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High-Efficiency Isolated Bidirectional Ac–Dc Converter for a Dc Distribution System

Sk. Zeba ahmed *, P.Purna Chander Rao **
*(Power Electronics, M.tech, JNTU university
Email: zeba.heikh@gmail.com)
** (Power Electronics, M.tech, JNTU University, Hyderabad
Email: Purnachander216@gmail.com)

Abstract
The isolated bidirectional ac–dc converter is for the 380-V dc power distribution system to control the bidirectional power flow and to improve its power conversion efficiency. Here 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 consisting of two MOSFETs to reduce the conduction loss in the rectification mode. PLL system shows lower detection fluctuation and faster transient response than the conventional techniques. And *CLLC* resonant converter can operate under the ZVS for the primary switches and the soft commutation for the output rectifiers. A dead-band control algorithm for the bidirectional dc–dc converter is developed to smoothly change power conversion directions only using output voltage information.

Keywords:- AC–DC boost rectifier, bidirectional isolated converter, *CLLC* resonant converter dc distribution system.

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 [1]–[3]. 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. The overall system configuration of the proposed 380-V dc distribution system is shown in Fig. 1. 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 nonisolated bidirectional ac–dc rectifier [4]–[9] for grid-connected operation and an isolated bidirectional dc–dc converter to interface dc bus and dc link of the rectifier [10]–[18].

The single-phase nonisolated bidirectional rectifier typically consists of a conventional full-bridge structure. It has two sinusoidal pulsewidth 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 peakto-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 antiparallel 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.

The phase estimation, so-called phase-locked loop (PLL), is required to control the bidirectional ac–dc rectifier; especially, the phase information of supply voltage is mandatory to generate a current reference. One of the popular PLL methods is synchronous reference frame (SRF-PLL) which uses a rotating reference frame for tracking a phase angle. However, the conventional SRF-PLL has a weak point of frequency tracking performance because it uses the constant angular frequency of a fundamental component. It can cause a tracking error in the PLL operation when the fundamental frequency changes to the different value of the constant angular frequency. Numerous methods for improved PLL have been presented and introduced in the literature [19]–[23]. Even though they have good performance against the frequency distortion, their algorithms are complicated to be implemented for various applications. Another PLL method has been proposed using a simple frequency detector and trigonometric calculations without any linear phase detector;

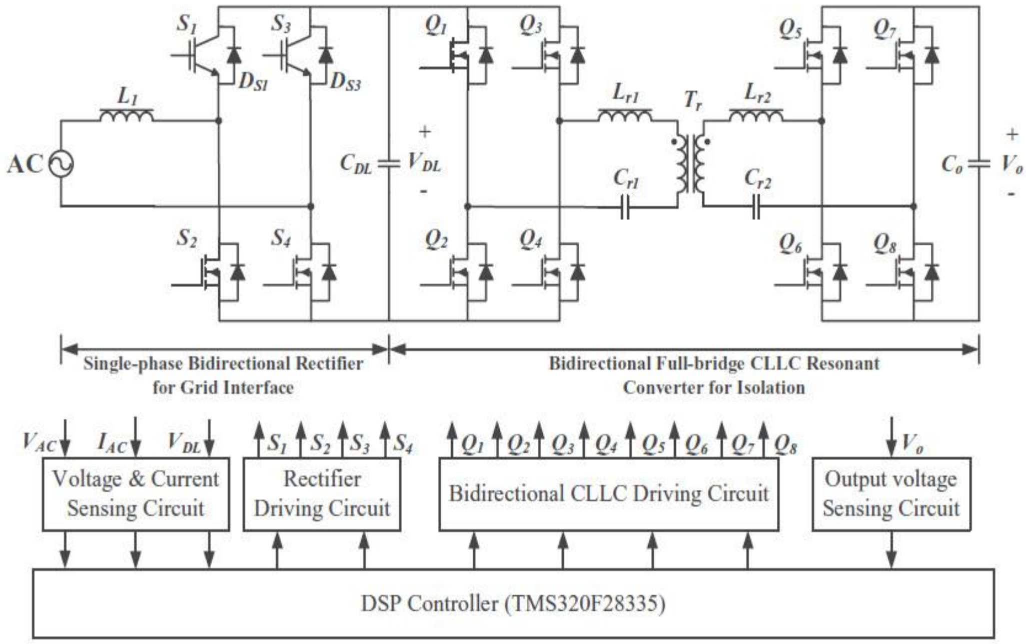

Fig. 2. Circuit configuration of the proposed isolated bidirectional ac–dc converter.

however, this method requires the halfcycle data acquisition of the fundamental frequency to detect the exact line frequency [24]. Therefore, a more simple, faster, and more intuitive frequency detection method should be upgraded for improving the performance of the single-phase bidirectional rectifier.

