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DESIGN AND IMPLEMENTATION OF DUAL ACTIVE BRIDGE CONVERTER WITH INTEGRATION OF RENEWABLE ENERGY SOURCES FOR DC DISTRIBUTION SYSTEM

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Abstract*—A high-efficiency isolated bidirectional ac–dc con- verter is proposed for a 380-V dc power distribution system to control bidirectional power flows and to improve its power con- version efficiency. To reduce the switches' losses of the proposed nonisolated full-bridge ac–dc rectifier using a unipolar switching method, switching devices employ insulated-gate bipolar transistors, MOSFETs, and silicon carbide diodes. Using the analysis of the rectifier's operating modes, each switching device can be selected by considering switch stresses. A simple and intuitive frequency detection method for a single-phase synchronous reference frame-phase-locked loop (SRF-PLL) is also proposed using a filter compensator, a fast period detector, and a finite impulse response filter to improve the robustness and accuracy of PLL performance under fundamental frequency variations. In addition, design and control methodology of the bidirectional full bridge CLLC resonant converter is suggested for the galvanic isolation of the dc distribution system. A dead-band control algorithm for the bidirectional dc–dc converter is developed to smoothly change power conversion directions only using output voltage information. Experimental results will verify the performance of the proposed methods using a 5-kW prototype converter

I. INTRODUCTION

DC distribution system is one of important future power systems to save energy and to reduce CO2 emission because it can improve the efficiency of systems due to the reduction of the number of power conversion stages. Especially, the DC distribution system for a residential house using DC home appliances can allow the flexibility of merging many renewable energy sources because most of the output of renewable energy sources is DC. In order to balance the power flow and to regulate the DC-bus voltage, the dc distribution system requires an isolated bidirectional ac–dc converter to interface between dc bus and ac grid. It usually consists of a non-isolated bidirectional AC-DC rectifier for grid-connected operation and an isolated bidirectional DC-DC converter to interface DC bus and dc link of the rectifier. The single-phase non-isolated bidirectional rectifier typically consists of a conventional full-bridge structure. It has two sinusoidal pulse width modulation (SPWM) methods such as the bipolar and the unipolar switching modes. One of the disadvantages of the bipolar switching mode is the need of a large inductor to reduce the input current ripple because the peak to-peak voltage of the inductor is more than twice the unipolar switching mode. If the full-bridge rectifier operates in the unipolar switching mode, inductance for a continuous current mode (CCM) power factor correction (PFC) operation can be reduced. One of full-bridge rectifier legs in the unipolar switching mode is operated at a line frequency while the other one is modulated at a switching frequency. However, the unipolar switching mode rectifier using conventional switching devices including a normal anti-parallel diode causes high reverse recovery current and turn-on switching noise. The switching and the conduction losses in the bidirectional rectifier are the main cause of decreasing power conversion efficiency.

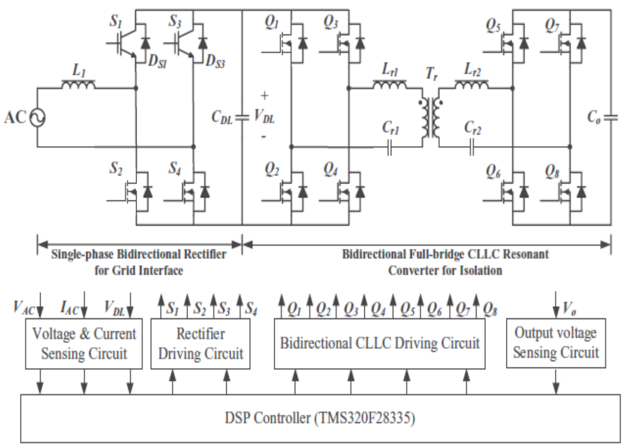

Fig. 1. Circuit configuration of the proposed isolated bidirectional ac–dc converter.

