Harmonic analysis of AC drive double PWM back to back network side

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Abstract. Aiming at the problem of harmonic pollution in the control system of large-scale steel rolling equipment in metallurgical plant, the mechanism of harmonic generation in AC-AC frequency conversion and AC-DC-AC variable-frequency speed regulation system is analyzed, and a double PWM back-to-back AC speed regulation system is proposed. This system can not only realize the regeneration energy of frequency converter, but also reduce the harmonic wave, and greatly improve the power factor of the system. Finally, through MATLAB simulation, the harmonic of AC-AC frequency conversion and AC-DC-AC variable-frequency speed regulation system is analyzed, and compared with PWM back-to-back AC speed regulation system, the superiority, effectiveness and feasibility of PWM back-to-back AC speed regulation system design for large-scale AC drive device control are proved.

1. Introduction

New energy development, power quality management and green energy environmental protection technology are of great significance to the rapid development of modern national economy. The wide use of modern power electronic devices provides a broad development space for industrial production process control and energy conversion. The converter of AC / DC speed regulation system occupies an important position. At the same time, the widespread use of these converters also brings harmonic damage to the power supply system [1-5]. In the hot rolling system of metallurgical industry, the main drive is generally controlled by AC-AC frequency conversion, and the auxiliary drive is controlled by AC-AC frequency conversion. Auxiliary drive mostly adopts AC-DC-AC frequency conversion speed regulation control, and these control systems have obvious energy-saving effect, but the harmonic problems generated by these control systems will directly affect the quality of rolling products and other equipment incorporated into the power grid [6]. In reference [1], a multi group inverter phase-shifting combined power supply method is proposed for multi group auxiliary drive system of hot rolling production line, and the effectiveness of this method is proved by simulation. Reference [3] mainly studies the back-to-back dual pulse width modulation converter and establishes its mathematical model. Reference [3] designs a double closed-loop controller structure from the perspective of realizing multiple control functions. A grid connected control method of flywheel energy storage system is proposed in reference [4]. In this method, a back-to-back Dual PWM converter with LCL filter is used as the interface between motor and power grid. The pre grid connection, grid connection and charging of flywheel energy storage system are tested. A design method of main circuit parameters of back-to-back converter is proposed in reference [5]. This method meets the overall requirements of three-phase asynchronous motor variable-frequency speed regulation system.

In the AC-DC-AC variable-frequency speed regulation system, the double PWM back-to-back AC speed regulation system has great advantages in improving power factor [7]. The harmonic generated by the system has little impact on the power grid. However, due to its higher cost than other AC-DC-
AC variable-frequency speed regulation system, it has not been widely used. However, with the development and update of controllable power electronic devices, it will be widely used in industrial production [8-13]. In this paper, we mainly use MATLAB software to analyze it, and give the specific analysis structure diagram.

2. AC-AC frequency control system

The AC-DC drive system is very complex in the AC-DC drive system, so the AC-DC drive system is very complex Frequency conversion rectifier device, not only has high-order harmonic current component, but also has low-order harmonic current component. The frequency of low-order harmonic current will even be lower than the frequency of power supply network, and the system may produce DC current component. The smaller the trigger angle is, the higher the phase-shifting voltage is. Within the allowable range of the system, the trigger angle decreases with the increase of the phase-shifting voltage. For the rectifier circuit, the three-phase current in the power supply network is square wave, and does not change with the output voltage of the rectifier bridge, so the influence of the harmonic content on the power grid changes little.

In AC-AC frequency conversion system, if the synchronous machine load is connected, the change of harmonic content at the output side is much more complex, which will also have a great impact on the harmonic in the power grid.

In the production of iron and steel industry in China, the steel rolling process involves many fields such as hydraulic, mechanical, electrical, material and computer control. It is a very complex process. The electrical control technology is a very important part in the steel rolling process, especially the precision control of the main drive mechanism, which greatly affects the quality of the products. The main drive mechanism is mostly driven by AC synchronous machine. AC-AC frequency conversion speed regulation and AC-DC-AC frequency conversion speed regulation system are widely used [14]. There are many factors that interfere with the control accuracy, and the harmonic of the electrical system is one of the key factors that cannot be ignored. Therefore, it is very important to detect and control the harmonic of the electrical system, so as to prevent the harmonic from harming the equipment and improve the quality of the product [15].

