other resonant converters. Hence it is used for electric vehicle applications. It maximizes battery life without penalizing the volume of the battery charger.

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