In this paper, the high-efficiency isolated bidirectional ac–dc converter system with several improved techniques will be discussed to improve the performance of a 380-V dc distribution system. In order to increase the efficiency of the non-isolated full-bridge ac–dc rectifier, the switching devices are designed by using insulated-gate bipolar transistors (IGBTs) without an antiparallel diode, MOSFETs, and silicion caribde (SiC) diodes. Through the analysis of operational modes, each switch is selected by considering switch stresses. The major novelty of the proposed PLL is the suggestion of a simple and intuitive frequency detection method for the single-phase SRF-PLL using an advanced filter compensator, a fast quad-cycle detector, and a finite impulse response (FIR) filter. Finally, design guides and gain characteristics of the bidirectional full-bridge *CLLC* resonant converter with the symmetric structure of the primary. Inverting stage and secondary rectifying stage will be discussed for a 380-V dc distribution system. Experimental results will verify the performance of the proposed methods using a 5-kW prototype converter.

II. CIRCUIT CONFIGURATION OF THE PROPOSED ISOLATED BIDIRECTIONAL AC–DC CONVERTER

Fig. 1 shows the circuit configuration of the proposed isolated bidirectional ac–dc converter. It consists of the single phase bidirectional rectifier for grid interface and the isolated bidirectional full-bridge CLLC resonant converter for galvanic isolation. To control the proposed converter, a single digital signal processor (DSP) controller (TMS320F28335) was used. The power flow directions in the converter are defined as follows: rectification mode (forward direction of power flow) and generation mode (backward direction of power flow).The switching method of the proposed single-phase bidirectional rectifier is unipolar SPWM. In order to reduce the switching losses caused by the reverse recovery current in the rectification mode, the high-side switches of the proposed rectifier are composed of two IGBTs without antiparallel diodes (S1 and S3) and two SiC diodes (DS1 and DS3). The low side switches are composed of two MOSFETs (S2 and S4) for reducing conduction loss and for using ZVS operation in the generation mode. The detailed circuit operation of the proposed bidirectional rectifier and advanced PLL method will be discussed in Section III. The proposed bidirectional full-bridge CLLC resonant converter has the full-bridge symmetric structure of the primary inverting stage and secondary rectifying stage with a symmetric transformer. Using the high-frequency transformer, the converter can achieve galvanic isolation between the primary side and the secondary side. The transformer Tr is modeled with the magnetizing inductance Lm and the transformer's turn ratio of 1:1. The leakage inductance of the transformer's primary and secondary windings is merged to the resonant inductor Lr1 and Lr2 , respectively. The resonant capacitors Cr1 and Cr2 make automatic flux balancing and high resonant frequency with Lr1 and Lr2. The detailed analysis and design guides of the proposed converter will be discussed in Section IV.

III. NONISOLATED AC–DC BIDIRECTIONAL RECTIFIER

High-power rectifiers do not have a wide choice of switching devices because there are not many kinds of the switching devices for high-power capacity. Generally, the full-bridge rectifier in high-power applications consists of the same four devices: IGBT modules or intelligent power modules (IPMs) are chiefly used. These modular devices have antiparallel diodes, which have fast recovery characteristics. A fast recovery diode (FRD) has a small reverse recovery time trr when the full bridge rectifier operates; the time trr causes a reverse recovery current which increases power loss and EMC problems. Therefore, soft-switching techniques using additional passive or active snubber circuits have been proposed [31]–[33]. Even though these methods require a relatively large number of passive or active components, which decrease the reliability of the rectifier system and increase system cost, the soft-switching techniques in the high-power rectifier are a unique solution for reducing the reverse recovery problems. On the other hand, a medium-power rectifier system around 5 kW for a residential house or building has a wide selection of switching devices such as discrete-type IGBTs and MOSFETs. Especially, commercial IGBTs without the antiparallel diode can be selected to replace antiparallel FRDs to SiC diodes. In theory, the SiC diode does not have trr Therefore, the combination of IGBTs without the antiparallel diode and the SiC diodes is another viable solution to reduce the reverse recovery problems.

