Power Bidirectional Flow Converter Based on Linear Phase Shift Transformer

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Abstract. This article points out that the bidirectional power converter based on a linear phase-shifting transformer can be modularized, designed to improve equipment utilization. The analysis of the working status of the bidirectional power flow converter under inverter and rectifier conditions is introduced. The working conditions of the converter in the inverter and rectification state are simulated, and the output voltage and harmonics are analysed. The simulation results show that the system can meet the output index requirements under both inverter and rectification conditions, can be modularized, can reduce the number of components used in the device, and provide strong support for the optimization of subsequent prototypes.

Keywords: Multiple superposition inverting, linear phase shift transformer, bi-directional power flow.

1. Introduction

As an important part of micro grid and uninterruptible power supply, the power bi-directional flow converter mainly realizes the following functions: when the external power grid is in normal operation, the external power grid will charge the battery; When the external power grid is out, the load is supplied by the battery [1]. Generally, the power conversion between the external power grid and the battery and the load needs rectification, inverter or frequency conversion. These functions are realized by two-way power flow converter [2].

The power bidirectional flow converter can be used for both rectification and inversion. As the core part of the microgrid, the research on AC/DC power bidirectional flow converter is increasingly deep. From the end of the 20th century. The power bidirectional flow converter has become a key research object in this field. After more than 20 years of development, the power bidirectional flow converter technology has become more and more mature [3]. With the development of more and more types of power bidirectional flow conversion devices, the power of the conversion devices is also increasing, the efficiency is getting higher and higher, and the applications are becoming more and more extensive. At present, the research of power bidirectional flow conversion device is mainly designed with power electronic devices as the core [4]. The research focuses on the design and optimization of the conversion circuit, as well as the improvement of control methods in order to achieve the improvement of power quality when power flows. The traditional two-way power flow conversion device separates the rectifier and inverter devices. As shown in Figure 1, the disadvantage of this structure is that it occupies a large volume, low device utilization, and requires additional electrical isolation devices [5].
Aiming at the shortcomings of the existing power two-way flow device, this paper uses a new type of linear phase-shifting transformer [6] to design a power two-way flow device that is conducive to modularization and improves the utilization rate of the device. Taking the power bidirectional flow converter as the object, the basic principle of the linear phase-shifting transformer is explained, and the mathematical model and working status of the converter are analyzed with a single module as an example. At the same time, simulation is used to verify the bidirectional power converter based on linear phase-shifting transformer designed in this paper, and verify the effectiveness of the device designed in this paper to reduce harmonic content and improve power supply reliability.

2. Structure and Basic Principles of a Power Bidirectional Flow Converter based on a Linear Phase-shifting Transformer

In the converter circuit part of the power bidirectional flow conversion device based on the linear phase-shifting transformer designed in this paper, the inverter and the rectifier are the same device. This design can reduce the volume and the number of components of the conversion device and improve the utilization of the device rate, the system structure is shown in Figure 2. When the grid charges the battery, the conversion device works in the rectification state; when the battery supplies power to the load, the conversion device works in the inverter state. The technical index to be achieved is to realize the output
voltage ripple coefficient of rectifier mode is less than 5%, and the output voltage harmonic component of inverter mode is less than 5% without external voltage stabilizing and filtering device.

Under inverter conditions, the output voltage waveform is controlled by controlling the pulse signals of 24 IGBT switch tubes to achieve phase-shift superimposed harmonic elimination [9]. The output voltage waveform superposition principle is shown in Figure 3. The phase voltage output by the three-phase inverter circuit is a six-step wave [10].

The power bidirectional converter can realize rectification if the power supply side and load side in Figure 3 are swapped. The power bidirectional converter is multi-pulse rectification. When the rectification works, the three coils on the primary side input three-phase alternating current, and the twelve coils on the secondary side induce 12-phase alternating current, which is then connected to the corresponding bridge circuit and rectified output. Direct current. Increase the number of pulses on the DC side by increasing the number of phases, reducing the fluctuation of the DC side current and making the waveform closer to a sine wave. When the control signal is set to turn off, the circuit is equivalent to twelve-pulse uncontrolled rectification, as shown in Figure 4. Controlling the switch tube signal can control the output DC voltage [11].

\[
\begin{align*}
V_{sa} &= \sqrt{2} V_s \sin \omega t \\
V_{sb} &= \sqrt{2} V_s \sin(\omega t - 120^\circ) \\
V_{sc} &= \sqrt{2} V_s \sin(\omega t + 120^\circ)
\end{align*}
\]

Where \( V_s \) is the effective value of the phase voltage of the AC power supply. Then there are:
Where $I_s$ is the effective value of the current flowing into the bidirectional converter from the AC power source, and $\phi$ is the power factor angle of $\dot{I}_s\text{lag}\dot{V}_s$.

