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Simulation of an Interleaved LLC Resonant Converter for Renewable Energy Systems

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ABSTRACT: This paper presents the simulation of an Interleaved LLC Resonant DC-DC converter for renewable energy sources. The proposed topology reduces the voltage and current stress of the components, increases the step down conversion efficiency and reduces the component count compared to the conventional dual LLC converters. Zero voltage switching (ZVS) is applied for the main switches and zero current switching (ZCS) for the resonant diodes to reduce the switching losses. The basic design of the proposed converter is discussed in this paper. Simulation studies are carried out in MATLAB. The results are verified.

KEYWORDS: Interleaved LLC, Zero Voltage Switching, Zero Current Switching, Renewable energy systems

I.INTRODUCTION

Nowadays power capacity and high conversion efficiency are essential for renewable power generation systems. For medium and high power applications full bridge and half bridge converters are frequently adopted. Variable duty ratio and modulating frequency are the control measures of these full / half bridge-type converters. Active-clamping converters [1], asymmetric half-bridge converters, and phase shift pulse width modulation converters performing zero voltage switching (ZVS) or zero current switching (ZCS) with lower switching losses and reach higher efficiency by duty ratio control. However, at wide input voltage range and different load conditions these converters are difficult to achieve ZVS resonant phenomenon [2-3]. At high frequency control, which effectively extend operating range for either ZVS or ZCS transient at various load conditions many full / half bridge resonant converters are operated. There are two main disadvantages for the pure series and parallel resonant converters. In series resonant converters at no-load conditions the output voltage cannot be controlled properly and in parallel resonant converters the circulating energy in resonant tanks is too high thereby the circuit efficiency is reduced [3-5]. The LLC resonant converter has many advantages than series and parallel resonant converters. It has high conversion efficiency and narrow frequency variation. For wide input voltage range and variable load conditions the power switches can be turned on at ZVS and the rectifier diodes can also be turned off at ZCS [5-6].

For higher power applications, dual converters are proposed for its input structure either in series or parallel connection with interleaved switching scheme. Some researchers focused on developing multi-resonant-tank converter for decreasing current and voltage stress on components [6-9]. These converters are used to double output power, reduce output current ripple and decrease stress on components. However, the parts count and size are getting increased. Large power capability can be attained by connecting two-phase interleaved LLC converters in series or in parallel [10]. Due to the input parallel or series connection these solutions reduce the current or voltage stress on components at primary side. Thus, to reduce the size and cost but still to transfer the same power, a novel LLC converter with parallel-input parallel-output resonant tank is proposed in this paper.

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II.INTERLEAVED LLC

LLC resonant converters exhibit a large voltage ripple on output filter capacitor because of the rectified sine-wave current injected through the transformer secondary windings. In order to reduce the capacitor size and/or the steady-state output voltage ripple, the interleaved approach can be profitably applied. The parameters of dual resonant tanks are identical. The duty cycle of gate signal v_{G1} and v_{G2} are both approximate 50 % complementary to each other. The active switches and output rectifiers reach ZVS and ZCS in the dead time zone. [11] .In Figure 1 the interleaved LLC resonant DC-DC converter is depicted: two identical modules are parallel connected and switched at the same frequency but with 180 degrees phase-shift of their driving signals.