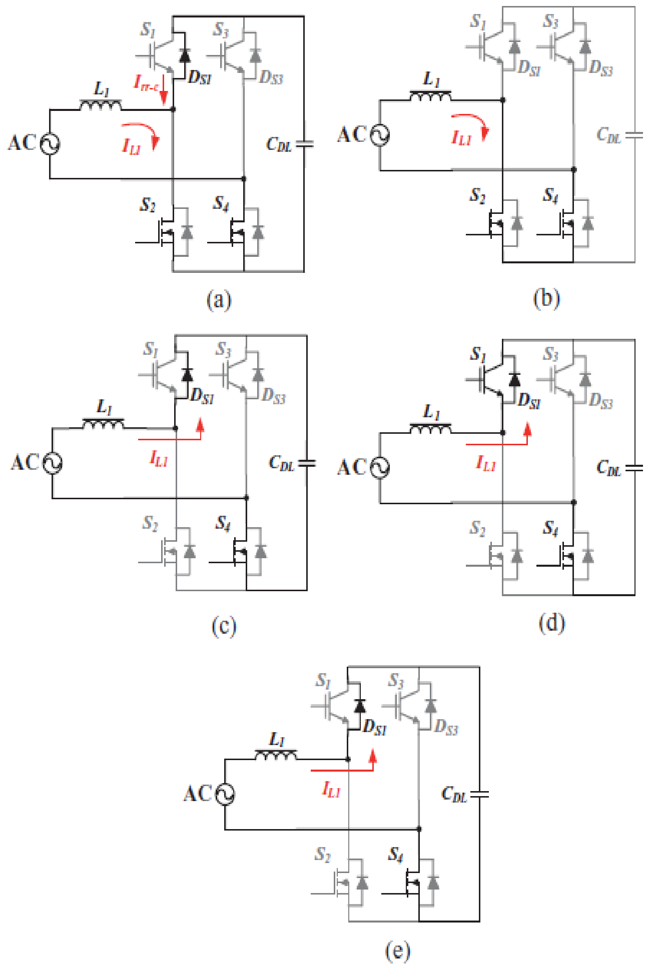

Fig. 2. Operating modes of the proposed bidirectional ac–dc rectifier in the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode* 5.

A. Consideration for Reverse Recovery Losses in a Rectification Mode

In the rectification mode, the bidirectional rectifier has five operating modes in a single switching cycle. The circuit operations in the positive half period of the input voltage are shown in Fig.2. The dark lines denote conducting paths for each state. The theoretical waveforms of the proposed rectifier are given inFig.3.At time $t0$, the low-side switch $S2$

turns ON. At this time, if *DS*1 is FRD, *DS*1 cannot immediately turn OFF because of its reverse recovery process. This simultaneous high reverse recovery current causes an additional switching loss on *S*2. The reverse recovery current increases the current stress on the low side switches and decreases the EMI performance of the rectifier. To solve this reverse recovery problem, the high-side switches of the proposed circuit should use IGBTs without antiparallel diodes and SiC diodes as antiparallel diodes of the IGBTs. Even though the reverse recovery current is not completely zero in a