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 nonisolated 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. 2 shows the circuit configuration of the proposed isolated bidirectional ac–dc converter. It consists of the singlephase 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.

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. This modular devices have antiparallel diodes, which have fast recovery characteristics. A fast recovery diode (FRD) has a small reverse recovery time trr . When the fullbridge 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 kWfor 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.

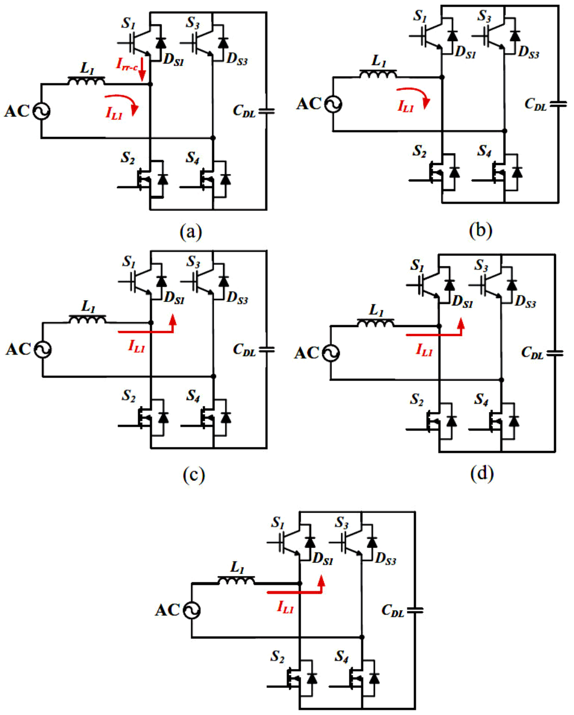

Fig.3. Operating modes of the proposed bidirectional ac–dc rectifier in the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode* 5.

IGBTs in the view point of the conduction loss when the same current flows into the switching devices. Therefore, MOSFETs are suitable for the low-side switches in the unipolar switching method.

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. 3. The dark lines denote conducting paths for each state. The theoretical waveforms of the proposed rectifier are given in Fig. 4.

At time $t0$, the low-side switch $S2$ turns ON. At this time, if $DS1$ is FRD, $DS1$ cannot immediately turn OFF because of its reverse recovery process. This simultaneous high reverse recovery current causes an additional switching loss on $S2$. The reverse recovery current increases the current stress on the lowside 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 practical manner, it is significantly reduced as compared with the FRD operation.

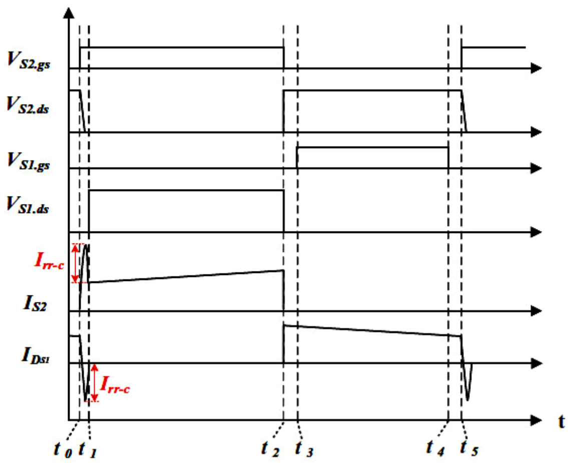

Fig.4. Theoretical operating waveforms of the proposed bidirectional ac–dc rectifier in the rectification mode.

At $t3$, the gate signal $VS1.gs$ turns ON. Since the IGBTs cannot conduct in the reverse direction, the energy in the input voltage source and the inductor $L1$ is still discharged through SiC diode $DS1$. 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 fullbridge 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. 5. 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

