Control Strategy Research of Ac-Dc-Ac Continuous Cophase Power Supply System

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Abstract: Aiming at the problems of power quality and phase separation in the current electrified railway power supply system, in response to the trend of high-speed and heavy-duty railways, a new type of continuous in-phase power supply system based on three-phase-single-phase intersection and orthogonality is proposed. The rectifier side of this in-phase power supply mode uses a three-phase bridge-type controllable rectifier circuit, and the inverter side uses a single-phase full-bridge SPWM converter. Double closed-loop control of voltage effective value and instantaneous value can suppress the negative influence of DC voltage fluctuation of uncontrolled rectifier circuit on AC voltage on inverter side, and provide stable voltage support for locomotive load. The power supply performance of the system under the condition of a single substation and multiple interconnections is analyzed, and a system model is established on the Matlab / Simulink platform. Simulation results verify the correctness and feasibility of the scheme.

1. Introduction

At present, Chinese electrified railway mainly adopts single-phase power frequency AC system. The non-linear characteristics of traction load lead to the need to use commutation connection to reduce the three-phase imbalance [1-2]. And, electrical phase separation is set up at the exit of the traction substation and in the sub-districts. When the train passes through the electrical phase separation, it will cause the loss of train speed and traction, which is not only detrimental to the driver's operation, but also seriously affects and restricts the development of Chinese railway industry [3-4]. Therefore, this paper studies a new type of power supply method for electrified railways that uses three-phase AC-DC-single-phase AC conversion-through-in-phase power supply. This method can not only realize the symmetrical transformation of the power system from three-phase to single-phase, and completely eliminate the negative sequence component; it can also adjust the amplitude and phase of the single-phase AC voltage, so that the traction network can eliminate the electrical phase separation link, which is beneficial to the traction network In addition, through the DC link isolation, the decoupling of the traction power supply system and the three-phase power system is realized. The independence of the two is enhanced. Harmonics and reactive power in the traction power supply system will not affect the three-phase power system. The through-in-phase power supply method is a very ideal new power supply method.

2. Through the Same Phase Power Supply System

2.1 Through-Phase Power Supply System Structure

Through-in-phase power supply is a power supply method using a single-phase traction transformer and through-in-phase power supply device in the substation. The structure of the through-phase traction substation is shown in Figure 1. The substation system uses AC-DC-AC power supply devices with three-phase rectification and single-phase inverter. The three-phase rectifier adopts SVPWM control to realize the change of power from a three-phase system to a stable DC source. A large-capacity capacitor is used as the energy buffer link on the DC side to keep the DC voltage stable. The single-phase inverting side adopts SPWM modulation technology to

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change the DC current to a single-phase AC voltage.

In a traction substation, the three-phase power grid draws three-phase power symmetrically from the power system, and rectifies and inverts it into single-phase AC power to supply electric locomotive loads. The structure and voltage level of each traction substation are the same. Therefore, the single-phase AC power of all traction substations can be connected to the grid. Such complete symmetrical power extraction will not cause pollution to the power grid, and realizes the same-phase power supply.

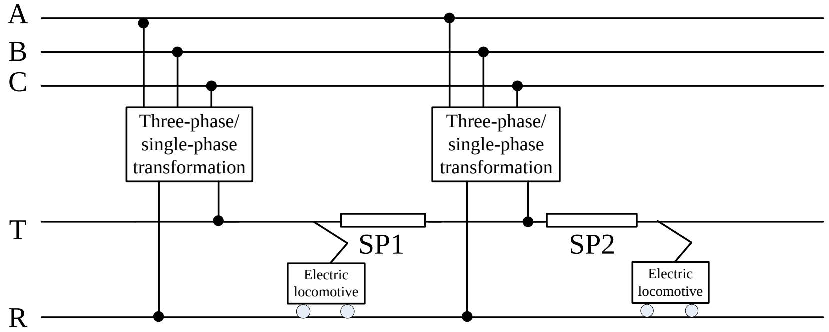


Fig.1 Structure of a through-in-Phase Traction Power Supply System

2.2 Through-in-Phase Power Supply

The basic structure of the through-phase power supply device is shown in Figure 2. The device in the figure consists of a three-phase controllable rectifier unit, a DC energy storage voltage stabilization unit, and a single-phase AC inverter unit.

(1) Three-phase controllable rectifier unit: transfers energy between the three-phase power grid and the DC link. In the traction mode, as a rectifier, the three-phase power on the grid side is converted into stable DC power to absorb energy from the power grid; in the regeneration mode, the inverter is used to convert DC power to three-phase power to feed back energy to the power grid;

(2) DC voltage stabilizing energy storage unit: Capacitor stores energy, provides DC voltage for back-to-back converter, and acts as an energy buffer to maintain the stability of DC voltage.

