A Bidirectional Power Converter for AC Grid and DC Bus

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Abstract

This paper presents the development of a bidirectional converter for AC grid and DC bus. The converter adopts a full-bridge structure and utilizes average current control and sine pulse width modulation techniques for power factor correction and inverter design. The system's control core is based on a control chip, combined with control technology. By sensing the input and output voltages, the pulse mdulation period is calculated to enhance the compensation speed of the overall control loop. This enables the converter to exhibit high power factor and stable output voltage capabilities, while functioning as an inverter with enhanced system reliability in the reverse mode, achieving the objective of bidirectional electrical energy transmission. Finally, a maximum rated output of 1 kW experimental platform was constructed to emulate AC grid of 220 V and a DC bus of 400 V, thereby validating the theoretical analysis and design methods proposed in this paper. The experimental results showed that with an AC grid voltage of 220 V, the efficiency reached a maximum of 97.09%. In the reverse mode, the efficiency reached a maximum of 96.98%. Through the converter, energy was fed back to the AC grid, achieving the objective of bidirectional energy scheduling.

1 Introduction

As the sales of DC appliances and electric vehicles continue to climb year by year, it will lead to a gradual increase in electricity demand. If proper energy management is not implemented in the future, it may result in an inadequate power supply, potentially impacting the operation of the AC electrical grid. To achieve higher conversion efficiency and more efficient energy utilization, numerous scholars are currently delving into research on DC grid systems [1]-[2], indicating that DC grids are poised to be the future development trend.

Moreover, the threat of extreme weather to the electrical grid is inevitable. Therefore, the optimal solution should involve fully leveraging energy dispatch systems to enhance the overall resilience of the electrical grid. Consequently, in future power systems, energy dispatch technology bridging the gap between AC and DC grids will be a critical component. Thus, this paper aims to implement a bidirectional converter between the AC grid and the DC bus, as depicted in Figure 1.

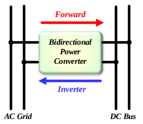


Figure 1 Bidirectional Converter Between AC Grid and DC Bus

Literature [3]-[6] introduces bidirectional AC/DC converters, all of which adopt a two-stage architecture. In [3], the front-end converter employs a full-bridge power factor correction circuit, combined with a rear-stage full-bridge resonant DC-to-DC converter, achieving the functionality of high-voltage boosting and bucking for bidirectional AC/DC energy conversion. Through parallel connection, it effectively reduces current stress on various circuit components, enhancing the converter's rated power. While this architecture provides bidirectional AC/DC energy conversion and electrical isolation, it still has drawbacks, such as a higher count of power components, complex feedback control methods, and a large overall converter volume. The converter in [4] is similar to [3], differing mainly in the lower number of power components and, consequently, lower output power. In [6], the AC/DC converter controls DC-to-DC conversion using phase shift control and DC-to-AC using sinusoidal pulse width modulation. This structure utilizes two sets of AC/DC converters and is suitable for higher-power applications, significantly reducing the AC-side filter inductance and resulting in a smaller size. In terms of feedback control, [3]-[6] all employ inductor current control with power factor correction at the front end. The rear stage also requires control of multiple switching components, making the control aspect complex. Additionally, the efficiency of a two-stage converter architecture is the product of the front-end efficiency and the rear-stage efficiency, resulting in lower overall efficiency compared to a single-stage architecture.

In [7], traditional two-stage bidirectional AC/DC converters are modified, allowing bidirectional energy transfer between AC and DC solely through a Grid-Tied converter. While the converter's architecture is straightforward and can handle a wide range of input voltage variations, it is suitable only for lower-wattage applications. [8] proposes a three-phase isolated AC/DC converter that uses an LCL filter and six switches for switching, offering advantages such as low output voltage ripple and electrical isolation. However, it requires more magnetic components and power switches, resulting in a larger circuit volume and higher power losses.

This paper integrates power factor correction technology with sinusoidal pulse width modulation control to address the complexity of the previously mentioned circuit architectures, the inability to bi-directionally transfer energy, complex control methods, and issues with the two-stage architecture. It achieves the development of a bidirectional converter between the AC grid and the DC bus.

2. Circuit Architecture and Controller Design

2.1 Circuit Architecture

Figure 2 illustrates the complete architecture of the bidirectional converter between the AC grid and the DC bus proposed in this paper. The hardware circuit primarily consists of (1) power factor correction inductors, (2) output voltage stabilization capacitors, (3) power switches, (4) gate drivers, (5) relays, (6) voltage sensors, (7) current sensors, and (8) a microcontroller controller, providing bidirectional energy transfer between the AC grid and the DC bus.

For the bidirectional converter between the AC grid and the DC bus, in the forward mode, it should provide stable DC output voltage, lower total harmonic distortion, improved power factor, and higher conversion efficiency. In the reverse mode, it should be capable of feeding excess energy from the DC bus back to the AC grid and output a voltage that is synchronized with the frequency and phase of the AC grid.