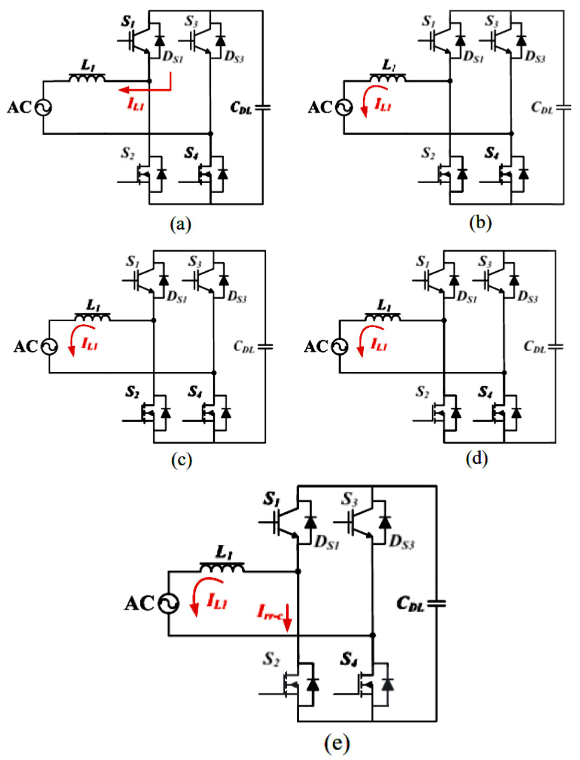

Fig. 5. Operating modes in the rectifier's generation mode using the same switching pattern as the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode* 5.

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. The selection of the MOSFET can determine the significant loss factor between switching and conduction losses. However, if IGBTs are used for the low-side switches, the ZVS operation is not significant to reduce their switching loss. There are also reverse recovery losses through the reverse recovery characteristics of the antiparallel diode. They can increase the turn-off switching losses through the IGBT's tailing current.

If the reverse recovery loss through the MOSFETs is significant, it can be overcome employing the inverted switching pattern in the generation mode. The operation mode of the inverted switching pattern is shown in Fig. 6. In this operation, the switching pattern is perfectly inverted and the turn-on period of the high-side switches is one and half times longer than the turn-on period of the low-side switches. In *Mode* 5, the low-side switch *S*4 turns ON. At the same time, the reverse recovery current should be limited by the SiC diode *DS*3 . Using this switching pattern in the generation mode, there are no benefits of the ZVS operation. However, the reverse recovery losses can be significantly reduced as compared with the same switching pattern of the rectification mode. The modified switching pattern does not affect the power conversion and control performances of the ac–dc rectifier.

C. Consideration for Conduction Losses

In the unipolar switching method, the turn-on period of lowside switches is one and half times longer than the turn-on period of high-side switches. To analyze the conduction loss of MOSFETs as the low-side switches, the circuit operation of the proposed bidirectional rectifier assumes that inductor *L*1 is sufficiently large to operate CCM and the ac input current is a perfectly sinusoidal waveform. Generally, the conduction loss in MOSFETs can be calculated using the rms current passing through MOSFET's *R*DS.on. Since the turn-on period of the low-side switches is 75% of the fundamental period of the ac input current, the rms current of the low-side switches can be calculated using the following equation:

$$I_{\mathrm{rms.low}} = \sqrt{\frac{1}{2\pi}\int_{o}^{\frac{3}{2}\pi}(I_{\mathrm{in}.P}\sin\omega t)^2 d\omega t}. \qquad (1)$$

Through the aforementioned assumptions, the peak current *I*in.*P* and the average current *I*in.av of the ac input can be derived as follows:

$$I_{\text{in}.P} = \sqrt{2}\frac{P_{\text{out}}}{\eta V_{\text{in.rms}}} \quad (2)$$

$$I_{\text{in.av}} = \frac{2}{\pi} I_{\text{in}.P} \quad (3)$$

where η is the power conversion efficiency.
Using the aforementioned equations, the total conduction losses of the rectifier's switches in the rectification can be where the conduction loss in the rectification mode is $P_{\text{con-rec}}$ and V_F is the forward voltage drop of the high-side SiC diode, respectively. In comparison to using IGBTs for the low-side switches, Fig. 7 shows the calculated conduction losses using (4). The low-side switches use MOSFETs, which have extremely low $R_{DS.on}$ (IXKR47N60C5) and the latest IGBTs (IKW75N60T), which have the very low collector–emitter threshold voltage V_{CE} . The high-side switches use SiC diodes (C3D20060D) as the antiparallel diode and IGBTs without antiparallel diode (IGW75N60T). The typical values of $R_{DS.on}$, V_F , and V_{CE} are obtained from their datasheets. Since V_F and V_{CE} are almost the same value, the conduction loss in the generation mode is expected to be nearly the same as the conduction loss in the rectification mod, $P_{\text{con-rec}}$. In Fig. 7, the conduction losses of MOSFETs are less than the conduction losses of IGBTs under the load condition of 6.5 kW or less. Under the light-load condition, MOSFETs is better than IGBTs in the view point of the power conversion efficiency. At the rated load (5 kW), the difference of the conduction losses between MOSFETs and IGBTs is about 12 W. If two MOSFETs are used in parallel, the conduction losses in the rated load will be reduced about 30 W.

