Operation Characteristics of the Bidirectional LCC Resonant DC-DC Converter

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Abstract—A novel bidirectional DC-DC converter with LCC resonant net was proposed. The converter was composed of LCC resonant net and traditional bidirectional DC-DC circuit with zero voltage switching (ZVS) operation of the primary side switches and zero current switching (ZCS) operation of the rectifier diodes in forward power transition. This paper analyzed the buck operation mode in the reverse direction. The simulation results illustrates that the proposed topology can realize the power transition in both directions.

Keywords—Bidirectional, LCC resonant, series-parallel resonant

I. INTRODUCTION

Resonant converters is well known for its applications in high power density and high energy efficiency [1-13] and LLC resonant converters have been studied in plenty literatures [4-12]. In literature [4], only the topology of bidirectional resonant circuit is mentioned. Up to date, bidirectional isolated LCC resonant converter has never been discussed in detail. In high voltage, high power and high frequency applications, there is a large turn ratio of the transformer, which is different from the ordinary one [3]. As the parasitic capacitance is referred to the parallel capacitor and the leakage inductance is included in the series inductor, it is also useful to study this type of topology.

This paper analyses the remarkable unidirectional performance of the LCC resonant converter including zero voltage switching (ZVS) operation of the primary side switches and zero current switching (ZCS) operation of the rectifier diodes in forward power transition in section II. The buck mode operation in reverse direction is discussed in section III. Then in section IV, the simulation results in forward operation and reverse operation in buck mode are listed. Finally, the conclusion is derived in section V.

II. OPERATION IN FORWARD DIRECTION

Fig.1 shows the basic circuit diagram of a bidirectional LCC resonant converter. The resonant tank consists of a series capacitor C_r , a series inductor L_r in which the leakage inductor of the transformer is concluded and a parallel capacitor C_p in which the parasitic capacitor is concluded.

In literature [1]-[3], the forward operation has already been analyzed in detail for the classical unidirectional LCC resonant converter. The switches of primary side full-bridge are controlled with the duty-cycle of 0.5, which provides a square-wave voltage u_{ab} . A near sinusoidal alternating current i_r will flow. The switches of secondary side full-bridge

works as a synchronous rectifier to increase the power conversion efficiency

Fig.1 Circuit diagram of the LCC converter equipped with full-bridges on both sides to allow for bidirectional power transfer

Fig.2 Key waveforms of LCC resonant circuit

Fig.3 Resonant state of LCC resonant circuit

Fig.2 shows the waveforms of LCC resonant converter and Fig.3 gives the operation states in a half period.

A. $t \in [t_0, t_1]$

The operation state is shown in Fig.3 (a). The resonant current is zero at t_0 . The diodes of M_1 and M_4 are naturally turned on with zero current switching. The resonant circuit is composed by series L_r , C_p , and C_r to charge C_p . There is no power flow through the transformer.

$$i_r(t) = \frac{V_{in} - V_{Cp}(t_0) - V_{Cr}(t_0)}{Z_{rp}} \sin \omega_p(t - t_0) \quad (1)$$

$$V_{Cp} = V_{Cp}(t_0) + \frac{1}{C_p} \int_{t_0}^t i_r(t) dt \quad (2)$$

$$V_{Cr} = V_{Cr}(t_0) + \frac{1}{C_r} \int_{t_0}^t i_r(t) dt \quad (3)$$

$$T_1 = t_1 - t_0$$

$$= \frac{1}{\omega_r} \cos^{-1} \left(\frac{V_{in} + AV_{Cp}(t_0) - V_{Cr}(t_0) - (1+A)V_e}{V_{in} - V_{Cp}(t_0) - V_{Cr}(t_0)} \right) \quad (4)$$

where $\omega_r = 1/\sqrt{L_r C_r}$, $Z_r = \sqrt{L_r / C_r}$,

$$C_r = \frac{C_r C_p}{C_r + C_p}, A = \frac{C_p}{C_r}, V_e = \frac{V_0}{n}$$

B. $t \in [t_1, t_2]$

The operation state is shown in Fig.3 (b). S_1 and S_4 are on and C_p is clamped. The resonant circuit is composed by series L_r and C_r . Power flows through the transformer to the secondary side.

$$i_r(t) = \frac{V_{in} - V_e - V_{Cr}(t_1)}{Z_r} \sin \omega_r(t - t_1) + i_r(t_1) \cos \omega_r(t - t_1) \quad (5)$$

$$V_{Cr}(t) = V_{Cr}(t_1) + \frac{1}{C_r} \int_{t_1}^t i_r(t) dt \quad (6)$$

$$T_2 = t_2 - t_1$$

$$= \frac{1}{\omega_r} \tan^{-1} \left(-\frac{i_r(t_1) Z_r}{V_{in} - V_e - V_{Cr}(t_1)} \right) \quad (7)$$

where $\omega_r = 1/\sqrt{L_r C_r}$, $Z_r = \sqrt{L_r / C_r}$.