(3) Single-phase AC inverter unit: transfers energy between the power supply line and the DC link. In the traction condition, the inverter converts DC power into single-phase power with adjustable frequency amplitude and phase, and absorbs energy from the DC side to power the locomotive. Under regeneration conditions, it acts as a rectifier to convert single-phase power to DC power. The DC side delivers energy.

The through-phase power supply device realizes the transfer of three-phase active power to single-phase active power.

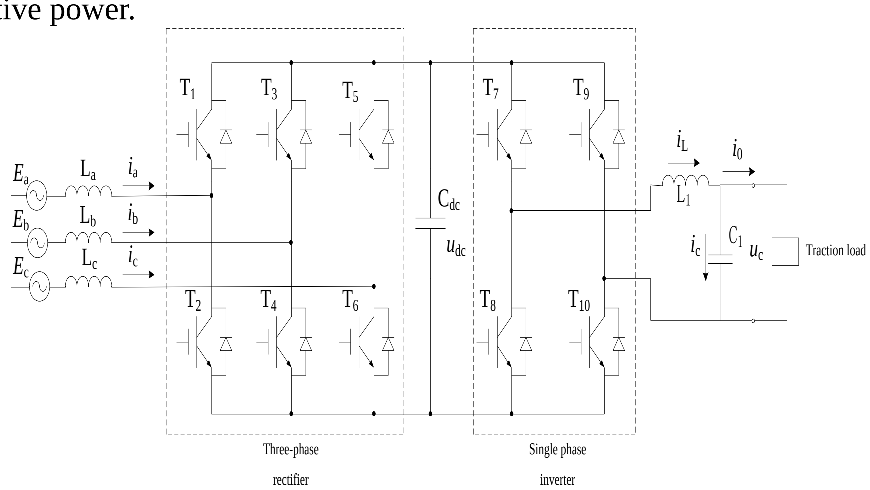


Fig.2 Schematic Diagram of the Structure of the through-Phase Power Supply Device

3. Compensation Principle of through-Phase Power Supply Device

3.1 Three-Phase Rectifier Unitthree-Phase Rectifier Unit

The three-phase bridge rectifier circuit is shown in Figure 3.

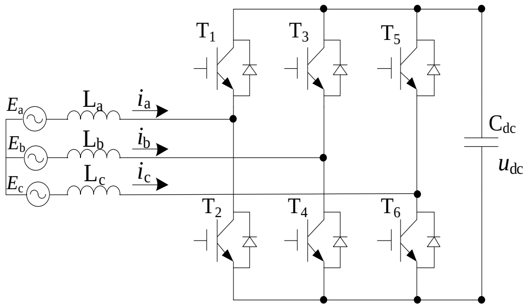


Fig.3 Schematic Diagram of Three-Phase Bridge Rectifier Circuit

The mathematical model of the three-phase rectifier circuit is:

$$\begin{bmatrix} L\frac{di_a}{dt} \\ L\frac{di_b}{dt} \\ L\frac{di_c}{dt} \end{bmatrix} = \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} u_{ra} \\ u_{rb} \\ u_{rc} \end{bmatrix} \quad (1)$$

Where $u_{rj} = u_{DC}(S_N - \frac{1}{3}\sum_{j=a,b,c} S_j)$, u_{ra} , u_{rb} , u_{rc} can be calculated in turn; u_a , u_b , u_c are three-phase symmetrical voltage; i_a , i_b , i_c are three-phase symmetrical current; S_a , S_b , S_c are the switching function of the rectifier. $S_j\,(j = a,b,c) = 1$ means that that the upper arm is turned on and the lower arm is turned off, and vice versa. u_{DC} is the voltage across the DC capacitor.

As shown in Figure 3, the three-phase full-bridge circuit is connected in parallel with the power grid through a series inductor. To complete the control goal, the voltage and current on the AC grid must be in the same phase and frequency, and the power factor is 1. The AC-side inductor L includes the internal inductance of the AC power supply and the inductance of the external reactor.

Taking single-phase structure rectification as an example, the basic principle of the rectifier is:Let the fundamental component of the AC bus voltage is $\dot{U}_s$, The fundamental component of the rectifier bridge output voltage is $\dot{U}_c$,Inverter reactor is X , $\dot{U}_c$ Lags behind $\dot{U}_s$ Angle δ .Then the active and reactive power absorbed by the rectifier are:

$$P = \frac{U_S U_C}{X}\sin\delta \quad (2)$$

$$Q = \frac{U_S(U_S - U_C con\delta)}{X} \quad (3)$$

From the formula $P = \frac{U_S U_C}{X}\sin\delta$,we can know, The amount of active power depends mainly on δ ,when $\delta < 0$,VSC sends out active power, Equivalent to working in inverter state; when $\delta > 0$,VSC absorbs active power, Equivalent to the rectifier running state. Controlling the size of the angle can control the size and direction of the active power.

