V2G 시스템을 위한 보조 LC 회로를 가진 고효율 양방향 공진형 컨버터

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A High Efficiency Bidirectional Resonant Converter With Auxilary LC Circuit for V2G System

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ABSTRACT

In this paper a high efficiency bidirectional resonant converterfor Vehicle–to-Grid applications (V2G) is proposed.The proposed converter has adopted an LC auxiliary circuit in the third winding of the transformer. With the proposed method full softswitching can be ensured in all switches over a wide range of loadsand the secondary ringing can be removed with no additional snubber or clamp circuitry.In addition, since the proposed resonant converter is able to operate at an almost constant resonant frequencyregardless of the load, CC/CV charge of the battery can be simply implemented with high efficiency. A 3.3 kW bidirectional converter for On-Board Charger of Electric Vehicle is implemented to verify the validity of the proposed method. The experimental results show the high efficiency characteristics of the proposed converter over the wide range of load in both charge and discharge mode. The maximum efficiency of the proposed system was 98.13 % at 2.3 kW during the constant voltage mode charge operation.

Index Terms –Vehicle–to-grid (V2G), bidirectional converter, soft switchingand Auxiliary LC circuit.

1. Introduction

Demand for electric vehicles (EVs) is growing around the world rapidly due to their significant advantages such as its environmentally friendly characteristics, higher efficiency and quietness. One of the important functions of EV may be V2G operation, which transfers the power from the battery in EV to the grid upon the demand request. The conventional phase-shift full bridge converter is the most widely used topology for high powerapplications [1-2]. However, this topology suffers from high duty cycle loss due to the large leakage inductance to ensure the soft switching andserious ringing in the secondaryside rectifiers. To damp this ringing the clamp circuits are used, but it increase the size, cost and complexity of the circuit. Another approach is to employ the high efficiency resonant converter such as CLLC resonant converter. However, for the wide range input or output voltage application, its magnetizing inductance needs to besufficiently small andit leads to a high current turn-off resulting in high switching losses in primary side switches [3]. To overcome these issues, a new bi-directional resonant converter with an LC auxiliary circuit is proposed in this paper.The major role of the additional LC resonant tank is to make the equivalent magnetizing inductance larger to achieve the ZCS of the switches. Therefore, the turn-off current of the switch is reduced significantly. The ZVS for all the primary side switches can be achieved with a small magnetizing current. In addition, the proposed converter is capable of operating in constant current mode or constant voltage mode at one frequency,the CC/CV charge can implemented without varying the switching frequency. The operating principle and design procedure of the proposed converter is provided and the validity of the proposed system is proved by the experiments.

2. Operating principle of the proposed converter

The proposed resonant converterwith auxiliary LC tank is shown in Fig.1.Switches S_1~S_4 in the primary side form a fullbridge inverter, while the switches in the secondary side Q_1~Q_4serve as a rectifier circuit. The resonant tank is composed of transformerT_r with turn ratio n:1, magnetizing inductance L_m, inductors L_1/L_2 and resonant capacitances C_1/C_2 . An additionalL_{au}/C_{au} circuit is added into the third winding of the transformer $T_r$and the equivalent magnetizing inductance can be expressed as shown in (1).

$$L_{m,eq} = L_m \frac{1-\left(\frac{f_{au}}{f}\right)^2}{1-\left(\frac{f_r}{f}\right)^2} \tag{1}$$

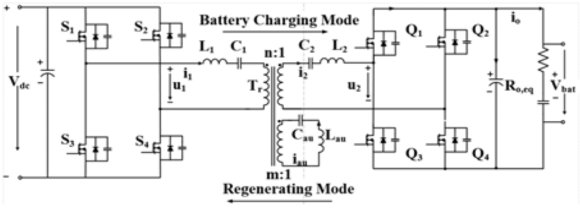

Fig.1.Configuration of the proposed bidirectional converter system.

