Design Topology of Low Profile Transformer with Improved Efficiency

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*Abstract:-*This paper presents the implementation of a topology for low Profile Planar Transformer using an LLC resonant converter. A new structure of slim-type transformer is proposed here, which is composed of copper wire as the primary winding and printed circuit board winding on the outer layer as the secondary winding. In order to increase the power density, the proposed circuit is operated at high switching frequency. The proposed structure has advantages of easy utilization and wide conductive cross-sectional area because of which it is suitable for a slim and high-efficiency converter. In addition to this, the voltage doubler rectifier is applied to the secondary side due to its simple structure of secondary winding, and a CLC filter is adopted to reduce the output filter size. The specification are to design input voltage 400V, power 120W with 17 ms hold time.

Index terms:- CLC output filter, voltage-doubler rectifier, LLC resonant converter, slim adaptor.

I. INTRODUCTION

Over the past several years energy efficiency and power density have become the top concerns for power conversions. Rising energy intensity is leading to higher cost for delivering power. Meanwhile, the demand for compact power supplies is growing significantly. This compact power supplies require power supplies with high efficiency, low profile and high power density. With the development of Information Technology, computing system applications, such as telecom, server and computers, consumer electronics, such as flat-panel TVs lighting systems, such as LED Lamps, have become a large market for the power supply industry. Recent statistic data show that the demands for these systems are continuously increasing [3]

Moreover, because of the improving of integrated circuit technology, that follows Moores Law, computing systems and consumer electronics are continually increasing their density and functionality. This increasing functionality requires more power consumption and higher density requires less size on the power supplies. Therefore, the power supplies for the computing, consumer electronics and lighting applications are required to provide more power with small size and low cost.

Front-end converters are normally implemented by the two-stage approach, which include a power factor correction (PFC) stage followed by a dc-dc stage. Therefore, laptop computers have become slim, and the adapter has been
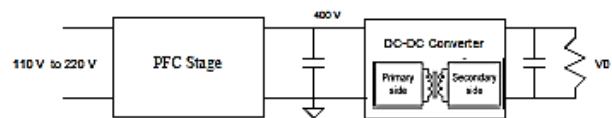

Fig. 1. Block diagram of Slim type Adaptor

demanded to be slim and have high power rating accordingly. The adapter provides high power loss and heat when it is operated with high power level [7]. Low operating temperature is one of the most important issues of adapter application; furthermore, it can be difficult to e achieved in the slim-type converter. Therefore, the high efficiency of the slim adapter is strongly required to reduce the power loss and operating hear. The boost converter has been adopted to the PFC stage generally due to its simple structure and high efficiency [3].

II. TOPOLOGY FOR PRIMARY SIDE

LLC resonant converter has an ability to achieve higher frequencies and low switching losses because of which it is gaining attention day by day. 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. As compared to LCC, soft witching can be achieved over the entire operating range in LLC. In LLC configuration, the uncoupled inductor can be replaced by a coupled one so that the size of the converter can be reduced. The performance parameters such as output voltage ripple, switching losses, efficiency and voltage gain are computed. Simulation studies are carried out using MATLAB/SIMULINK. The advantage of LLC is achievement of ZVS even under no-load condition and narrow switching frequency at light load [1]

The circuit diagram of LLC resonant converter is as shown in fig 2. The DC characteristics of LLC (Inductor Inductor Capacitance) 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 L_r and C_r. The other one is determined by magnetizing inductance, resonant capacitance and load condition. The two resonant frequencies are given by

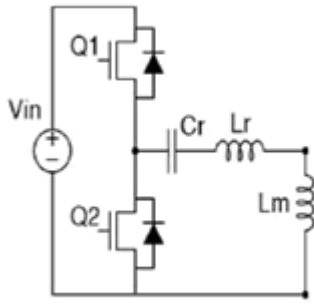$$F_r1 = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad (1)$$

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Fig 2. LLC Resonant Converter

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

When LLC operates in ZVS condition, L_m never resonates with resonant capacitor C_r; 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 [5]. Under ZCS operating region, the waveforms could be divided into two time intervals. In first time interval L_r resonates with C_r. L_m is clamped by output voltage. When L_r current resonated back to same level as L_m current, the resonance of L_r and C_r is stoped, instead, now L_m will participate intot he resonance and the second time interval begins. During this time interval, the resonant components will change to C_r and L_m in series with L_r. The operation of LLC resonant converter is divided into three modes namely Mode 1, Mode 2, Mode 3.