Because the main drive equipment of rolling mill belongs to large AC equipment, its power is also very large, so it will produce harmonics, which will not only affect the load, but also produce serious harmonic interference on the power supply side of the power grid. In practice, in order to ensure the stable operation and reliability of the system and devices, and reduce the harm of harmonics to the current and voltage of the transformer network terminal, it is necessary not only to conduct a thorough physical test on the actual control system and protection circuit, but also to conduct digital simulation. Through the software simulation, it can be approximately considered that the equipment is connected with the actual operating device, and the various operating conditions can be obtained And detailed harmonic data analysis.

When AC-AC frequency conversion is used in the main drive of hot rolling mill, the finishing mill has 6 to 7 stands, and the roller can be directly driven with the power between 5000kW and 8000kw. In practical application, there are many harmonic analysis on the grid side and the load side after AC-AC frequency conversion, but the research on the influence of the combination of multiple sets on the grid side harmonic of the transformer is relatively small, and the vibration of the drive system is generally caused by high-order harmonics, which will cause mechanical damage and fatigue of metal structures when the harmonic is serious, which makes the control accuracy of the system unable to achieve high performance requirement. Harmonics can even form electromagnetic coupling through distributed parameter systems, causing serious interference to nearby communication systems. The model calculation method is difficult to apply to this kind of analysis [16-18], and it is necessary to apply simulation technology to harmonic analysis [19].
3. Design of Dual PWM AC-DC-AC frequency control system

3.1. Design basis of multi unit data displacement method

This method is designed based on the actual 1700mm hot strip mill of a certain factory in China. The rolling direction of each stand roll is four roll irreversible. The equipment parameters of the mill are shown in Table 1. The key parameters involved in the table are work roll diameter \( \phi_d \) and gear reduction ratio \( i_k \).

**Table 1.** Parameter table of 1700mm rolling mill

| Frame number | F1    | F2    | F3    | F4    | F5    | F6    |
|--------------|-------|-------|-------|-------|-------|-------|
| Work roll diameter \( (\phi_d \text{mm}) \) | 800/710 | 800/710 | 800/710 | 700/625 | 700/625 | 700/625 |
| Diameter of support roll (mm) | 1550/1400 | 1550/1400 | 1550/1400 | 1550/1400 | 1550/1400 | 1550/1400 |
| Length of work roll body (mm) | 1700 | 2000 | 2000 | 2000 | 2000 | 2000 |
| Length of back up roll body (mm) | 1700 | 1700 | 1700 | 1700 | 1700 | 1700 |
| Main motor power (kW) | AC7000 | AC7000 | AC7000 | AC7000 | AC6000 | AC5000 |
| Main motor speed (rpm) | 180/425 | 180/425 | 180/425 | 180/425 | 140/350 | 180/425 |
| Maximum rolling force (t) | 3500 | 3500 | 3500 | 3500 | 3000 | 3000 |
| Reduction ratio \( (i_k) \) | 4.97 | 3.31 | 2.26 | 1.53 | 1.00 | 1.00 |

According to the typical process distribution, the thickness of the steel plate at the inlet is 25 mm, the thickness of the outlet steel plate is 2.5 mm, the speed of the steel plate at the outlet of the final frame is 15 m / s, and the target value of the thickness at the outlet of other racks is shown in Table 1. For such load distribution, the linear velocity at the outlet of each rack can be calculated by the formula of equal flow per second. The calculation formula is as follows:

\[
V_k = \frac{V_h}{h_k} = \frac{15}{2.5}h_k = 3.75h_k
\]  

(1)

The output frequency of each stand can be calculated by the outlet line speed of each stand, roll diameter, gear reduction ratio and the number of poles of the motor (set the pole number of synchronous machine \( p = 3 \)). The calculation formula is as follows:

\[
f_k = \frac{V_k}{\pi \phi_d} i_k p
\]

(2)

The linear velocity and output frequency of each stand outlet are shown in Table 2 (the thickness of steel plate inlet is 25 mm).

**Table 2.** Rack outlet thickness, speed and output frequency table

| Project                              | F1    | F2    | F3    | F4    | F5    | F6    |
|--------------------------------------|-------|-------|-------|-------|-------|-------|
| Thickness of steel plate \( h_s \)   | 15.0  | 10.0  | 7.0   | 5.0   | 3.5   | 2.5   |
| Linear velocity \( f_s \)            | 2.5   | 3.75  | 5.357 | 7.5   | 10.714 | 15.0 |
| Output frequency \( f_k \)           | 14.8  | 14.5  | 14.5  | 15.654 | 14.616 | 20.46 |
The distance between the frames is 6m. After calculation, the steel biting time of F1 frame is 1s, and the time to F2 rack is 2.4s. Based on this, the steel biting time of each rack can be calculated. The steel biting sequence and speed of each rack are shown in Fig. 1.