Then the phase voltage on the AC side is:

\[
\begin{align*}
    V_a(t) &= \sqrt{2}V_s\sin(\alpha t - \phi) \\
    V_b(t) &= \sqrt{2}V_s\sin(\alpha t - 120^\circ - \phi) \\
    V_c(t) &= \sqrt{2}V_s\sin(\alpha t + 120^\circ - \phi)
\end{align*}
\] (3)

Where $V_s$ is the effective value of the phase voltage at the AC input of the three-phase bridge, and $\delta$ is the phase lag angle of $\dot{V}_s$ lagging $\dot{V}_s$. As shown in Figure 5.

**Figure 4.** Single-module bidirectional converter.
The voltage and current vector relationship is:

\[ V_s = V_i + jX_i \]  

(4)

The voltage vector \( \dot{V}_i \) at the AC input of the converter. The d-axis \( V_{id} \) and the q-axis component \( V_{iq} \) are:

\[ V_{id} = V_i \cos \delta = OF = OH - FH = V_s - XI_q \]  

(5)

\[ V_{iq} = V_i \sin \delta = FE = XI_d \]  

(6)

Reactive current:

\[ I_q = \frac{V_s - V_{id}}{X} = \frac{(V_s - V_i \cos \delta)}{X} = I_s \sin \varphi \]  

(7)

Then the active current is based on the triangle rule:

\[ I_d = \frac{V_{iq}}{X} = \frac{V_i \sin \delta}{X} = I_s \cos \varphi \]  

(8)

\[ \dot{I}_s = I_d - jI_q \]  

(9)

Then the conjugate vector is:

\[ \dot{I}_s^* = I_d + jI_q \]  

(10)

From this, the complex power \( \dot{S} \) of the converter can be obtained:
In summary, the active and reactive power input from the AC grid to the converter by the converter is:

\[
\dot{S} = P + jQ = 3V_s \cdot \dot{I}_s = 3V_s I_d + 3V_s jI_q \tag{11}
\]

\[
P = 3V_s I_d = 3V_s I_s \cos \phi = 3V_s \frac{V_{sd}}{X} = 3V_s \frac{V_s \sin \delta}{X} \\
Q = 3V_s I_q = 3V_s \left( \frac{V_s - V_s \cos \delta}{X} \right) = 3V_s I_s \sin \phi \tag{12}
\]

When the value of voltage \( V_s \) is large, and \( V_s \cos \delta \) is greater than \( V_i \), then \( I_q \) is negative and \( Q \) is negative. At this time, the AC terminal inputs advanced reactive current, reactive power, or AC to the converter [12]. Terminal inputs lagging reactive current and reactive power from the converter. If \( V_i \) is smaller and \( V_s \cos \delta \) is smaller than \( V_s \), the situation is reversed.

When the voltage phase \( \dot{V}_i \) lags behind \( \dot{V}_s \) at the AC input of the converter, that is, when the phase lag angle \( \delta \) is positive, the active current \( I_d \) in formula (12) is positive, and the active power \( P \) is positive, indicating that the AC The end-to-end converter outputs active power. After the conversion circuit, it outputs DC power to the DC end load. The converter works in the rectification state; on the contrary, when \( \dot{V}_i \) leads \( \dot{V}_s \), the active power \( P \) is negative, which means AC The terminal inputs active power from the converter, and the converter inverts the DC power into AC power and feeds it back to the AC terminal, and the converter works in the inverter state [13].

**4. Simulation analysis verification**

The mathematical model is established in MATLAB. The conversion circuit is a three-phase bridge circuit, the transformer is written by s-function, and the load is a symmetrical three-phase load. It works under fundamental frequency conditions and under inverter conditions, the input DC power supply is 100V. Under rectification conditions, the input three-phase power supply amplitude is 200V.

The no-load output voltage waveform [14] is shown in Figure 6. The voltage waveform is approximately a 24-step wave. The conduction angle is 180 degrees.

![No-load voltage waveform](image)

**Figure 6. No-load voltage waveform**

At rated load, the inverter output voltage waveform is basically a sine wave.
In rectification mode, the rectified output voltage waveform is 12-pulse uncontrolled rectification [15].

5. Conclusion
After simulation verification, the bidirectional power flow device of this design can achieve both rectification and inverter. This design can integrate the rectifier and inverter to form a bidirectional AC/DC converter, reducing the number of modules and improving the power factor of the system, and reduce harmonic pollution [16]. Without the addition of an external voltage regulator and filter device, the output voltage ripple coefficient of the rectifier working condition can be less than 5%, and the output voltage harmonic component of the inverter working condition is less than 5%, which meets the design requirements and provides a powerful force for the next engineering application support.

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