VSC control uses sinusoidal pulse width modulation (SPWM) technology. Its basic principle is: compare the triangular carrier with a given sine wave (the expected output voltage waveform of each phase of the rectifier bridge) to determine the opening and closing of each bridge arm switch. Shutdown state. When the DC-side voltage remains constant, the amplitude of the output AC voltage of each phase of VSC depends on the modulation degree of SPWM, and the frequency and phase of the output voltage of each phase of VSC depends on the frequency and phase of a given sinusoidal signal[7-9].

To achieve independent adjustment of active power and reactive power, only the phase and modulation of a given sinusoidal signal of SPWM can be controlled.

3.2 Dc Stabilized Energy Storage Unit

The DC-side support-side capacitor is to provide the DC voltage required for the back-to-back converter to work in order to buffer energy, and its pulsation must not be excessive during operation.

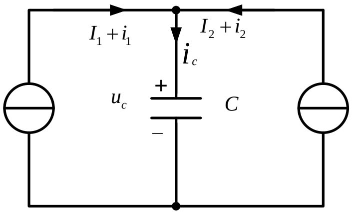


Fig.4 Dc-side Equivalent Schematic

the Capacitor Voltage Equation is:

$$C\frac{d\dot{u}_c}{dt}=I_1+i_1+I_2+i_2 \tag{4}$$

where:

I_1, i_1:The DC and AC components of the output current on the left VSC DC side.

I_2, i_2:The DC and AC components of the output current on the left VSC DC side.

When the active power balance on both sides of the in-phase power supply device is penetrated, $I_1+I_2=0$,then:

$$u_c=\frac{1}{C}\int(i_1+i_2)dt \tag{5}$$

The double-frequency ripple voltage caused by the current i_1 alone is:

$$\Delta u_{c1}=\frac{1}{C}\int i_1 dt=\frac{1}{C}\int I_1\cos 2\omega t dt=\frac{I_1\sin 2\omega t}{2\omega C} \tag{6}$$

The magnitude Δu_{m1} is:

$$\Delta u_{m1}=\frac{I_1}{2\omega C} \tag{7}$$

When the DC side capacitor buffer energy is the most serious, the capacitor voltage fluctuates the most. Set the maximum value of the double-frequency ripple voltage amplitude $\Delta u_{c\max}$ is :

$$\Delta u_{c\max}=2\Delta u_{m1}\frac{I_1}{\omega C}$$

DC side voltage ripple cannot be greater than $\sigma\%$,which is $\Delta u_{c\max}$ Need to meet:

$$\sigma\% U_d>\frac{I_1}{\omega C}$$

Take $k=27500/1800$, $I_x=S_N/27.5$, $\sigma\%=2\%$ into the following formula to get the DC-side support capacitor of the three-level power flow controller:

$$C > \frac{\sqrt{2}kI_x}{\omega\sigma\%U_d}$$

Supporting capacitance is C=0.18F.

3.3 Single-Phase Inverter Unit

The single-phase inverter unit realizes the conversion from DC to single-phase AC, which requires the output voltage on the AC side to reach the rated 27.5 kV. At present, it is difficult for power electronic devices to reach such a high voltage level. Therefore, it is often necessary to take measures on the AC side, such as using a step-up transformer Cascade of multiple low-voltage units.

The single-phase full-bridge inverter main circuit topology is shown in Figure 5.

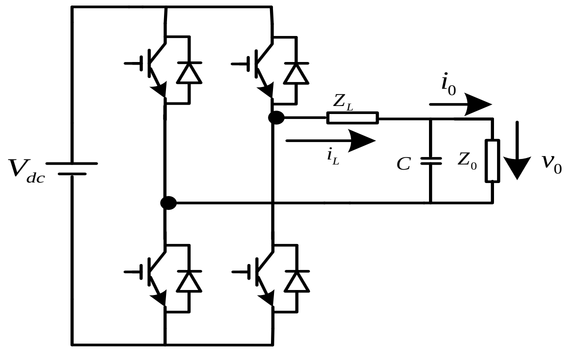


Fig.5 Single-Phase Full-Bridge Inverter Main Circuit

As shown in Figure 5 above, the single-phase full-bridge inverter consists of a single-phase full-bridge switching device plus a set of LC filters. DC side voltage is V_{dc},The inductor current is i_L,Inductance resistance is r_L,Load impedance is Z_0,Load-side voltage is v_0,Load output current is i_0.To filter the high-frequency part of the inverter output voltage V_i,The LC filter cutoff frequency is usually required to be designed to be much smaller than the circuit switching frequency. In this way, the average value will be equivalent to the instantaneous value V_i. In the analysis, V_i can be regarded as the power amplification of V_m, and the relationship can be expressed as:

$$v_i(t) = Kv_m(t) \quad (8)$$

Fig.6 Shows the Inverter Equivalent Circuit Diagram.