A. Mode 1.

Begins when Q2 is turned off at t_0. At this moment, resonant inductor L_r current is negative. It will flow through body diode of Q1, which creates a ZVS condition for Q1. Gate signal of Q1 should be applied during this mode. When resonant inductor L_r current flow thorough body diode of Q1, IL_r begins t_0 rise, this will force secondary diode D1 to conduct and I_0 begin to increase. Also, from this moment, transformer sees output voltage on the secondary side. L_m is charged with constant voltage.

B. Mode 2.

Begins when resonant inductor current IL_r 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 clamed at V_0. L_m 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 SCR with resonant Inductor L_r and resonant capacitor C_r. This mode ends when L_r current is the same as L_m current. Output current reach zero.

C. Mode 3

The two inductors 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 L_m in series with L_r resonates with C_r. This mode ends when Q1 is turned off.

To meet the increasing stringent requirement of high efficiency and highpower density, improvement of dc-dc conversion technology over wide input voltage range is a must. Therefore, this dissertation mainly focuses on the investigation of novel techniques to improve the overall performance of front-end dc-dc converters with wide input voltage range operation. The leakage reactance is very important parameter in LLC resonant Converter because its directly related to resonance. And it is calculated by distance between primary andsecondary winding so it's not required any external resonant inductor. [8]

ZVS capability from the zero load to the full load and low turn-off current for primary side switches, so switching loss is low. Zero-current-switching (ZCS) is achieved for secondary side rectifiers and low voltage stress and High voltage gain capability, which is suitable for holdup time operation, and means that bulky capacitors can be reduced considerably.
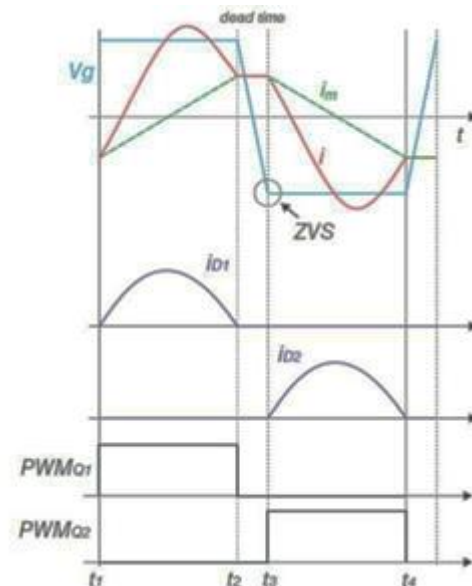
Fig. 3. LLC resonant converter waveforms at resonant frequency

Soft switching means the one or more power switches in a dc-dc converter have either turn ON or turn OFF switching loses eliminated. The inductive character of the resonant frequency allows to achieve zero voltage switching(ZVS), which is preferred for MOSFET transistors.LLC Resonant Converters can achieve ZVS for Primary side devices and ZCS for secondary side devices.Switching transitions occur under favorable conditions device voltage or current is zero.Allows the operation at a higher frequency and at higher input volt-ages without sacrificing efficiency.it eliminates diode reverse recovery effects.it can be operate without snubber.

III. TOPOLOGY OF SECONDARY SIDE

Topology selection of secondary is important to build a high efficiency and slim type converter.

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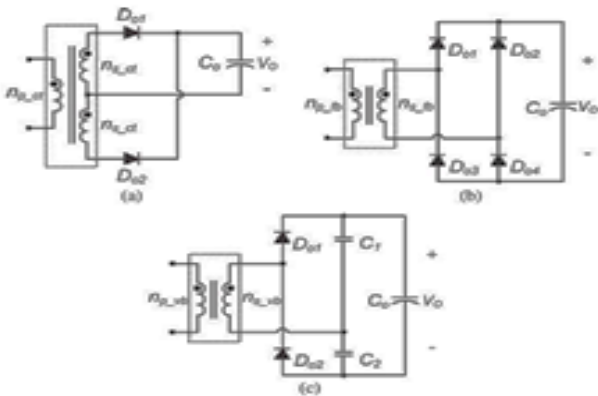Selection of topology secondary side:

Fig. 4. (a) Center tapped (b) Full bridge (c) Voltage doubler

Center-tapped, full bridge and voltage doubler are topologies for secondary side. The configuration of secondary side of transformer is very difficult to design due to large current on secondary side and its large current flow on secondary side and its required wide conductive area. In full bridge is obtain same conversion ratio. Although the center tapped configuration needs to different secondary winding so it is not appropriate for transformer because of it is complex structure of secondary side. Hence the voltage doubler rectifier can be selected for the secondary side with just one turn in the secondary winding.