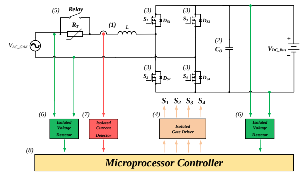


Figure 2 Architecture of the Bidirectional Converter Between AC Grid and DC Bus

2.2 Feedback Control Method

In order to achieve advantages such as higher rated power, higher conversion efficiency, and a smaller circuit volume for the converter in this paper, the average current control method in continuous conduction mode will be used as the design foundation. Figure 3 illustrates the feedback block diagram of the average current control method.

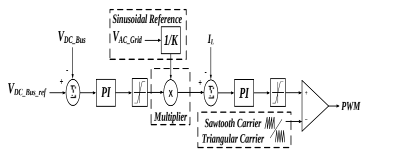


Figure 3 Feedback Block Diagram of Average Current Control Method

The control method operates at a fixed frequency and, after comparing the output voltage with a reference value, the resulting error signal is multiplied by a multiplier to generate an average current reference signal. This reference signal is then used in conjunction with the inductor current for current loop compensation. After comparing it with a triangular/saw tooth carrier signal, a duty cycle signal is obtained, which changes with variations in the input voltage, to control the energy on the inductor, ensuring that the inductor current tracks the average current, as shown in Figure 4.

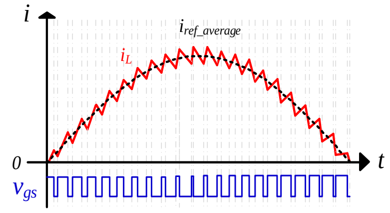


Figure 4: Inductor Current Waveform in Average Current Control Method

2.3 Sine Wave Pulse Width Modulation Design

Sine Wave Pulse Width Modulation (SPWM) is a modulation technique based on pulse width modulation. It involves comparing a sine wave signal with a triangular carrier or saw tooth carrier signal. As a result, the duty cycle of the pulses is determined by the sine wave. When the sine wave has a higher magnitude, the pulse width modulation has a higher duty cycle, and conversely, when the sine wave has a lower magnitude, the duty cycle decreases. This method significantly reduces high-order harmonic components in the current, effectively reducing total harmonic distortion. Therefore, the bipolar sinusoidal pulse width modulation is chosen as the switching signal modulation method for the bidirectional converter. Figure 5 shows the switching state waveform.

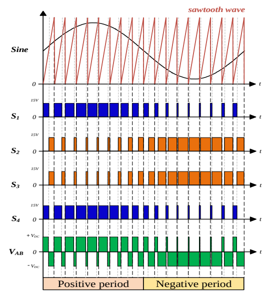


Figure 5 Bipolar Switching State Waveforms

3 Results

This paper designs and simulates a 1 kW bidirectional converter between the AC grid and the DC bus, taking into account relevant specifications for the AC grid system and the DC bus, as well as market demands for electricity consumption in AC grid and DC bus systems. The circuit specifications are shown in Table 1.

Table 1 Electrical Specifications of the Converter

Parameters	Specifications
Rated Voltage at the AC Grid Side	AC 220 V
Rated Current at the AC Grid Side	AC 5 A
Power Frequency at the AC Grid Side	60 Hz
Rated Voltage at the DC Bus	DC 400 V
Rated Maximum Conversion Power	1000 W
Circuit Switching Frequency	80 kHz

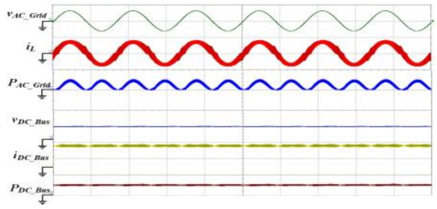
Table 2 presents the selected actual circuit component parameters for this converter. In order to improve the efficiency of the converter, this paper uses new wide-bandgap switches instead of traditional silicon switches. These switches have lower switching losses at high frequencies, which can enhance the circuit's conversion efficiency.

Table 2 Selection of Circuit Component Parameters

Component Parameter	Values
Power Factor Correction Inductor	473.5μH
DC-Side Stabilization Capacitor	1299μF
DC-Side Filtering Capacitor	0.68μF
Thermistor	20Ω
Power Switch	UF3C065080K4S (SiC)

3.1 Steady-State Implementation Waveforms in Forward Mode

The practical circuit waveforms of AC voltage, current, DC voltage, and current under different loads with an AC voltage of 220 V are shown in Figure 6. The waveforms demonstrate that the circuit operates in the forward energy storage mode, and it achieves power factor correction under different loads.