![Figure 1](image1.png)

**Figure 1.** Time sequence of frame biting steel and speed of steel plate passing through frame

The main factor that affects the harmonic distortion rate of the converter is that it is different from that of the total phase shift of the converter. Secondly, according to the process of rolling production line, for each rolling mill, the load distribution is relatively balanced, so the typical load simulation data of one rolling mill can be taken as the basis to replace the simulation data of other stands. In addition, it can be seen from the steel biting sequence diagram that the running time of the simulation will be more than 10 seconds if the data generated from the biting sequence of each rack to the steady-state operation is based on. In order to save computing equipment resources and improve the efficiency of simulation, the data generated by one load can be used to simulate the superposition of different time sequence data of other racks. In order to ensure the real-time performance of current data of each rack, the phase-shifting angle of transformer can be simulated by data shift, and the total harmonic distortion rate analysis of synthetic network side can be completed finally.

In the AC-DC-AC frequency conversion speed regulation system, the general rectifier system uses the uncontrollable rectifier bridge. Although this way is simple in structure and easy to control, its power factor is low, and the harmonic interference to the grid side is fixed and serious. In recent years, the rectifier side also adopts controllable PWM. The new type of IGBT AC-DC-AC control technology has been widely used, which is called Double PWM back-to-back variable-frequency speed control technology. The structure of the converter is shown in Fig. 2. The inverter with this structure can be used not only for the main drive of the rolling mill, but also for the auxiliary drive control.

The characteristic of this AC speed regulation system is that it is not necessary to add additional circuit to realize the regenerative energy feedback of the inverter to the power grid, and the PWM control of the rectifier part adopts the sine wave modulation technology, so that the input current and voltage phase of the inverter are the same and close to the sine wave, so that the harmonic components of the primary and secondary sides of the transformer only contain the same high order as the electronic switching frequency Harmonics, because of their high frequency, are easy to be filtered out in inductive circuits[20]. The power factor of the whole system is close to 1, which can greatly reduce the harmonic damage to the power grid.

![Figure 2](image2.png)

**Figure 2.** Structure of Dual PWM Variable Frequency Speed Regulation System
3.2. Establishment of simulation model of Dual PWM AC-DC-AC variable frequency speed control system

The simulation structure diagram of Dual PWM AC-DC-AC variable-frequency speed regulation control system is shown in Fig. 3. The purpose of PWM rectifier regulation at rectifier side is to keep the capacitor voltage of DC side constant and provide variable load current. At the same time, the rectifier frequency is 50 Hz to ensure that the rectifier frequency is consistent with the power frequency.

![Simulation structure diagram of Dual PWM AC-DC-AC variable frequency speed control system](image)

**Figure 3.** Simulation structure diagram of Dual PWM AC-DC-AC variable frequency speed control system

When the load is suddenly applied, the rectifier side ensures the DC voltage stability, improves the frequency and voltage regulation ability of the output side, so that the PWM at the inverter side can stabilize the frequency output in the original regulation range, and ensure that the speed change of the synchronous machine is very small. The inverter PWM works according to the adaptive voltage frequency ratio regulation mode. The output frequency is determined by the given speed. The speed deviation input is adjusted by pi to control the voltage output of the inverter.

The parameter settings of each link in Figure 3 are described as follows:

1) The rectifier and inverter adopt IGBT electronic devices, which are constituted by PWM (pulse width modulation), and the modulation wave frequency in the module is 4000Hz.

2) DC post filter capacitance \( C = 2000 \mu F \)

3) The load is three-phase high-voltage synchronous machine. The main content of this paper is the influence of synchronous machine on grid side harmonic when the rated power is stable, rather than observing the dynamic process of synchronous machine speed regulation, so only the harmonic influence of synchronous machine under steady-state operation is investigated.
4) The voltage regulator of rectifier side and speed regulator of inverter side are both PI operation, and other control algorithms can be used. However, because we study the harmonic influence of grid side, it has little to do with the specific control mode.

5) The simulation step size is \( t = 0.00001 \) s, and the given speed is 157.08 rad / s.

1) The power supply voltage and frequency are 35kV, 50 Hz, the capacity of each equipment is 6300KVA, and the power supply power can reach 43mva.