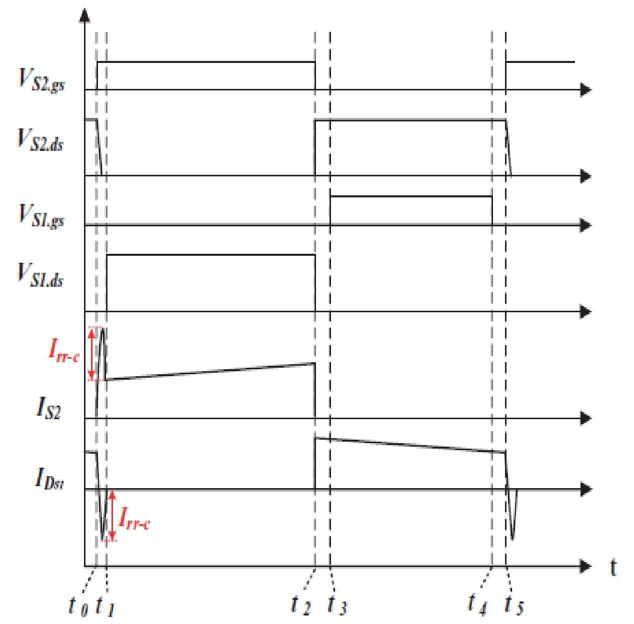

Fig. 3. Theoretical operating waveforms of the proposed bidirectional ac–dc rectifier in the rectification mode.

practical manner, it is significantly reduced as compared with the FRD operation. At *t*3 , the gate signal *VS*1.gs turns ON. Since the IGBTs cannot conduct in the reverse direction, the energy in the input voltage source and the inductor *L*1 is still discharged through SiC diode *DS*1. In the rectification mode, the high-side SiC diodes instead of the IGBTs are fully operated during entire rectification modes. Therefore, the conduction loss of the high-side switches depends on the forward voltage drop of the SiC diodes. Other operation modes are not different from the conventional full bridge rectifier using a unipolar switching method.

B. Consideration for Switching Losses in a Generation Mode

In the generation mode using the same switching pattern as the rectification mode, the proposed bidirectional rectifier has five operating modes in a single switching cycle. The circuit operations in the positive half period of the input voltage are shown in Fig. 4. After the discharge operation of dc-link's energy, the antiparallel diode including the low-side switch *S*2 will be conducted by freewheeling operation using inductor's energy as shown in *Mode* 2. During this period, the energy stored in the output capacitance of *S*2 can be fully discharged. In *Mode* 3, *S*2 turns ON under the ZVS condition. Through these operation modes, the turn-on losses in the low-side switches can be reduced. When the high-side switch *S*1 turns ON in *Mode* 5, the antiparallel diode of *S*2 cannot immediately turn OFF because of poor reverse recovery performance of the MOSFET's antiparallel diode. It causes an additional switching loss on *S*1 through the reverse recovery current. Therefore, the generation mode using the same switching pattern of the rectification mode has advantages of soft switching and disadvantages of reverse recovery loss. The MOSFET's losses in the generation mode depend on the MOSFET's *R*DS. on and the reverse recovery characteristics of the antiparallel diode.

IV. ISOLATED BIDIRECTIONAL CLLC RESONANT CONVERTER

In this section, the design methodology of the power stages of the proposed bidirectional *CLLC* resonant converter will be discussed. The new control schemes are proposed to decide power flow directions and to regulate output voltage under bidirectional power flows. In addition, the dead-band control algorithm is proposed to smoothly change the power conversion direction only using output voltage information. This algorithm is based on a hysteresis control method to decide the power flow direction of bidirectional converters.

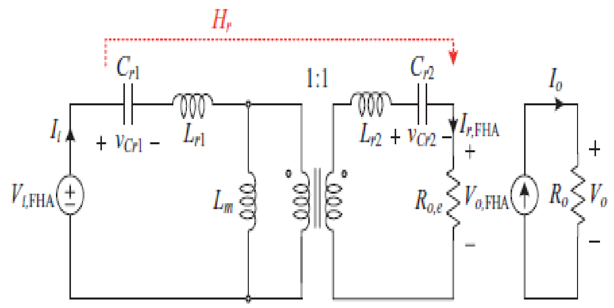

Fig.4 FHA model of the proposed bidirectional *CLLC* resonant converter.