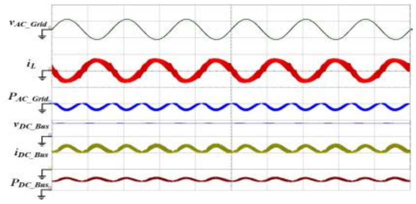


v_{AC_Grid} : 500V/div i_L : 10A/div
P_{AC_Grid} : 5kW/div v_{DC_Bus} : 500V/div
i_{DC_Bus} : 2A/div P_{DC_Bus} : 2kW/div time : 10ms/div
$V_{AC\_Grid} = 220V$, $V_{DC\_Bus} = 400V$, $i_{DC\_Bus} = 2.5A$

Figure 6 Experimental Waveforms in Forward Mode at 220 V

3.2 Steady-State Implementation Waveforms in Inverter Mode

Figure 7 displays the practical circuit waveforms during 1 kW grid feedback in the inverter mode. The waveforms illustrate that the converter maintains stable operation in the inverter mode and can feed back power to the AC grid port at different power levels. To verify maximum power feedback to the grid, this paper uses a fixed inductor current probe measurement direction and implements inversion at V_{AC_Grid} =220 V.



v_{AC_Grid} : 500V/div i_L : 10A/div
P_{AC_Grid} : 5kW/div v_{DC_Bus} : 500V/div
i_{DC_Bus} : 2A/div P_{DC_Bus} : 2kW/div time : 10ms/div
$V_{AC\_Grid} = 220V$, $V_{DC\_Bus} = 400V$, $P_{DC\_Bus} = 1000W$

Figure 7 Experimental Waveforms in Inverter Mode at 220 V

3.3 Experimental Data for the Bidirectional Converter

Figure 8 shows the efficiency curve of the converter operating in forward mode, with the AC grid V_{AC_Grid} fixed at 220 V and the DC bus V_{AC_Grid} fixed at 400 V, while varying the DC bus load current from light load to full load. From the curve, it can be observed that efficiency improves with increasing wattage, with the highest conversion efficiency being 97.07% near full load at 220 V.

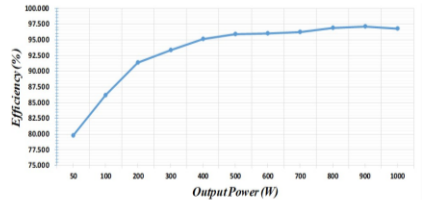


Figure 8 Efficiency Curve in Forward Mode at 220 V

Figure 9 illustrates the efficiency curve of the converter operating in the inverter mode at 220 V. The AC grid port V_{AC_Grid} is fixed at 220 V, and the DC bus V_{DC_Bus} is set at 400 V, while varying the feedback power from the DC bus to the grid, ranging from light load to full load. From the curve, it can be observed that efficiency improves with increasing wattage, with the highest conversion efficiency being 96.98% near full load at 220 V.

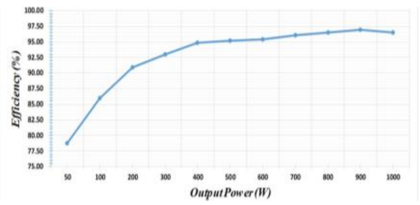


Figure 9 Efficiency Curve in Inverter Mode at 220 V

Through actual circuit measurements, power factor (PF) curves and total harmonic distortion (THD) curves for the bidirectional converter operating in forward and inverter modes can be obtained, as shown in Figures 10 and 11. It can be observed that except for extremely light loads, the PF values are all above 0.9, and the THD values are all below 0.3.

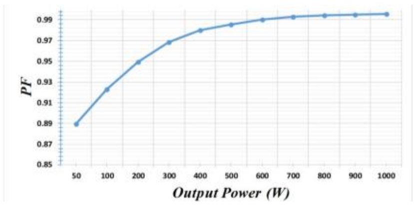


Figure 10 Power Factor (PF) Curve of the Bidirectional Converter Between AC Grid and DC Bus

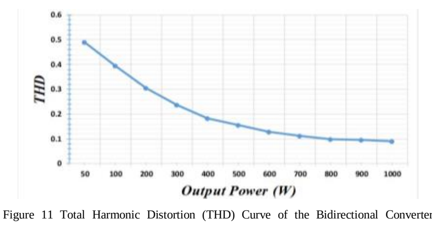


Figure 11 Total Harmonic Distortion (THD) Curve of the Bidirectional Converter Between AC Grid and DC Bus

4 Conclusion

This paper presents a bidirectional converter between the AC grid and the DC bus, designed and realized using digital signal processing. The converter achieves a rated power of 1 kW for both the AC grid and the DC bus. The circuit architecture primarily consists of a full-bridge converter, and the system utilizes average current control and sinusoidal pulse width modulation (SPWM) techniques for bidirectional energy transfer control. To enhance the stability and reliability of the system, this paper combines control techniques. It employs digital signal sensing of input and output voltages and calculates pulse width modulation periods, addressing the issue of slow compensation in traditional control loops. This design enables the converter to operate in forward mode with a high power factor and stable output voltage. Additionally, in inverter mode, it functions as an inverter to achieve bidirectional energy transfer.