$$P_{\text{con-rec}} \simeq 2(I_{\text{rms.low}})^2 R_{\text{DS.on}} + 2\left(\frac{1}{4} I_{\text{in.av}}\right) V_F$$
$$= \frac{3}{4} I_{\text{in}.P}^2 R_{\text{DS.on}} + \frac{1}{\pi} I_{\text{in}.P} V_F \quad (4)$$

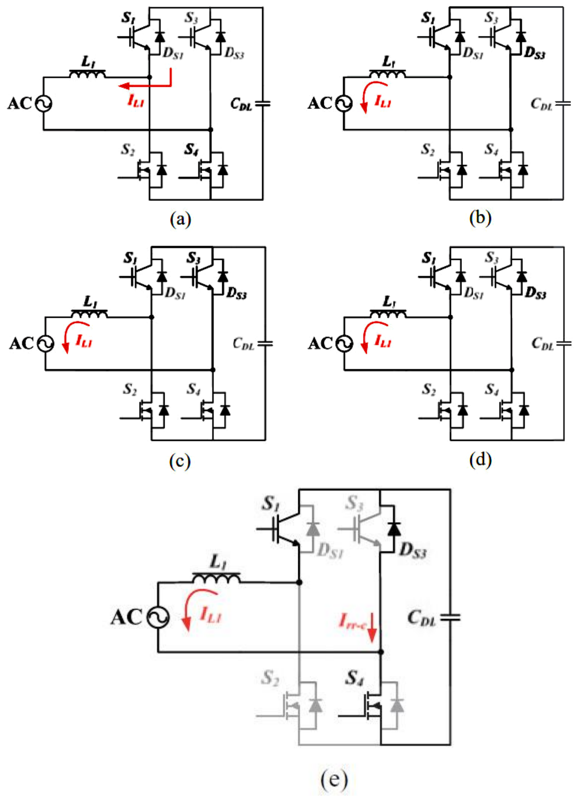

Fig. 6. Operating modes in the rectifier's generation mode using the inverted switching pattern against the rectification mode: (a) *Mode* 1, (b) *Mode* 2, (c) *Mode* 3, (d) *Mode* 4, and (e) *Mode* 5.

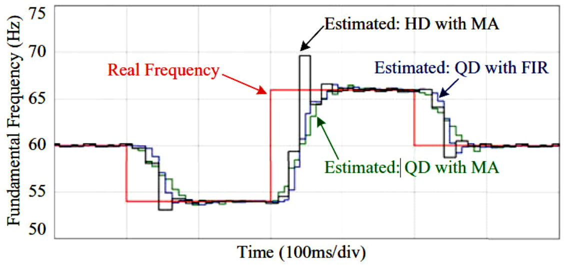

Fig. 7. Simulation results of the proposed single-phase PLL for comparison of frequency detection speed.