In the operating condition, in meanwhile the capacitor output filter is adapted, because the current flowing output capacitance is discontinued, so the rms ripple current of output capacitance is very large, for that bulky capacitor are needed to overcome it.

A. Voltage doubler with CLC output filter

For reduce the output filter size and large ripple current in that case, a CLC filter is used. due to small inductor, large current ripple is generated in the left side of capacitor C_f and ripple current right side capacitor C_0 is small. [9]
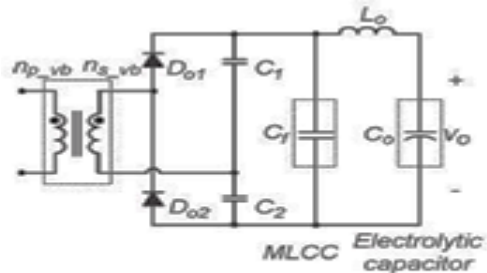

Fig. 5. voltage-doubler rectifier with CLC output filter

The electrolytic capacitor is applied to C_0 since it has large capacitance value with the voltage doubler, using the CLC filter. Its already having two capacitor C_1 and C_2.so only small inductor is needed to complete the CLC filter configuration.
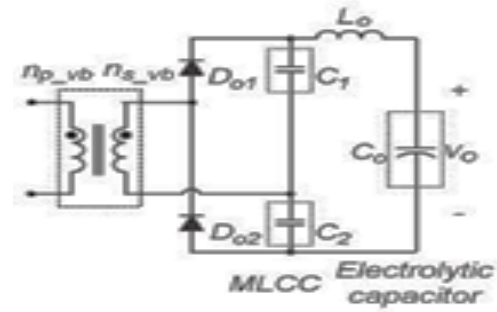

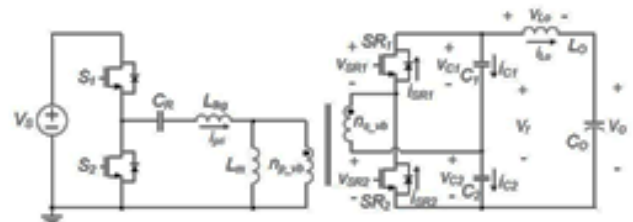Fig. 6. simplified voltage-doubler rectifier with CLC output filter.

Fig. 7. Circuit diagram of LLC resonant converter with voltage-doubler rectifier and CLC output filter.

IV. DESIGN OF TOPOLOGY

A. Define the system specifications

➢ Estimated efficiency (Eff)
➢ Input voltage range: hold up time should be considered for minimum input voltage [2]

$$V_{in}min = \sqrt{V_{0.PFC}^2 - \frac{P_{in}T_{HU}}{c_{DL}}} \qquad (3)$$

Assuming the Efficiency is 97%

$$P_{in} = \frac{P_0}{eff} \qquad (4)$$

$$V_{in}min = \sqrt{V_{0.PFC}^2 - \frac{P_{in}T_{HU}}{c_{DL}}} \qquad (5)$$

$$V_{in}min = \sqrt{400^2 - \frac{2*123*17*10^{-3}}{100*10^{-6}}} = 343V \qquad (6)$$

$$V_{in}max = V_{0.PFC} = 400V \qquad (7)$$
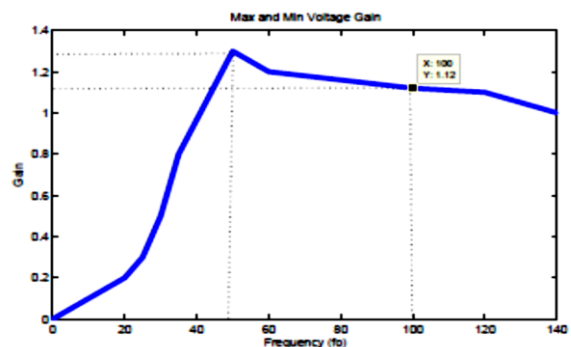
Fig. 8. Minimum and Maximum Voltage Gain