2) The parameters of rectifier transformer are set as follows: U1 is set at 35kV, U2 is set as 3.15kv, transformer capacity is set as 6300KVA, winding connection method is YG / \( \Delta \) - 11, no-load loss \( P_0 \) is set as 8150w, short-circuit loss \( P_K \) is set as 52460w, impedance voltage drop \( V_K \) is set as 7.5%, and no-load current \( I_0 \) is set as 0.7%. As shown in Fig. 3 simulation structure diagram of Dual PWM AC-DC-AC variable frequency speed regulation control system, according to the model and combined with the parameters set above, it is not difficult to calculate the specific parameters of transformer as follows: \( R_1 = R_2 = 0.813 \) \( \Omega \), \( L_1 = L_2 = 0.026 \) (H), \( R_M = 5129 \) \( \Omega \), \( L_M = 86.25 \) (H).

3) The rectifier adopts three-phase bridge rectifier circuit, which is composed of uncontrollable diode.

4) In the system, IGBT electronic devices are selected as inverter bridge, and pulse width modulation mode is adopted, and the frequency of modulation wave is selected as 2000Hz.

5) The filter circuit after DC is selected as LC filter circuit. The basic parameters are: \( L_1 \) is set to 0.01 (H), \( C = 10 (\mu f) \).

6) The LC filter output from the inverter has an inductance of 5mh and a capacitor absorption power of QC = 3000kva.

7) Considering the joint effect of rated current, power, voltage and electromotive force of motor, the three-phase high-voltage synchronous machine can be equivalent to three-phase resistance inductive load. The phase load \( r \) of the motor is set to 2 \( \Omega \) and 1 to 0.01 (H).

8) The PWM pulse generator uses six phase trigger module.

9) The voltage regulator uses PI regulator to compare the input set voltage with the output voltage under the premise of setting the output frequency, so as to realize the closed-loop feedback regulation.

4. Simulation result analysis and practical application
The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

4.1. Simulation result analysis and practical application
The simulation process type is set as the fixed step size simulation of discrete data. The sampling control period TS is modulated to 0.01ms, the simulation duration is set to 0.35s, the data sampling period is set to 0.1ms, and the time period used for data analysis is set in the range of 0.05-0.35s. This is because the initial state of DC filter capacitor is unstable when the AC-DC-AC converter is working and starts at zero time The state process should be omitted when the fast Fourier transform is used to analyze the steady state.

The following are the whole process steps of the simulation:
1) Firstly, the basic parameters of the system need to be set, and then the harmonic simulation analysis of the corresponding rectifier transformer input current under different frequency output is carried out.

2) The input current of rectifier transformer is analysed by changing load parameters.

3) The parameters of the output filter are changed, and the harmonic analysis of the input current of the rectifier transformer is carried out.

4) The parameters of DC filter are changed, and the harmonic analysis of rectifier transformer input current is carried out.

5) The parameters of transformer (incoming reactor) are changed, and the harmonic analysis of rectifier transformer input current is carried out.

6) When multiple units are working at the same time, the total input current of power supply is analysed.

In order to reduce the influence of harmonics on the power grid, in order to reduce the impact of harmonics on the power grid, each group of rectifier transformers are shifted to 30° and connected to the power supply system after the combination of multiple groups of rectifier transformers. The multi groups of transformers in this paper are designed based on this practical principle.

4.2. Analysis of simulation results

The simulation process is set as sudden load disturbance in the simulation process, and the speed regulator and voltage regulator constitute a closed-loop system. The output torque of the inverter decreases and the current rises rapidly, which makes the output speed angle frequency of the inverter decrease very little, and the speed drop is less than 0.1%. The simulation results of DC voltage, output torque, load current, three-phase power supply current and synchronous machine speed of Dual PWM AC speed regulation system under sudden load are shown in Fig. 4.

![Figure 4. Waveform of simulation results of Dual PWM Variable Frequency Speed Regulation System](image)

Through Fourier analysis, the current distortion of the dual PWM inverter control system at the load side has little effect on the primary side of the transformer, as shown in Fig. 5 and Fig. 6. It is further explained that for the dual PWM back-to-back AC-DC-AC variable-frequency speed regulation system, the influence on the power grid side is very small, and it is the smallest compared with the
AC-AC frequency conversion and uncontrollable AC-DC-AC variable-frequency speed regulation system.

