Abstract

In recent years, a system that makes use of various types of energy has been sought after and the distributed generation system that uses alternative energy such as vehicle power sources like the uninterrupted power system and hybrid electrical vehicles, fuel cells, solar cells and etc. are being studied actively. In these systems, for the greatest efficiency, the control of the charging and discharging systems to give and take energy between the DC bus and storage equipment’s and the dual voltage system require voltage step-up since the load increase in independent power source systems are essential. Therefore, bidirectional DC/DC converters are required to enable the give and take of energy between the different dc sources and to allow for control using efficient modulation scheme. Due to the limitations of energy sources of these systems, the conversion efficiency is very important. Generally, as a bi-directional coupled Buck-Boost DC/DC converter, in the isolated mode does not reverse the polarity and the current although the switch and diode is smaller than that of other converters. As such the conduction loss is small and the efficiency is high and utilization of SVPWM achieves low switching loss and more flexible to control. But the converter has the problems of current and voltage pulsation at input and output, which is like the shortage of the Buck and Boost converter. A high-efficiency isolated bidirectional AC-DC converter for a 380-V dc power distribution system to control bidirectional power flows and to improve its power conversion efficiency is proposed in this work. The dynamic analysis is evaluated by using Matlab/Simulink tool and simulation results are conferred.

1 Introduction

The single phase AC/DC PWM converter is widely used in many applications such as adjustable speed drives, switch mode power supplies, and uninterrupted power supplies. Recently, due to the development of renewable resources, the single phase ac/dc PWM converters are usually employed as utility interface in the grid-tied system. The energy from DC Bus can be easily transferred to the AC grid when distribution energy resources (DERs) have enough power. On the other hand, when the power of DERs does not have enough energy to provide electricity to the load in the DC Bus, the bidirectional AC/DC converters can simultaneously and quickly change the power flow direction
form AC grid to DC grid and give enough power to DC load and energy storage system [1]-[5]. Therefore, there are many advantages in the AC/DC PWM converter involving unity power factor, low distortion line currents, high quality dc output voltage with a small size filter capacitor and bi-directional power flow capability. Moreover, it is also suitable for modular system design and system reconfiguration. In this report, a novel PWM control strategy with feed-forward control scheme of a bidirectional single phase AC/DC converter [6],[7].

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 Figure1. 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 [8].

![Figure 1. 380-V dc distribution system with an isolated bidirectional AC-DC converter.](image)

It usually consists of a non isolated bidirectional AC-DC rectifier [9] for grid-connected operation and an isolated bidirectional dc–dc converter to interface dc bus and dc link of the rectifier [10]–[12]. 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, in that using space vector modulation scheme. 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 antiparallel diode causes high reverse recovery current and turn-on switching noise [13]. 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 and send to vector. Therefore, a
simpler, faster, and more intuitive frequency detection method should be upgraded for improving the performance of the single-phase bidirectional rectifier. Some isolated full-bridge bidirectional dc–dc converter topologies have been presented in recent years.

A boost full bridge zero-voltage switching (ZVS) PWM dc–dc converter was developed for bidirectional high-power applications. However, it needs extra snubber circuits to suppress the voltage stress of the switches. A bidirectional phase-shift full-bridge converter was proposed with high-frequency galvanic isolation for energy storage systems [9], [10]. This converter can improve power conversion efficiency using a zero-voltage transition feature; however, it requires input voltage variations to regulate constant output voltage because this topology can only achieve the step-down operation. A bidirectional full-bridge LLC resonant converter was introduced for a UPS system without any snubber circuits [17]. 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 silicon carbide (SiC) diodes. 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. Simulation results will verify the performance of the proposed methods using a space vector modulation scheme.

2. Proposed Isolated Bi-Directional AC-DC Converter

Figure 2 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 LLC resonant converter for galvanic isolation. 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) [14],[15]. 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
The proposed bidirectional rectifier and advanced PLL method will be discussed. The proposed bidirectional full-bridge LLC 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 $T_r$ is modeled with the magnetizing inductance $L_m$ 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 $L_{r1}$ and $L_{r2}$, respectively. The resonant capacitors $C_{r1}$ and $C_{r2}$ make automatic flux balancing and high resonant frequency with $L_{r1}$ and $L_{r2}$. The detailed analysis and design guides of the proposed converter will be discussed.

Figure 3 Operating modes of the proposed bidirectional AC-DC rectifier in the rectification mode: (a) Mode1, (b) Mode2, (c) Mode3, (d) Mode4, and (e) Mode5.

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. 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 3.4. At time $t_0$, the low-side switch $S_2$ turns ON. At this time, if
$D_{S1}$ is FRD, $D_{S1}$ 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.

![Figure 4 Theoretical operating waveforms of the proposed bidirectional AC-DC rectifier in the rectification mode.](image)

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 Figure 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 Mode2. 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.
The operation mode of the inverted switching pattern is shown in Figure 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 $D_{S3}$. Using this switching pattern in the generation mode, there are no benefits of the ZVS operation.