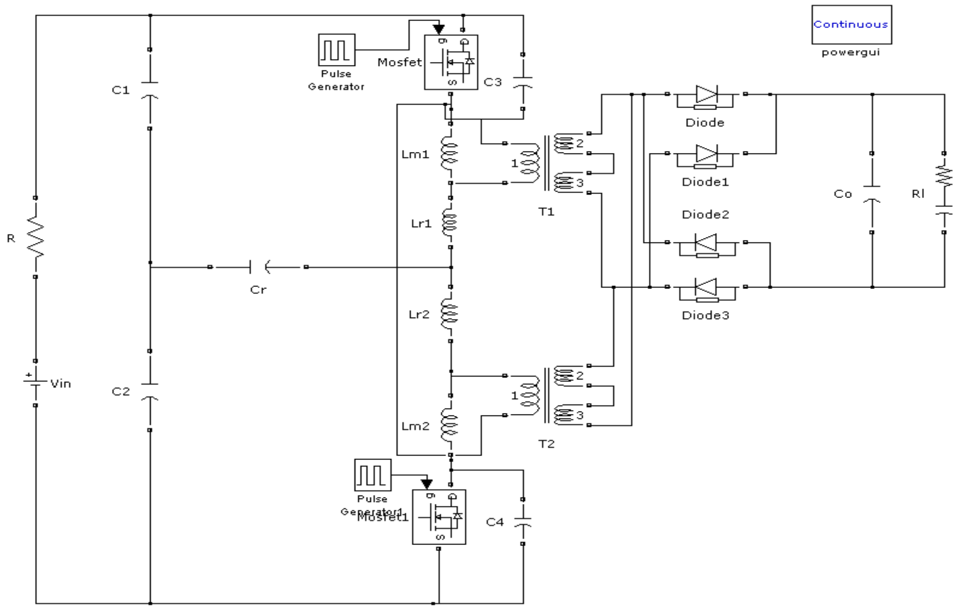

Fig.1.Circuit diagram of Interleaved LLC Resonant DC-DC Converter

III.MODES OF OPERATION

The interleaved LLC resonant DC-DC converter has 12 operating modes in a switching period. Mode I to Mode VI and Mode VII to Mode XII can be seen as the same operating status but different switches. [15]

Mode I $[t_0, t_1]$:

During this transition interval, S_1, S_2, and D_1 are off. The transformer is decoupled. The resonant tanks current let C_3 discharging but C_4 charging respectively. When the voltage on C_3 (it also can be seen as V_{DS1}) drops to zero, thus the anti-paralleled diode of S_1 is turned on. Meanwhile, the voltage on C_4 (it also can be seen as V_{DS2}) rise to V_{in} at the end of this mode.

Mode II $[t_1, t_2]$:

During this transition interval; S_1 and S_2 are off, but D_1 is conducted. The current of resonant inductor i_{L_r} is larger than magnetizing inductor current i_{L_m} so that power can be transferred to secondary side of two transformers

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respectively. Because D_1 is turned on, the voltage on L_{m1} and L_{m2} are respectively clamped to $-nV_O$ and nV_O. When S_1 turns on, this mode end.

Mode III $[t_2, t_3]$**:**

During this transition interval; S_1 and D_1 are conducted but S_2 is turned off. The anti-paralleled diode of S_1 keeps turning on so that V_{DS1} is clamped as diode forward voltage, thus the S_1 is commutated as ZVS. This mode is ended when the resonant inductor currents $i_{L_{r1}}$ and $i_{L_{r2}}$ down to zero.

Mode IV $[t_3, t_4]$:

During this interval, S_1 and D_1 are conducted but S_2 is turned off. The upper resonant tank is receiving energy from capacitor C_1. The magnetizing inductor L_{m1} is transferring energy to secondary side of transformer T_1. The lower resonant tank is receiving energy from V_{in} through capacitor C_2. The magnetizing inductor L_{m2} is transferring energy to secondary side of transformer T_2. The resonant capacitor current i_{C_r} is the sum of $i_{L_{r1}}$ and $i_{L_{r2}}$. This mode ends when the magnetizing currents $i_{L_{m1}}$ and $i_{L_{m2}}$ become zero.

Mode V $[t_4, t_5]$:

During this interval, S_1 and D_1 are conducted but S_2 is turned off. The upper resonant tank is receiving energy from capacitor C_1 to magnetizing inductor L_{m1} and transferring energy to secondary side of transformer $T1$. The lower resonant tank is receiving energy from V_{in} to magnetizing inductor L_{m2} and transferring energy to secondary side of transformer T_2. When the magnetizing inductor current i_{L_m} is equal to resonant inductor current i_{L_r}, this mode ends.