![FFT analysis](image1.png)  
**Figure 5.** Harmonic content of load side

![FFT analysis](image2.png)  
**Figure 6.** Harmonic content of transformer primary side

From the simulation results and theoretical analysis, it is not difficult to see that under the condition of AC-AC frequency conversion, when the load changes, the harmonic at the network side will have a small change, and the influence on the total harmonic distortion is not great, but it is much greater than that of the AC-DC-AC frequency conversion; when the external conditions are identical, the secondary voltage phase difference of N rectifier transformers will be 60 / n degree when multiple motors are running. This method can minimize the total harmonic distortion rate of the grid side current of the connected system; when the output frequency changes, it will have a certain impact on the harmonic distortion; at low frequency, the total harmonic distortion rate is large, at this time, the frequency is 15 ~ 20 (Hz); the design of rectifier transformer, the setting of output frequency and the design of DC filter capacitance of AC-DC-AC speed regulation system will bring harmonic impact on the power grid. When the number of motors increases, the total harmonic distortion rate presents a downward trend, which indicates that the harmonics will cancel each other when the multi units are coupled. When using insulated gate bipolar transistor or turn off thyristor for PWM AC-DC-AC frequency conversion, the influence on the waveform distortion of grid side current is less than that of thyristor. For the dual PWM variable-frequency speed regulation system, the rectifier PWM control adopts sine wave modulation technology, which makes the input current and voltage phase of the inverter are the same and close to the sine wave, the power factor is close to 1, and the harmonic distortion rate of the load side current is not high, which reflects that the total harmonic distortion rate of the transformer network side is less than 1%. Moreover, the harmonic components reflected in the primary and secondary sides of the transformer only contain higher harmonics which are the same as the electronic switching frequency. These harmonics are easy to be processed by the filter because of
the high frequency. Whether it is AC-DC-AC frequency conversion or AC-AC frequency conversion drive system, the harmonic content of the system can be improved by properly selecting the parameters of the incoming line reactor, so as to ensure that the harmonic interference suppression of the grid voltage is within the scope specified by the State Grid. When the inductance value of the reactor is larger, the quality of the system will be better, but it is not the bigger the better. It is found that when the inductance value of the reactor is 30% - 50% of the transformer inductance value, the cost performance ratio is the highest. At this time, the harmonic quality entering the public power grid can be controlled within the allowable range, so as to ensure the quality of electric energy, prevent the harmonic from harming the user's electrical equipment, various electrical appliances and power grid, and ensure its economic and safe operation.

In AC speed regulation system, the influence of grid side harmonics is related to the overall structure of converter. The harmonic generated by AC-AC frequency conversion has a great impact on the grid side of the transformer. The harmonic generated by the drive motor is fed back to the grid side through the AC-AC frequency conversion system. For the controllable and uncontrollable structure of AC-DC-AC frequency conversion, the harmonics mainly come from the rectifier part, and the harmonic generated by the inverter part is less affected due to the isolation effect of DC capacitor and rectifier bridge. The average total harmonic distortion rate (TDH) of the grid side generated by a single AC frequency conversion unit can reach about 8% ~ 25%. After the combination of several sets and the transformer phase-shifting treatment, the total harmonic distortion rate can be controlled within 5%. The total harmonic distortion rate of the network side generated by the single unit of uncontrollable AC-DC-AC frequency conversion is 6% ~ 10%, and the combined simulation of multiple units can reach about 4.0%. The simulation results of single dual PWM back-to-back AC-DC-AC speed regulation load side harmonic is 7.06%, which reflects that the harmonic of the transformer network side is 0.82%. For the combination of multiple sets, the harmonic will be less after the transformer phase-shifting processing. For the combination of multiple units, it is related to the size of the load, and has little relationship with the time sequence of the added load. The phase shift angle of the transformer connection group has a great impact on the harmonic. With the increase of the number of simulation groups, the harmonic tends to weaken. No matter AC or AC-DC-AC frequency conversion, adding power reactor at the inlet of converter can reduce the harmonic content.

5. Conclusion
In this paper, a dual PWM back-to-back speed control system is designed for the hot rolling system in metallurgical industry. The influence of load parameters, output filter parameters, DC filter parameters and transformer parameters on the harmonic wave of rectifier transformer input current is analyzed by simulation, and compared with AC-AC frequency conversion and uncontrollable AC-DC-AC frequency control system. It is difficult to see that the double PWM back-to-back speed control system has the least influence on the power grid side and the power factor is close to 1. The results of this study have important reference value for harmonic suppression of power supply system composed of large-scale multi group AC speed regulation system, and provide qualitative and quantitative analysis for power quality regulation and reactive power compensation system in industrial enterprises.