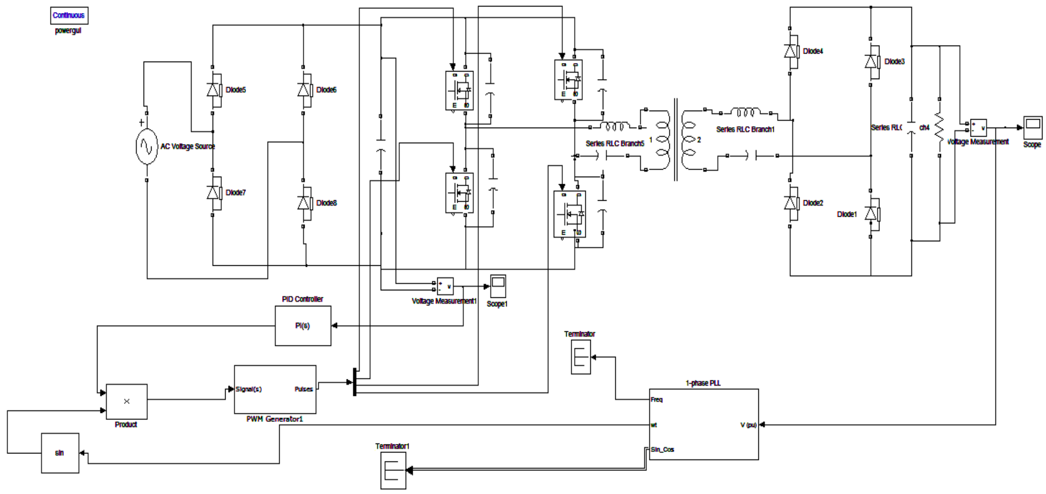

Fig 8. Simulation model for forward biase

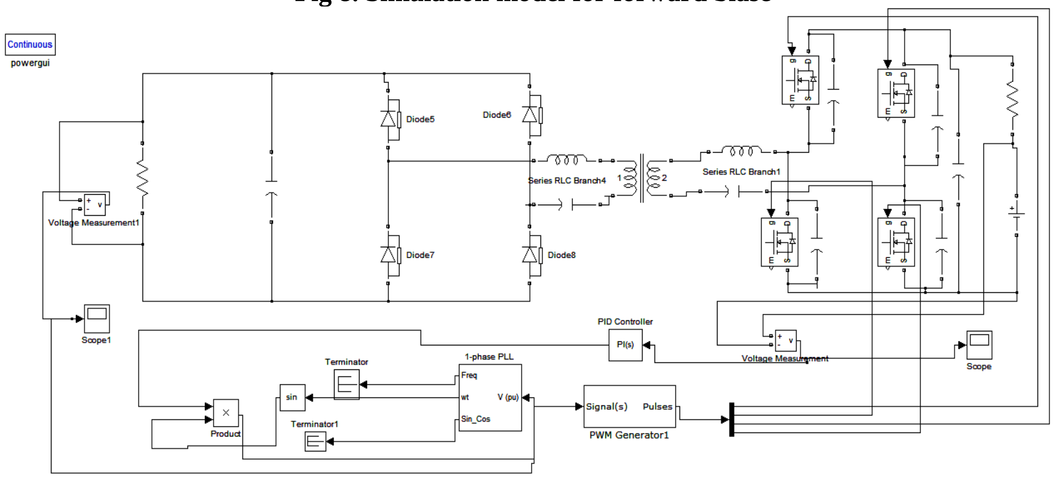

Fig 9. Simulation model for reverse biase

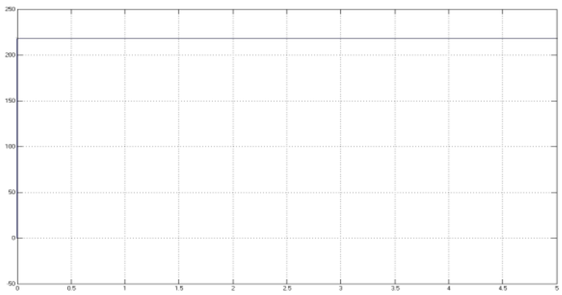

Fig 10. DC voltage From the Rectifier

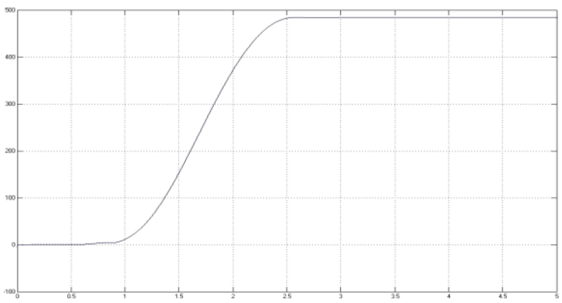

Fig 11. Output DC Voltage in forward biase

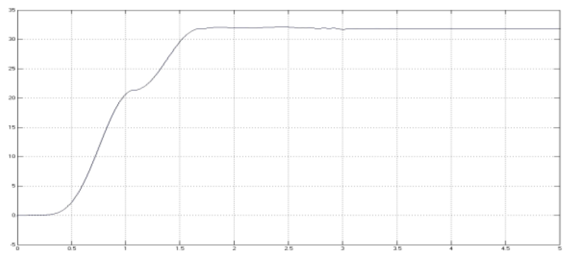

Fig 12. Output DC Voltage in reverse biase

IV. CONCLUSION

The isolated bidirectional ac–dc converter is proposed for the 380-V 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 antiparallel 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. The simple and intuitive frequency detection method for the single-phase SRF-PLL is also using the filter compensator, fast QD, and FIR filter to improve the robustness and accuracy of the PLL performance under fundamental frequency variations. The proposed PLL system shows lower detection fluctuation and faster transient response than the conventional techniques. Finally, the proposed *CLLC* resonant converter can operate under the ZVS for the primary switches and the soft commutation for the output rectifiers. The soft-switching condition of the converter is derived to obtain the design methodology of the resonant network. Gain properties are also analyzed to avoid gain reduction and non monotonic gain curve under high-load conditions. In addition, 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

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