Mode VI $[t_5, t_6]$:

During this interval, S_1 is conducted but S_2 and D_1 are turned off. The integrated resonant capacitor C_r starting resonate with magnetizing inductor L_m and leakage inductor L_r of individual resonant tank. The resonant energy did not transfer to secondary side of these two transformers; they are decoupled at this moment thus the D_1 is commutated as ZCS. When S_1 is turned off, this mode ends.

IV.DESIGN EQUATIONS

The design equations for the resonant frequency , transformer turns ratio, resonant inductor and resonant capacitor are shown as below:

The two resonant frequencies are,

$$F_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (1) \qquad F_{r2} = \frac{1}{2\pi\sqrt{(L_m + L_r)C_r}} \quad (1)$$

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Transformer Ratio & Resonant inductor

$$N_n = \frac{V_{in(nom)}}{2(V_{o(\min)} + V_d)} \quad (2) \qquad L_r = \frac{N_n . V_{in(nom)} . V_{o(nom)}}{8. f_{s\_\max} . P_o} \quad (3)$$

Resonant capacitor & Magnetizing inductor

$$C_r = \frac{1}{(2.\pi . f_o)^2 . L_r} \quad (4) \qquad L_m = \frac{t_{dead} . N_n . V_{o(\min)} . (\frac{1}{4. f_{s\_\max}} - \frac{t_{dead}}{2})}{C_{HB} . V_{in(\max)}} \quad (5)$$

Based on the Equations (1)- (5), the converter is designed and the parameters are shown in Table V.

V.SIMULATION PARAMETERS

Simulation parameters for LLC resonant converter		
Parameter	**Designator**	**Value**
Input Voltage	V_{in}	400V
Resonant Inductor	L_r	25µH
Resonant Capacitor	C_r	264nF
Magnetizing Inductor	L_m	2.88H
Resonant frequency	F_r	92KHz
Switching frequency	F_S	80KHz
Turns ratio	N_n	5:1:1

VI. RESULTS AND DISCUSSION

In Fig.2.gating pulses of two switches are shown. Also the voltage and current waveforms are depicted for switch 1. Voltage and current of switch 1 are obtained as 400V ,50A respectively

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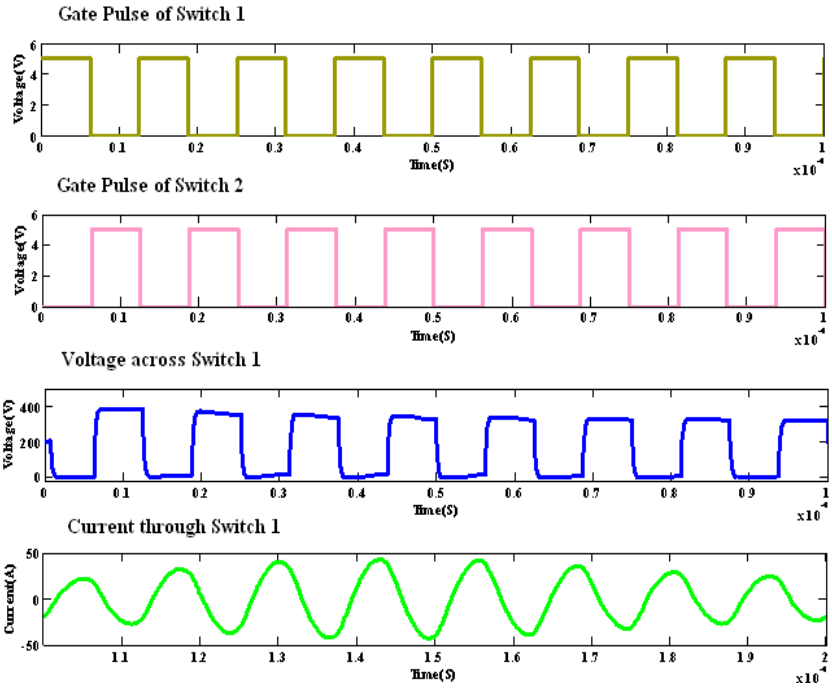

Fig.2.Waveforms of Switch 1(Mosfet)

Voltage and current waveforms of switch 2 are shown in Fig.3. They are obtained as 400V, 50A respectively. Here the achievement of ZVS is shown.