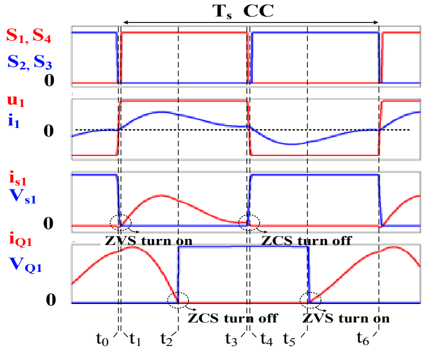

Fig.2. Key waveforms of the converter in CC mode charge.

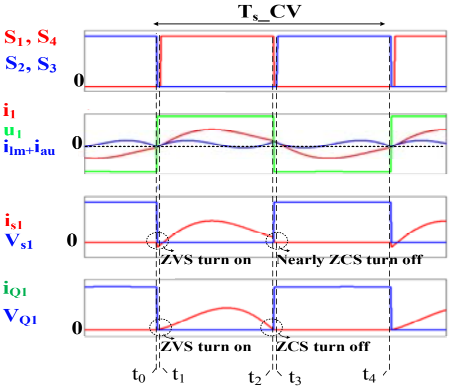

Fig.3. Key waveforms of the converter in CV mode charge.

where, f is the switching frequency, $f_{au} = \frac{1}{2\pi\sqrt{L_{au}C_{au}}}$ and $f_r = \frac{1}{2\pi\sqrt{L_1C_1}}$.

A. Operation of the converter in CC mode

The switching frequency in this mode is the resonant frequency f_{CC} as shown in (2).

$$f_{CC} = \frac{1}{2\pi\sqrt{(L_1 + L_{m,eq})C_1}} \tag{2}$$

The operating principlein CC mode charge is shown in Fig. 2

Mode 1 [t_0~t_1]: At $t = t_0$, $S_2$and $S_3$are turned off. The primary current $i_1(t)$ discharges the output capacitances of $S_1$and S_4.

Mode 2 [t_1~t_2]: At $t = t_1$, $S_1$and $S_4$are turned on with ZVS.The primary current $i_1(t)$starts to flowand power is transferredto the battery through the secondary rectifier switches Q_1 and Q_4.

Mode 3[t_2~t_3]: The resonance between C_2 and the total sum of L_2 and $L_{m,eq}$is ended at $t = t_2$. Q_1 and Q_4 are turned off with ZCS, meanwhile Q_2 andQ_3turns on with ZVS.

Mode 4[t_3~t_4]:$S_1$and $S_4$are turned off with ZCS at $t = t_3$. The primary current $i_1(t)$ discharges output capacitances of S_2 and S_3

Mode 5[t_4~t_5]: The remaining half switching period operates similar to ths operating modes from Mode 1 to Mode 4.

B. Operation of the converter in CV mode

In CV mode, the converter operates at thefrequencyf_{CV}.

$$f_{CV} = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{3}$$

Fig. 3 illustrates the operation in CV mode charge.

Mode 1 [t_0~t_1]: At $t = t_0$, $S_2$and $S_3$are turned off. This mode is a dead-time interval.

Mode 2 [t_1~t_2]: At $t = t_1$,$S_1$and $S_4$are turned on with ZVS. Power is transferred to the battery through the secondary rectifier switches Q_1 and Q_4.

Mode 3[t_2~t_3]: At $t = t_2$,switches S_1 and S_4 are turned off with nearly ZCS condition. The primary current $i_1(t)$ discharges output capacitances of the switches S_2 and S_3

Mode 4[t_3~t_4]: The other half switching period operates similar to the operating modes from Mode 1 to Mode 3.

C. The operation principle in regeneration mode

In theregenerating mode, the converter regulates the dc bus voltage constant withthe battery voltage by varying the switching frequency of MOSFETs Q_1~Q_4. Meanwhile, the switches S_1~S_4 act as the rectifier bridge delivering power from the battery to the dc bus.

