직류 배전 시스템을 위한 고효율 양방향 컨버터의 설계

Design of the High Efficiency Bidirectional Converter for DC Distributed Power System

Duc-Hung Tran and Woojin Choi

Department of Electrical Engineering, Soongsil University

ABSTRACT

This paper introduces a high efficiency bidirectional resonant converter using an additional LC auxiliary circuit for dc-distribution applications. The LC auxiliary circuit operates as a variable inductor and the additional LC circuit helps to increase the effective magnetizing inductance, thereby reducing the turn-off and primary circulating current. A 5 kW bidirectional converter for dc-distribution system 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 direction of power flow. The maximum efficiency of the proposed system was 98.1 % at 3 kW
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Index Terms – Dc-distribution system, bidirectional converter, soft switching and auxiliary LC circuit.

1. Introduction

Recently, dc distribution system has widely adopted in many industrial applications because it can reduce the number of power conversion stages and reduce the component counts. The dc distribution system requires a bidirectional converter to interface the dc bus with as grid. The conventional phase-shift full bridge topology is widely used for high power applications [1-2]. However, this topology suffers from high duty cycle loss due to the large leakage inductance to ensure the soft switching and serious ringing in the secondary side rectifiers. To damp this ringing the clamp circuits are used, but it increase the size, cost and complexity of the circuit. Resonant converter such as CLLC resonant converter is another method which can achieve high efficiency. However, for the wide range input or output voltage application, its magnetizing inductance needs to be sufficiently small and it 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 auxiliary circuit is to make the effective magnetizing inductance larger to minimize the turn-off current of the switches. The ZVS for all the primary side switches can be achieved with a small magnetizing current. 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 bidirectional resonant converter with auxiliary LC circuit is shown in Fig.1. While the switches S_1~S_4 in the primary side form a full bridge inverter, the switches in the secondary side Q_1~Q_4 serve as a rectifier circuit. The resonant tank is composed of transformer T_r with turn ratio n:1, magnetizing inductance L_m, leakage inductors L_{lk1}/L_{lk2} and resonant capacitances C_1/C_2. An additional L_{au}/C_{au} circuit is added in parallel with magnetizing inductance L_m which forms an effective magnetizing inductance $L_{m,ef}$ expressed as (1).

$$L_{m,ef} = L_m \frac{m^2\left(j\omega L_{au} + \frac{1}{j\omega C_{au}}\right)}{j\omega L_m + m^2 j\omega L_{au} + \frac{m^2}{j\omega C_{au}}} = L_m \frac{1-\left(\frac{f_{au}}{f}\right)^2}{1-\left(\frac{f_r}{f}\right)^2} \qquad (1)$$

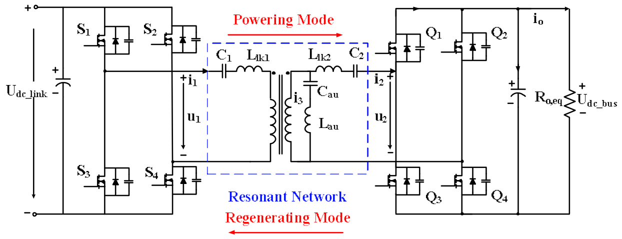

Fig.1.Configuration of the proposed bidirectional converter system.

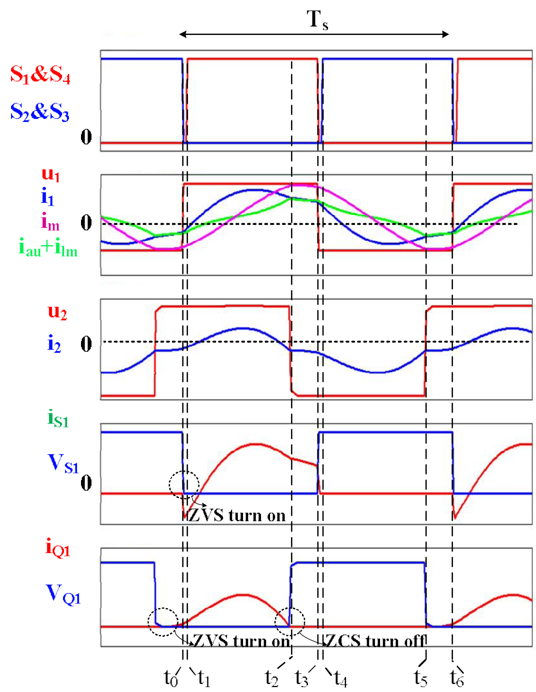

Fig.2. Key waveforms of the converter in CV mode charge.

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

A. Operation of the proposed converter in powering mode

The operating principle in powering 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 flow and power is transferred to the dc bus through the secondary rectifier switches Q_1 and Q_4.

Mode 3 [t_2~t_3]: The resonance is halted and power is not transferred to the primary side any more. The current $i_1(t)$ equals to the sum of $i_m(t)$ and $i_{au}(t)$ during this mode.

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

Mode 5 [t_4~t_5]: Switches S_2 and S_3 turn on. In this mode, the converter starts to transfer power from the dc bus to dc link in the primary side. The direction of the current $i_1(t)$ is opposite to that of Mode 2 but the same operation principle applies.