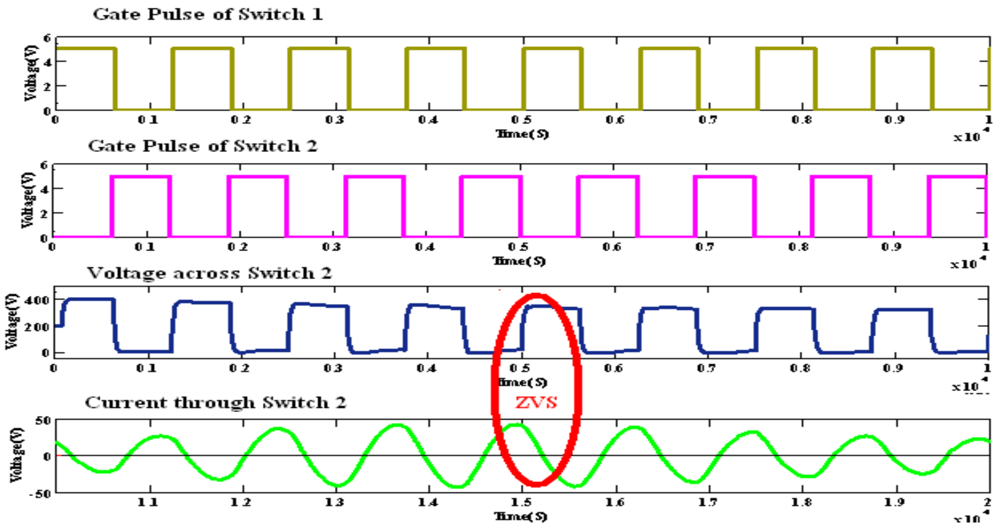

Fig.3.Waveforms of Switch 2(MOSFET1)

In Fig.4.Voltage across capacitor 1, capacitor 2, resonant capacitor and current through the resonant capacitor are shown. Voltage across the capacitors 1 and 2 is obtained as 110V. It is clear from the figure that the voltage and current of resonant capacitor are in phase

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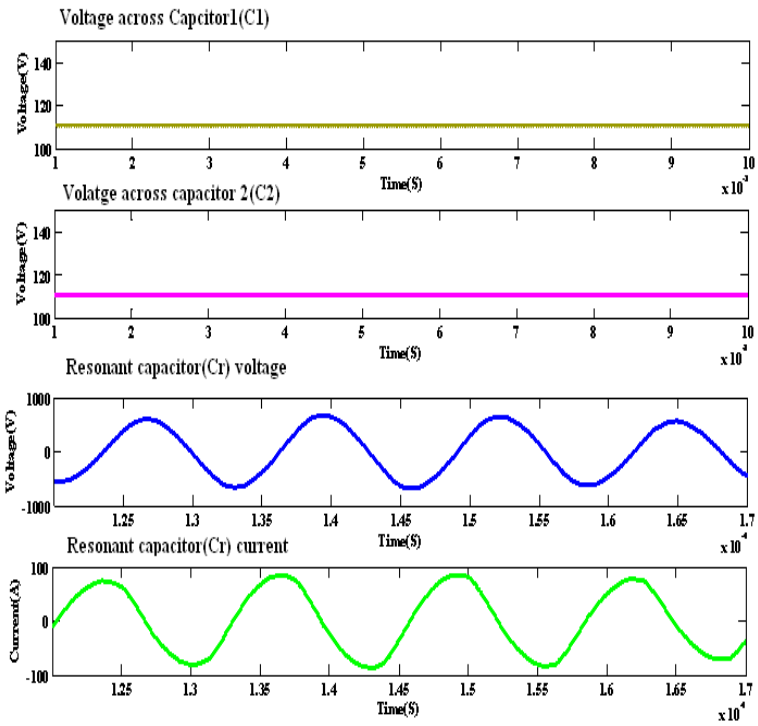

Fig.4.Voltage and current waveforms of the capacitors C1,C2,Cr

In Fig.5.voltage and current waveforms of secondary side diode are shown. Here ZCS is achieved.