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B. *Determine the maximum and minimum voltage gains of the resonant network by choosing K*

It is typical to set K to be 5-10, which results in a gain of 1.1-1.2 at f_0 where K is coefficient, where M is Voltage Gain

$$Mmin = \frac{V_{R0}}{\frac{V_{in}mac}{2}} = \frac{L_m + (n^2)L_{lks}}{L_m}$$

$$= \frac{L_m + L_{lks}}{L_m} = \frac{K+1}{K} \quad (8)$$

$$Mmax = \frac{V_{in}max}{V_{in}min} + Mmin \quad (9)$$

In design example. The ratio (k) between L_m and L_{lkp} is determined as 8, which result in the min gain as,

$$Mmin = \frac{V_{R0}}{\frac{V_{in}mac}{2}} = \frac{K+1}{K} = 1.12 \quad (10)$$

$$Mmax = \frac{V_{in}max}{V_{in}min} + Mmin = 1.30 \quad (11)$$

C. *Determine the transformer turns ratio.*

$$n = \frac{N_p}{N_s} = \frac{V_{in}max}{2(V_0 + V_f)} * Mmin$$

$$= 12 \quad (12)$$

D. *Calculate the equivalent load resistance (Rac)*

$$Rac = \frac{8(n^2)}{\pi^2} \frac{V_0^2}{P_0max} = 294\Omega \quad (13)$$

E. *Design the resonant network*

With k chosen in STEP-2, read proper Q from gain curves k=8, M_{max}=1.30,
Peak Gain = 1.30*110% = 1.43
As calculated in step 2 the maximum voltage gain (M_{max}) for the minimum input voltage ($V_{in\ max}$) is 1.30 with 10% margin, a peak gain of 1.43 is required k has been chosen as 8 in step 2 and Q is obtain 0.4 from peak gain curves by selecting the resonant frequency as 100KHz the resonant components are

$$C_r = \frac{1}{2\pi Q F_0 R_{ac}} = 13.5\eta F \quad (14)$$

$$L_r = \frac{1}{(2\pi F_0)^2 C_r} = 187\mu H \quad (15)$$

$$L_p = \frac{(k+1)^2}{(2k+1)} L_r = 891\mu H \quad (16)$$

$$F_r = \frac{1}{2\pi\sqrt{L_r C_r}} = 100kHz \quad (17)$$

$$F_s = \frac{1}{2\pi\sqrt{L_p C_r}} = 47kHz \quad (18)$$
$$L_p = L_r + L_m = 704\mu H \quad (19)$$

$$T_r = \frac{1}{F_r} = 0.00001s \quad (20)$$

$$T_s = \frac{1}{F_s} = 2.12 * 10^{-5}s \quad (21)$$

$$F_n = \frac{F_s}{F_r} = 0.47s \quad (22)$$

Adopting the voltage doubler rectifier on the secondary side with only one turn so it is easy to design a PCB trace winding on secondary side. Hence it would be very simple structure and also maximum losses are minimized. CLC filter is used to reduce the ripple current of the output capacitance with the assumption that the capacitance C_0 is large enough so that the output voltage ripple can be neglected so only filter inductor L_0 and doubler capacitors C_1 and C_2 are in the circuit. [3]
Calculation of Ripple current:

$$\Delta i_{L0}(t_0 - t_1) = \frac{1}{L_0} \int_{t_0}^{t_1} V_{Lo}(t)dt \quad (23)$$

$$= \frac{T_R}{4L_0 C_s} I_0 \left(\frac{T_s}{\pi} - \frac{T_R}{4}\right)$$

$$\Delta i_{L0}(t_1 - t_2) = \frac{1}{L_0} \int_{t_1}^{t_2} V_{Lo}(t)dt \quad (24)$$

$$= \frac{I_0}{L_0 C_s}\left(\frac{T_R^2}{16} + \frac{T_s^2}{16} - \frac{T_R T_s}{8}\right)$$