Mode 6 [t_5~t_6]: The current $i_2(t)$ meets the total current of $i_m(t)$+ $i_{au}(t)$. The resonance and the power transfer are then halted.

B. Operation of the proposed converter in regeneration mode

In the regenerating mode, the converter regulates the dc link voltage constant by varying the switching frequency of MOSFETs Q_1~Q_4. Meanwhile, the switches S_1~S_4 act as the rectifier bridge which delivers the power from dc bus side to ac bus side.

3. Design considerations

A. Effective magnetizing inductance

The selection of effective magnetizing inductance is depended upon the required voltage gain of the converter. However, a large effective magnetizing inductance results in a small turn-off current which reduces the switching loss of the primary side switches. Hence, the auxiliary inductor L_{au} and capacitor C_{au} are designed to increase the effective magnetizing inductance $L_{m,ef}$ as high as possible. It means that the auxiliary inductor L_{au} and capacitor C_{au} are designed to be resonant around the frequency $f_o = \frac{1}{2\pi\sqrt{L_1 C_1}}$ as (2)

$$f_r = \frac{1}{2\pi\sqrt{(L_m + L_{au})C_{au}}} = 1.2\, f_0 \qquad (2)$$

B. Full ZVS for all the switches in CV mode

The primary current should be sufficiently large to discharge the output capacitances of the primary side switches during the dead–time. The magnitude of this current depends on the effective magnetizing inductance and the duration of the dead-time. Hence, the ZVS in the primary side depends on the effective magnetizing inductance, the output capacitance of the switch, the operating switching frequency, and the dead-time. So the effective magnetizing inductance $L_{m,ef}$ is designed to satisfy (3) [3]

$$(L_{m,ef}) \le \frac{t_{dt}}{16 C_s f_r} \qquad (3)$$

C. Voltage stress of the auxiliary resonant capacitor

The voltage stress of C_{au} is another constraint of the proposed converter. The voltage stress of the capacitor is calculated as follows.

$$V_{C_{au}} = V_{dc} + \frac{\sqrt{2} I_{au}}{2\pi f_s C_{au}} \qquad (4)$$

As shown in (4), the voltage stress V_{Cau} is depended upon the value of capacitor C_{au} If the C_{au} is small, the voltage stress of the auxiliary capacitor can be significantly increased.

4. Experimental results
5.

In order to prove the validity of the proposed bidirectional DC/DC converter for dc distribution system, a 5 kW prototype was implemented. The specification of the proposed converter can be found in the Table 1.

TABLE 1: SPECIFICATION OF TOPOLOGY

Power rating (P_o)	5 [kW]
Nominal dc link voltage (V_{dclink})	365-400 [V]
Dc bus voltage (V_{bus})	380 [V]
Rated output load current (I_o)	13.2 [A]
Resonant frequency range (f_{CC})	55-70 [kHz]

*Fig. and Fig.*5 show the measured waveforms in powering mode. The ZVS condition is achieved at the primary inverter MOSFETs at minimum dc link voltage: $V_{dclink} = 365\,V$; $V_{bus} = 380V$; $P_o = 5\,kW$ since the converter operates in inductive region. *Fig.*4 shows the measured waveforms of the transformer.

*Fig.*4 *and Fig.*6 shows the measured waveforms in the regenerating mode. *Fig.*6 verifies the ZVS condition at: $V_{bus} = 380V$; $V_{dclink} = 380V$; $P_o = 2.5\,kW$.

The efficiency of powering mode operation is measured in *Fig.*7 according to various dc link voltage from 365V to 400V. The efficiency of regeneration mode operation of the proposed and conventional CLLC converter is measured in *Fig.*8 at V_{bus}= 380 V. The figure shows the superior performance of the proposed converter compared with CLLC topology, especially in light load condition.

Fig. 3. S_1,Q_1 waveforms in PM

Fig. 4. S_1,Q_1 waveforms in RM

Fig. 5. Transformer waveforms in PM

Fig.6. Transformer waveforms in RM

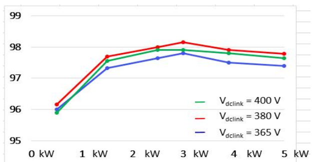

Fig.7. Efficiency in PM

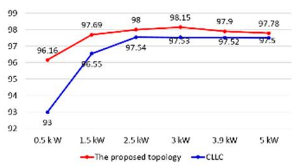

Fig.8. Efficiency in RM of the proposed and CLLC converter

6. Conclusion

In this paper, a novel bidirectional converter using an extra LC auxiliary circuit for the dc distribution system has 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 dc distributed power system.

References

[1] J H Jung, H S Kim, J H Kim, M H Ryu and J W Baek, "High efficiency bidirectional LLC resonant converter for 380V DC power distribution system using digital control scheme," *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, 2012, pp 532-538

[2] B R Lin, J J Chen, Y E Lee and H K Chiang, "Analysis and implementation of a bidirectional ZVS dc-dc converter with active clamp," *2008 3rd IEEE Conference on Industrial Electronics and Applications*, Singapore, 2008, pp 382-387

[3] J H Jung, H S Kim, M H Ryu and J W Baek, "Design Methodology of Bidirectional CLLC Resonant Converter for High-Frequency Isolation of DC Distribution Systems," in *IEEE Transactions on Power Electronics*, vol 28, no 4, pp 1741-1755, April 2013