V. EXPERIMENTAL RESULTS

Table I shows the designed parameters of the proposed prototype converter. A 5-kW isolated bidirectional ac–dc converter has been designed and evaluated at 220 Vac input voltage. This prototype converter used a DSP of TI's TMS320F28335 as a digital controller to implement the proposed control algorithms: the unipolar SPWM control for the bidirectional ac–dc rectifier, the proposed SRF-PLL algorithm, the PFM control for the bidirectional CLLC resonant converter, and the dead-band and switch transition controls for the bidirectional power conversion. The switching frequency of the ac–dc rectifier is 13.8 kHz and the dc–dc converter operates within the range of 58–65 kHz. The magnetizing inductance is selected as 130 μH in the prototype dc–dc converter which is the overload condition containing 10% margin from the rated load of 5 kW. Fig.5 shows the configuration of the prototype converter. As shown resonant converter at the full load. The figure illustrates the waveforms of the drain-source voltage of Q1 , the primary current and the secondary current, and the output voltage. At the full load, the operating frequency of the converter is 58 kHz and the primary current and the secondary current are almost sinusoidal because of the converter's operation near the resonant frequency determined by the designed resonant network. All the waveforms are measured in the powering mode; however, the generating mode has the same waveforms because of the converter's symmetric structure. The current waveforms show that the ZVS of the primary switches and the soft commutation of the secondary rectifiers are well achieved under the full-load condition.in Fig.6 (a), the line voltage and current waveforms of the bidirectional ac–dc rectifier under the 5-kW full-load condition are almost in phase. From this result, the proposed SRF-PLL is well operated under the steady-state condition. Fig.6 (b) shows experimental waveforms of the proposed bidirectional CLLC

TABLE I
DESIGN SPECIFICATIONS OF THE PROTOTYPE ISOLATED BIDIRECTIONAL AC–DC CONVERTER

Specifications	Values
Input voltage (V_{in})	AC 220 V
Output Voltage (V_{out})	DC 380 V
Rated Power (P_{out})	5 kW
S_1 and S_3	IGW75N60T
D_{S1} and D_{S2}	C3D20060D
S_2 and S_4	IXKR47N60C5
$Q_1 \sim Q_8$	SPW47N60CFD
T_r	EE6565(PM7)
L_1	1.6 mH
L_m	130 μH
L_r	30 μH
C_r	200 nF

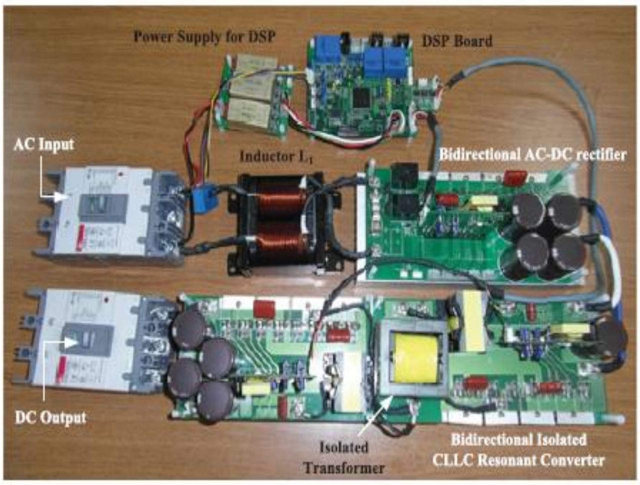

Fig.5. Prototype of a 5-kW bidirectional isolated ac–dc converter.