![Diagrams of the AC-DC bidirectional converter](image)

Figure 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. Switching and conduction losses.

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. In the unipolar switching method, the turn-on period of low side 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:

$$I_{\text{rms,low}} = \sqrt{\frac{1}{2\pi} \int_0^{\frac{3\pi}{2}} (I_{\text{in,\text{P}}} \sin \omega t)^2 d\omega t}. \quad (1)$$

Through the aforementioned assumptions, the peak current $I_{\text{in,P}}$ and the average current $I_{\text{in,av}}$ 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 calculated as follows:

\[ P_{\text{con-rec}} \approx 2(I_{\text{rms,low}})^2 R_{\text{DS.on}} + 2 \left( \frac{1}{4} I_{\text{in,av}} \right) V_F \]

\[ = \frac{3}{4} I_{\text{in,p}}^2 R_{\text{DS.on}} + \frac{1}{\pi} I_{\text{in,p}} V_F \]  

(4)

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. The low-side switches use MOSFETs, which have extremely low \( R_{\text{DS.on}} \) and the latest IGBTs, which have the very low collector–emitter threshold voltage \( V_{\text{CE}} \). The high-side switches use SiC diodes as the antiparallel diode and IGBTs without antiparallel diode. The typical values of \( R_{\text{DS.on}} \), \( V_F \), and \( V_{\text{CE}} \) are obtained from their datasheets. Since \( V_F \) and \( V_{\text{CE}} \) 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 mode. Under the light-load condition, MOSFETs is better than IGBTs in the view point of the power conversion efficiency [18].

3. SRF PLL With Enhanced Frequency Estimator

For the application of the grid-interactive power converters, the phase estimation of the supply voltage is required to control the entire power system; especially, the phase information of the supply voltage is mandatory to generate the current reference. The phase estimation method requires robustness to noise and disturbance from grid, accuracy to the fundamental frequency variation and harmonic distortion, and easy implementation using analog or digital platforms. The SRF-PLL is one of the popular methods. It has a weak point of a frequency tracking performance. In Figure 7, the constant angular frequency of the fundamental component \( \omega_s \) is used as a feed forward term for compensating the phase angle tracking.

**Figure 7:** Block diagram of a conventional single-phase SRF-PLL.

It can cause a tracking error in the PLL operation when the fundamental frequency changes to the different value of the constant \( \omega_s \). To track unexpected fundamental frequencies, the SRF-PLL requires a frequency estimator instead of the constant angular frequency. The SRF-PLL method uses the \( \pi/2 \) phase-shifted wave of the supply voltage using the all-pass filter (APF). Therefore, the PLL has four zero crossing points in a period of the supply voltage and they are located at every 0.5\( \pi \). It means that the frequency information can be obtained at every quarter of the period. However, the conventional research has updated the frequency information at every half of the period. Space-vector pulse-with-modulation (SVPWM) is another technique of driving a voltage source three-phase H-bridge inverter, for generating voltage waveforms that are devoid of low-frequency harmonic content.
The principle of an SVPWAM control is to eliminate the zero vectors in each sector. The modulation principle of SVPWAM is shown in Figure 8. In each sector, only one phase leg is doing PWM switching; thus, the switching frequency is reduced by two-third. This imposes zero switching for one phase leg in the adjacent two sectors. For example, in sector VI and I, phase leg A has no switching at all. The dc-link voltage thus is directly generated from the output line-to-line voltage [13].

In sector I, no zero vectors are selected. Therefore, $S_1$ and $S_2$ keep constant ON, and $S_3$ and $S_6$ are doing PWM switching. As a result, if the output voltage is kept at the normal three-phase sinusoidal voltage, the dc-link voltage should be equal to line-to-line voltage $V_{ac}$ at this time [14]. Consequently, the dc-link voltage should present a $6\omega$ varied feature to maintain a desired output voltage.

4. Matlab/Simulink Modeling And Results

Here simulation is carried out in several cases, in that 1). Proposed Bi-directional AC-DC Converter Operating under the PLL Estimation Theory, 2). Proposed Bi-directional AC-DC Converter Operating under the Space Vector Modulation Scheme.

Case A: Proposed Bi-directional AC-DC Converter Operating under the PLL Estimation Theory

Figure 9 shows the Matlab/Simulink Model of Proposed Bi-directional Converter with SRF-PLL Estimation Scheme with the help of Matlab/Simulink Software Package.
Figure 10 Simulation Results of full load (5 kW) resonant currents with output voltage in the dc–dc converter.

Figure 10 Simulation Results of full load (5 kW) resonant currents with output voltage in the dc–dc converter, in that VQ1 represents the Q1 across drain to source voltage, transformer primary current, transformer secondary current due to the perfect estimation of PLL gets good steady state response, low transient response with low peak overshoots, operated under good stability factor.