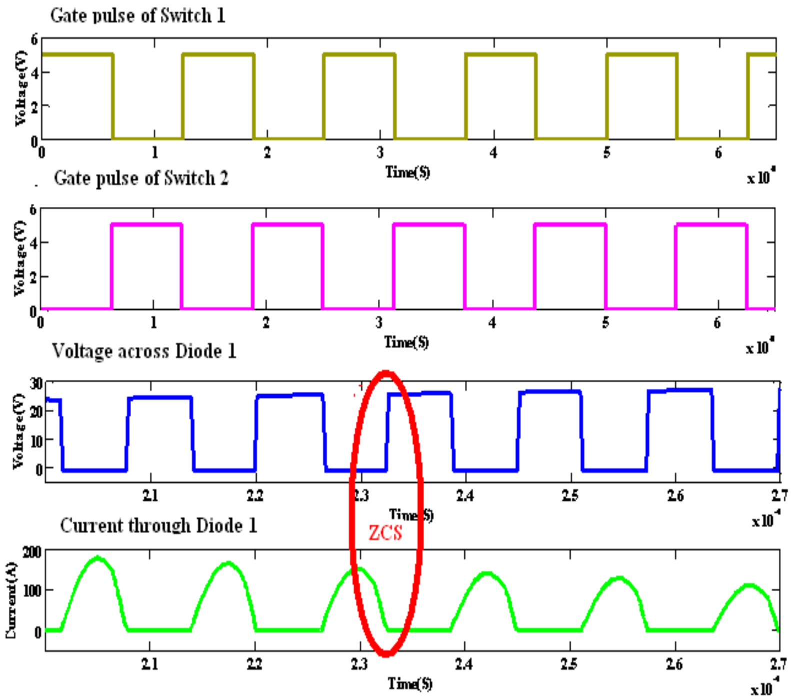

Fig.5.Voltage and current waveforms of Diode 1 at the secondary side

In Fig.6.output voltage waveform is shown. For the input of 400V the output is obtained as 28V.

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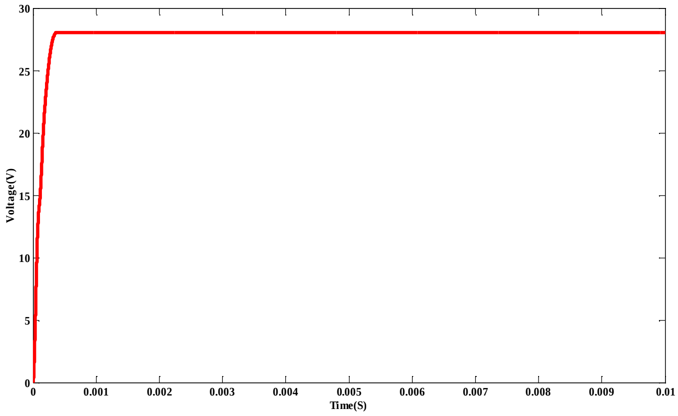

Fig.6.Output voltage of interleaved LLC resonant DC-DC converter

VII. CONCLUSION

Simulation of an Interleaved LLC Resonant DC-DC converter is presented in this paper. The proposed converter reduces the current and voltage stress on the components and for an input of of 400V, the output obtained is 28V. By soft switching, the losses are reduced and the component count of the proposed LLC results in reduced size compared to the dual LLC topology.

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