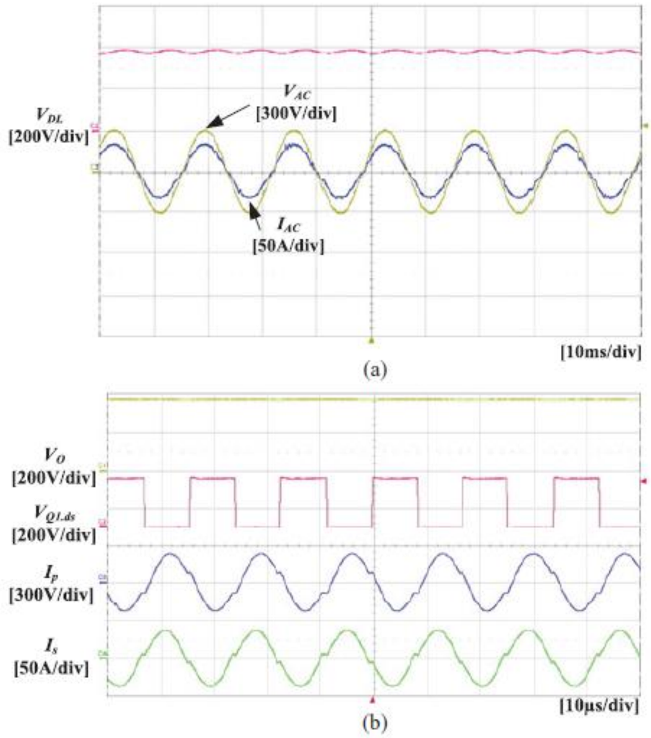

Fig 5.Experimental waveforms at full load (5 kW): (a) input voltage and current with dc-link voltage in the ac–dc rectifier and (b) resonant currents with output voltage in the dc–dc converter.

proposed SRF-PLL is well operated under the steady-state condition. Fig. 5(b) shows experimental waveforms of the proposed bidirectional *CLLC* resonant converter at the full load. The figure illustrates the waveforms of the drain-source voltage of *Q*1, the primary current and the secondary current, and the output voltage. At the full load, the operating frequency of the converter is 58 kHz and the primary current and the secondary current are almost sinusoidal because of the converter's operation near the resonant frequency determined by the designed resonant network. All the waveforms are measured in the powering mode; however, the generating mode has the same waveforms because of the converter's symmetric structure. The current waveforms show that the ZVS of the primary switches and the soft commutation of the secondary rectifiers are well achieved under the full-load condition. Fig. 6 shows efficiency curves of the prototype ac–dc rectifier, dc–dc converter, and overall converter system, respectively. They are measured at the input voltage of 220 Vac. Fig.6 (a) shows the power conversion efficiency in the rectification mode. The maximum efficiency of rectifier is 98.6% at 2 kW. In addition, the bidirectional *CLLC* resonant converter has a good efficiency characteristic under middle- and high-load conditions. The power conversion efficiency is higher than 97.5% at more than 50% (2.5 kW) of the full load. Finally, the power conversion efficiency of the overall converter system is 94.5% at the rated output power of 5 kW. The maximum efficiency is almost 96% at 2.5 kW. Fig. 6(b) shows the power conversion efficiency in the generation mode. The maximum efficiency of the rectifier is 98.3%. The efficiency of the bidirectional *CLLC* resonant converter is the same as the efficiency of the rectification mode because of its symmetric structure. The power conversion efficiency of the overall converter system is 94.2% at 5 kW and at 95.6% at 2.5 kW.

VI. CONCLUSION

The Isolated bi-directional AC-DC converter is proposed for the simple DC power distribution system to control the bidirectional power flow and to improve its power conversion efficiency. In order to improve the reverse recovery problem, the high-side switches of the AC-DC rectifier employ IGBTs without anti-parallel diodes and SiC diodes. In addition, the low-side switches are composed of two MOSFETs to reduce the conduction loss in the rectification mode. For comparison with the conventional IGBT switches, the total conduction losses of the rectifier's switches are calculated in the rectification mode.
Further the system can be improved by the dead-band and switch transition control algorithms are proposed to smoothly change the power flow direction in the converter. From light to full load, the overall power conversion efficiency of the 5-kW prototype converter was measured to almost 96% at 2.5 kW and 94.5% at the full load of 5 kW.

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