Figure 11 Simulation Results of full load (5 kW), (a) Source Side Power Factor (b) Output

Figure 11 shows the simulation results of full load (5 kW), (a) Source Side Power Factor (b) Output of the Proposed Bi-directional Converter with SRF-PLL Estimation Scheme, due to the small range of
DC filter no affect on source side parameters, or else attain many distortions in grid current and output voltage also maintained as constant with good steady state response.

![Simulation waveforms of the bidirectional operation at full load operating under rectification mode](image1.png)

Figure 12: Simulation waveforms of the bidirectional operation at full load operating under rectification mode

Figure 12 Simulation waveforms of the bidirectional operation at full load operating under rectification mode, the proposed AC-DC rectifier operates in the rectification mode with the grid synchronization operation to convert ac-grid power to dc bus under the full-load condition.

![Simulation waveforms of the bidirectional operation at full load operating under generation mode](image2.png)

Figure 13: Simulation waveforms of the bidirectional operation at full load operating under generation mode

Figure 13 Simulation waveforms of the bidirectional operation at full load operating under generation mode, shows the generation mode to send surplus power from the dc bus to the ac grid. From these results, the bidirectional operation of the proposed rectifier in both the rectification mode and the generation mode is verified.
Figure 14: Switching waveforms of the AC-DC rectifier using SiC diode

Figure 14 shows the switching waveforms of the AC-DC rectifier using SiC diode, shows the switching waveforms of the AC-DC rectifier using SiC diode, respectively. Since the SiC diode which has very small reverse recovery charge replaces the FRD diode. The low reverse recovery current can increase the power conversion efficiency of the AC-DC rectifier and reduce heat emission from rectifying diodes and switching MOSFETs in the rectifier.

Figure 15 Simulation results of phase detection performance by using proposed PLL.

Figure 15 shows the simulation results of phase detection performance by using proposed PLL, shows the phase detection performance using the proposed SRF-PLL method. The phase detector of the proposed PLL can follow the step-changed phase angle within two fundamental periods. It verifies that the proposed PLL has good performance of the phase angle tracking.
Figure 16: Step load response (bidirectional power conversion from 2.5 to −2.5 kW) of overall bidirectional converter with the AC-DC rectifier part.

Figure 16 shows the step load response (bidirectional power conversion from 2.5 to −2.5 kW) of overall bidirectional converter with the AC-DC rectifier part. When a bidirectional step load changes from 2.5 to −2.5 kW, the ac input current smoothly changed its phase angle within two cycles using the proposed SRF-PLL.

Figure 17: THD response of Primary Current & Secondary Current of Proposed Bi-Directional AC-DC Rectifier

Figure 17 shows the THD response of Primary Current & Secondary Current of Proposed Bi-Directional AC-DC Rectifier; attain 27.32% and 19.08%.
Case 2: Proposed Bi-directional AC-DC Converter Operating under the Space Vector Modulation Scheme

Figure 18 shows the Matlab/Simulink Control Circuit of Proposed Bi-directional Converter under Space Vector Modulation Scheme with the help of Matlab/Simulink Software Package.

Figure 19: Simulation Results of full load (5 kW) resonant currents with output voltage in the dc–dc converter operating under SVPWM.

Figure 19 Simulation Results of full load (5 kW) resonant currents with output voltage in the dc–dc converter operating under SVPWM scheme, in that VQ1 represents the Q1 across drain to source.
voltage, transformer primary current, transformer secondary current due to the SVPWM gets good sinusoidal response, low ripples compared to conventional methodology.

Figure 20 shows the THD response of Primary Current & Secondary Current of Proposed Bi-Directional AC-DC Rectifier under SVPWM scheme; attain 6.29% and 9.05%.

5. Conclusion
Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage with lower total harmonic distortion. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. 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 converter employ IGBTs without antiparallel diodes and SiC diodes. The simple and intuitive frequency detection method for the single-phase SRF-PLL and SVPWM scheme is also proposed using the filter compensator, to improve the robustness and accuracy of the PLL performance under fundamental frequency variations. The proposed SVPWM system shows lower detection fluctuation and faster transient response than the conventional techniques. Simulation results are conferred based on the pertaining models and achieves good stability factor with low steady state error values.

6. References

Biographies

**Mr. N. Sudheer** is currently pursuing as M.Tech in power electronics & electric drives at Anurag Engineering College, Kodad, Nalgonda (Dt), Telangana, India. His areas of interests are Power Electronics, Power Converters, and Electrical Machines.

**Mr. MUDUSU.SRINU** graduated in EEE from JNT University Hyderabad in 2006. He received M.Tech degree in the stream of Power and Industrial Drives in JNT University Kakinada in 2011, presently working as Assistant Professor in Anurag Engineering College. His areas of interests are Power Electronics, Power Converters, and Electrical Machines.