References
[1] Jizhong Wang, Chaonan Tong, Qin Li. Analysis of the influence of a kind of multi group AC-DC-AC variable frequency speed regulation system on Power Grid Harmonics[J]. Journal of Beijing University of science and technology, 10,1394-1399(2014).
[2] Mian Wang, Guozhu Chen. A new method of DC energy balance for wind power back to back PWM converter[J]. Power automation equipment,36(7),28-33+46(2016).
[3] Yangwu Shen, Xiaotao Peng, Yuanzhang Sun. Coordinated control strategy of back to back Dual PWM converter[J]. Power grid technology,36(1),164-152(2015).
[4] Wenjun Liu, Xisheng Tang, Long Zhou, Zhiping Qi. Research on grid connected control method of flywheel energy storage system based on back to back Dual PWM converter[J]. Journal of Electrotechnics,30(16),120-128(2015).
[5] Gaoyu Zou, Zhengming Zhao, Liqiang Yuan, Lu Yin. Design of main circuit parameters of high performance three phase back to back converter[J]. Power automation equipment,34(1),72-79(2014).

[6] Weiliang Jian, Liang Ling, Renhan Shu. Design of Dual-PWM VVVF System Based on ARM[J]. Advanced Materials Research,2534,569-573(2013).

[7] Jifang Zhang, Wei Liu, Shiwei Sun. Inhibition of Double PWM Welding Power Supply Voltage Fluctuation of the Intermediate Links[J]. Applied Mechanics and Materials, 734,897-900(2015).

[8] Xianlian Huang, Xiangdong Feng, Xinwen Zhang. Influence of PWM loading mode on the adaptability of converter to weak current network[J]. Electric drive,50(3),22-27(2020).

[9] Yaai Chen, Junwei Zhao, Jinghua Zhou, Yongshuai Shi, Sai Wang. Control strategy of single phase grid connected / off grid dual mode inverter[J]. Electric drive,50(5),39-47(2020).

[10] Rong Hu, Yong Wang. Doubly fed wind power generation system based on double PWM control technology[J]. Electric drive,50(8),93-99(2020).

[11] Yang Liu, Xuhong Yang, Jianyu Lan. Novel active damping control for three phase LCL grid connected inverter[J]. Electric drive,50(10),35-39(2020).

[12] Zhaoyu Zhang, Shi Jin, Zhifeng Zhang, Fengge Zhang, Baolai Li. Novel space vector PWM technology with lower common-mode voltage for dual three-phase PMSM[J]. IET Power Electronics, 7(13),1426-1433(2020).

[13] Bo Fan, Lu Song, Shuzhong Song, Jiexin Pu. Double PWM coordinated control based on model predictive algorithm and power compensation[J]. International Journal of Reasoning-based Intelligent Systems, 1(11),38-46(2019).

[14] Yangyang She, Weidong Jiang, Chaohao Kan, Wangmin Li, Zhiqing Wu. Optimal control method for front end rectifier of back to back system in asymmetric power grid[J]. Chinese Journal of Electrical Engineering, (9), 2261-2271(2015).

[15] Yijun Dong. Historical development and current situation of circuit simulation software[J]. Modern information technology, (9), 83-84+87(2018).

[16] Jianlin Li, Zhigang Gao, Shuju Hu, Xinbo Fu, Honghua Xu. Application of parallel back to back PWM converter in direct drive wind power generation system[J]. Power system automation, (5),59-62(2008).

[17] Fangui Yan, Junhui Li, Guiqiang Jiang, Tao Chen, Yafeng Qiang, Jian Wang. Nonlinear decoupling vector control of back to back voltage source converter[J]. Journal of Electrotechnics,(5),129-135(2010).

[18] Ning Zhu, Haisheng Yu. Modeling and Simulation of four quadrant control system of induction motor based on back to back converter [J]. Journal of Qingdao University, (3),1-7(2013).

[19] Binqian Zhou, Wenyi Li, Minjing Yang, Qian Li, Xiaodong Du. Simulation of single phase back-to-back H-bridge cascaded structure[J]. Shaanxi Electric Power, (4),41-44(2014).

[20] Kui Wan, Zedong Zheng, Yongdong Li, Jianghua Feng, Kean Liu. Vector control system of induction motor based on five level active neutral point clamped PWM converter [J]. Journal of Electrotechnics,(2),247-252(2014).