C. $t \in [t_2, t_3]$

The operation state is shown in Fig.3 (c). S_1 and S_4 are turned off and S_2 and S_3 are turned on with zero voltage switching. The resonant circuit is composed by series L_r and C_r . Power flows through the transformer to the secondary side.

$$i_r(t) = \frac{-V_{in} - V_e - V_{Cr}(t_2)}{Z_r} \sin \omega_r(t - t_2) + i_r(t_2) \cos \omega_r(t - t_2) \quad (8)$$

$$V_{Cr}(t) = V_{Cr}(t_2) + \frac{1}{C_r} \int_{t_2}^t i_r(t) dt \quad (9)$$

$$T_3 = t_3 - t_2$$

$$= \frac{1}{\omega_r} \tan^{-1} \left(\frac{i_r(t_2) Z_r}{V_{in} + V_e + V_{Cr}(t_2)} \right) \quad (10)$$

At t_3 , the half period of operation state is end. The other half period of operation state is similar.

The switching frequency is

$$f_s = \frac{1}{2(T_1 + T_2 + T_3)}$$

In the forward direction, the on-off switching loss is reduced for the switches of the primary side full-bridge are turned on and turned off with zero voltage switching and the diodes of the secondary side switches are turn on and turned off with zero current switching.

III. OPERATION IN REVERSE DIRECTION IN BUCK MODE

When power is flow in backward direction, the LCC converter works in backward buck mode. Fig.4 shows the characteristic voltages and currents for this mode and Fig.5 gives the equivalent circuits in a half period. The switching period is defined to begin at t_0 , when the primary side resonant tank current i_r is zero. The primary side switches perform synchronous rectifications, so ZCS is achieved on the primary side switches. The switching works as follows:

Fig.4 Key waveforms of LCC resonant circuit in buck mode of reverse operation

Fig.5 Equivalent circuit in the reverse operation in buck mode in a half period

A. $t \in [t_0, t_1]$

The operation state is shown in Fig.5 (a). The resonant current is zero at t_0 . The diodes of S_1 and S_4 are turned on with zero current switching. The resonant circuit is composed by series L_r and C_r . Power flows through the transformer to the primary side.

$$i_r(t) = \frac{V_{in} - V_e - V_{Cr}(t_0)}{Z_r} \sin \omega_r(t - t_0) \quad (11)$$

$$V_{Cr}(t) = V_{Cr}(t_0) + \frac{1}{C_r} \int_{t_0}^t i_r(t) dt \quad (12)$$

$$T_1 = t_1 - t_0$$

$$= \frac{1}{\omega_r} \cos^{-1} \left(\frac{V_{in} - V_e - V_{Cr}(t_1)}{V_{in} - V_e - V_{Cr}(t_0)} \right) \quad (13)$$

B. $t \in [t_1, t_2]$

The operation state is shown in Fig.5 (b). The switches of secondary side full-bridge are turned of and turn off with zero voltage switching. The resonant circuit is composed by series L_r and C_r . Power flows through the transformer to the secondary side.

$$i_r(t) = \frac{V_{in} + V_e - V_{Cr}(t_1)}{Z_r} \sin \omega_r(t - t_1) + i_r(t_1) \cos \omega_r(t - t_1) \quad (14)$$

$$V_{Cr}(t) = V_{Cr}(t_1) + \frac{1}{C_r} \int_{t_1}^t i_r(t) dt \quad (15)$$

$$T_2 = t_2 - t_1$$

$$= \frac{1}{\omega_r} \tan^{-1} \left(-\frac{i_r(t_1) Z_r}{V_{in} + V_e - V_{Cr}(t_1)} \right) \quad (16)$$

The half period of operation state is end. The other half period of operation state is similar.

The switching frequency is

$$f_s = \frac{1}{2(T_1 + T_2)}$$

In the buck mode of reverse direction, the on-off switching loss is reduced for the switches of the secondary side full-bridge are turned on and turned off with zero voltage switching and the diodes of the primary side switches are turned on and turned off with zero current switching.

IV. SIMULATION

A time-domain simulation has been performed with PSIM9 to verify the analytic considerations.

In the forward operation, very low power losses occur. ZVS is always achieved on the primary side, and ZCS is always achieved on the secondary side. Fig.6 shows the simulation results with the parameters are listed as follows:

Input voltage V_{in} : 100V;

Output voltage V_o : 350V;

Switching frequency f_s : 20kHz;

Turn ratio of the transformer n : 2;

Leakage inductor L_r : 70uH;

Resonant capacitor C_r : 9uF;

Winding capacitor C_p : 0.9uF;

In the reverse operation, ZVS is always achieved on the switches of secondary side. The waveforms of u_{cd} , u_{cp} , i_r , i_{cp} in buck mode is shown in Fig.7.

Fig.6 Forward operation waveforms of u_{ab} , u_{cp} , i_r , i_{cp}

Fig.7 Reverse operation waveforms of u_{cd} , u_{cp} , i_r , i_{cp} in buck mode

V. CONCLUSION

By using the leakage inductance and the winding capacitance of the transformer as the resonant elements, only an additional series resonant capacitor is needed to form the LCC resonant topology, which can be used in high voltage, high power and high efficiency applications. The switches of power input side are turned on with ZVS and the switched of power output side are turned off with ZCS. This paper gives the simulation results of the both directional waveforms, which verifies the analysis.

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