3. Design consideration

A. Soft switching condition in CC mode

In CC mode charge, the converter operates at the resonant frequency f_{CC}.In order to achieve ZVZCS, the input impedance of system is required to become zero. It means the primary voltage $u_1(t)$ is in phasewith the primary current $i_1(t)$as in Fig. 2. Therefore the resonant frequency in CC mode is designed as

$$f_{CC} = \frac{1}{2\pi\sqrt{(L_1 + L_{m,eq})C_1}} = \frac{1}{2\pi\sqrt{(L_2 + L_{m,eq})C_2}} \tag{4}$$

B. Full ZVS for all switches in CV mode

In CV mode charge, a large magnetizing inductance will result in a small turn-off current which reduces the switching loss of the primary side switches. Therefore, the auxiliary inductor L_{au} and capacitor $C_{au}$are designed as (3) to maximize the equivalent magnetizing inductance $L_{m,eq}$.

$$f_r = \frac{1}{2\pi\sqrt{\left(L_{au} + \frac{L_m}{m^2}\right)C_{au}}} \tag{5}$$

However, the primary current should be sufficiently large to discharge the output capacitances of the primary side switches during the dead–time the magnetizing of this current depends on the equivalent magnetizing inductance and the duration of the dead-time. So, the ZVS in the primary side depends on the equivalent magnetizing inductance, the switch output capacitance, the operating switching frequency, and the dead-time. So the equivalent magnetizing inductance $L_{m,eq}$ is designed tosatisfy (6) [2]

$$\left(L_{m,eq}\right) \leq \frac{t_{dt}}{16 C_S f_r} \tag{6}$$

4. Experimental results

In order to prove the validity of the proposedbidirectional DC/DC converter,a3.3kWprototype was implemented.The specification of the proposed converter can be found in the Table 1.Fig.4 and Fig. 5 showthe voltage and current waveforms of the MOSFETsS$_1$, Q$_1$in both CC and CV charge mode, respectively. ZVS turn-on and ZCS turn-off of the switches areachieved. Fig.6 and Fig. 7 show the waveforms of switches S$_1$ andQ$_1$ inthe regenerating mode (RM) at the full load.The overall efficiency plots in two operation modes are presented in Fig. 8 and Fig. 9. The peak efficiency of 98.13%was obtained at 2.3 kW in CV mode.

TABLE 1
SPECIFICATION OF
TOPOLOGY

Power rating (P_o)	3.3[kW]
Nominal input voltage (V_{in})	400 [V]
Output voltagerange(V_o)	250 - 420 [V]
Rated output load current (I_o)	7.85 [A]
Switching frequency in CV (f_{CV})	59[kHz]
Switching frequency in CC (f_{CC})	39[kHz]

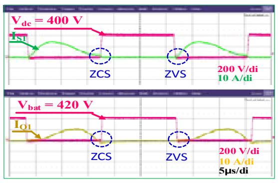

Fig. 4. S_1,Q_1 waveforms in CC

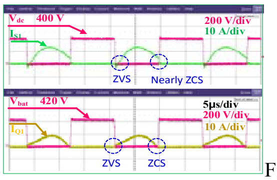

Fig. 5. S_1,Q_1 waveforms in CV

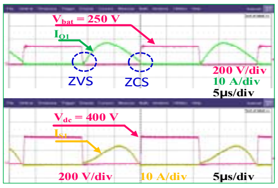

Fig. 6. S_1,Q_1 waveforms in RM

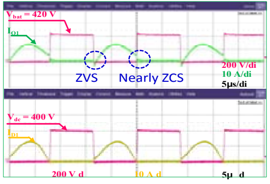

Fig. 7. S_1,Q_1 waveforms in RM

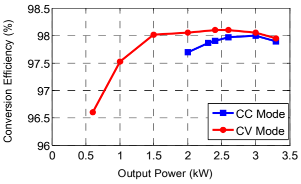

Fig.8. Efficiency in CC and CV

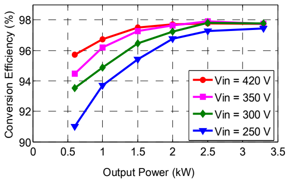

Fig. 9.Efficiency in RM

5. Conclusion

In this paper, a new bidirectional converter using an extra LC auxiliary circuit for the V2G systemhas been presented. It has been proved that the proposed system exhibits excellent efficiency in both directions of power transfer.The soft switching is possible over the wide range of operation.The proposed system is suitable for the on-board charger of electric vehiclefor V2G operation.

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