Therefore, the output ripple current can be expressed as:

$$\Delta I_{L0} = \Delta i_{L0}(t_0 - t_1) + \Delta i_{L0}(t_1 - t_2)$$

$$\Delta I_{L0} = \frac{I_0}{L_0 C_s}\left(\frac{T_s^2}{16} + \frac{T_s T_R}{4\pi} - \frac{T_s T_R}{8}\right) \quad (25)$$

Output Voltage Ripple:

$$V_{ripple} = V_{max} - \frac{V_{min}}{V_{avg}} \quad (26)$$

TABLE I
DESIGN PARAMETERS OF LLC RESONANT CONVETER

Parameter	Designator	Value
Input value	V_{in}	400
Resonant inductor	L_r	187µH
Resonant Capacitor	C_r	13.5nF
Magnetising Inductor	L_m	704µH
Resonant frequency	F_r	100kHz
Switching frequency	F_s	47kHz
Turn Ratio	N_n	12

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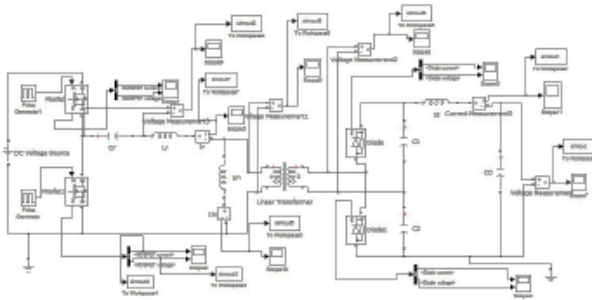**ISSN: 2278-0181**
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Fig. 9. Simulation Ciruit of LLC resonant converter with voltage-doubler rectifier and CLC output filter.

V. CIRCUIT SIMULATION AND RESULTS

From the above calculations of the parameters of the converter the input voltage $V_s = 400$ V, output voltage $V_0 = 18 V$, turn ration $np_v d = 12$, switching frequency $F_s = 47 kHz$, lekage inductance $L_r = 187 \mu H$, magnetizing inducatance $L_0 = 5e - 7H$, resonant capacitance $C_R = 13.5 nF$, doubler capacitance $C_1 = C_2 = 1000 \pi F$. Simulation circuit shown in fig. 9 and fig. 10 to fig 13 shows the outputs of the Low Profile Transformer by using various topology.
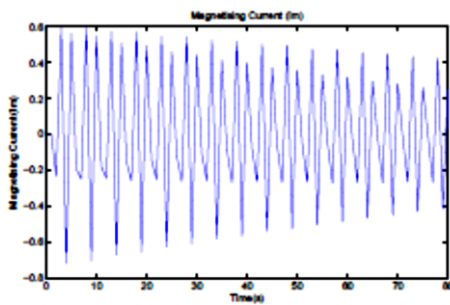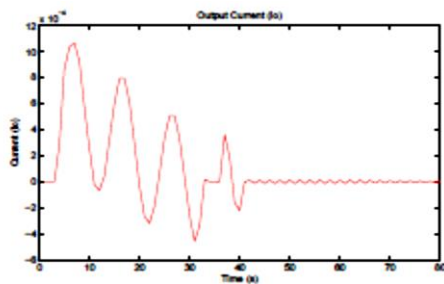

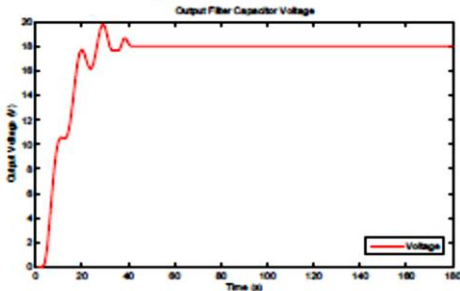Fig. 10. Magnetising Inductor Current

Fig. 11. Output Current

Fig. 12. Output Voltage

VI. CONCLUSION

The LLC resonant converter and voltage doubler rectifier are applied to the topologies of the primary and the secondary side. The secondary side of the transformer can be simplified with this configuration, and the effective PCB winding of the secondary side can be achieved easily. Its having easy utilization and wide conductive cross-sectional area. Also, the output filter size can be reduced using the CLC filter, and it is suitable for the voltage-doubler rectifier since just the small filter inductor is added. So, using various topologies the losses will be minimized and efficiency will be increased. As shown all the output parameters that meet required specification.

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