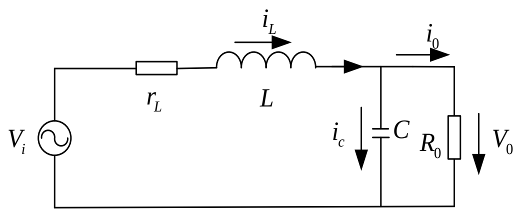


Fig.6 Rter Equivalent Circuit Analyzing Figure 6, We Get:

$$i_0 = \frac{v_0}{R_0} \quad (9)$$

$$i_C = j\omega C \cdot v_0 \quad (10)$$

$$v_0 = v_i - (r_L + j\omega L)i_C - (r_L + j\omega L)i_0 \quad (11)$$

Combining the above three types can be obtained:

$$v_i = \left[\left(1+\frac{r_L}{R_0}\right) + j\omega\left(\frac{L}{R_0} + r_L C\right) - \omega^2 LC \right] v_0 \tag{12}$$

Therefore, the inverter's transfer function of V_0 with respect to V_i in the frequency domain is:

$$G_i(s) = \frac{V_0(s)}{V_i(s)} = \frac{1}{s^2 LC + s\left(\frac{L}{R_0} + r_L C\right) + \left(1+\frac{r_L}{R_0}\right)} \tag{13}$$

4. Control Strategy

4.1 Inverter Control of a Single Substation

A single substation is a controllable voltage source when it is not connected to the Internet. There are various forms of control for single-phase inverters. Common are single-voltage closed-loop, voltage quasi-double-loop, and voltage-current dual-loop. Among them, voltage-current dual-loop is fast in response and the output voltage waveform distortion is small. Applications are widely used[10-11]. This text mainly adopts step-up transformer structure and voltage and current double loop control, as shown in Figure 7.

The voltage outer loop is proportional integral control, where K_{vp} and k_{vi} are the proportional adjustment coefficient and the integral adjustment coefficient in the voltage outer loop respectively; while the current inner loop only adopts single proportional control to speed up the dynamic response, where the current loop proportional adjustment coefficient is K_C. $G_0(s)$ is the system transfer function when the inverter is open-loop.

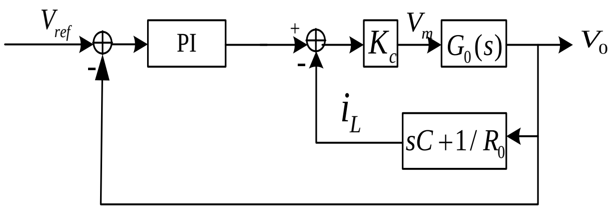


Fig.7 Double-Loop Control Block Diagram

4.2 Multiple Substation Grid Control

When multiple through-substations are distributed along the line, it is equivalent to the grid connection control of multiple voltage source converters. The control strategies that can be adopted between substations are master-slave control and external characteristic droop control. Among them, the master-slave control in the event of a failure of the master converter will cause the entire control to fail. It is unacceptable for a system with a high safety margin requirement for the traction power supply system, and the external characteristic droop control can satisfy individual converters Exiting or joining at any time does not affect the normal operation of other converters, and is particularly suitable for controlling the same-phase power supply system[12-13].

The following will discuss the power droop control characteristics of the inverter. Taking two inverters in parallel as an example, considering the output line impedance, a circuit as shown in Fig. 7 is established. The equivalent output voltages of the inverter are:

$E_1\angle\theta_1, E_2\angle\theta_2$,The equivalent output impedances are $Z_1 = R_1 + jX_1$, $Z_2 = R_2 + jX_2$,The output currents are i_{01}, i_{02}.Load impedance is Z_0,Load current is i_0,Load point voltage $E_0\angle 0^\circ$.

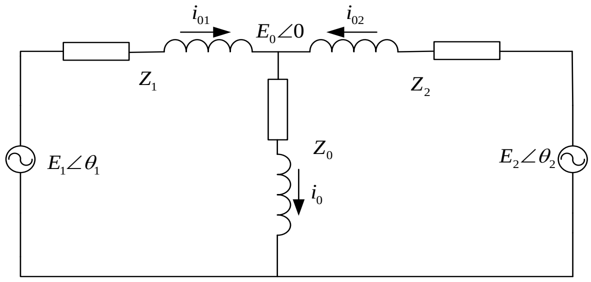


Fig.8 Equivalent Model of Two Inverters in Parallel Output

In the circuit shown in Figure 8, the output current of inverter 1 is:

$$I_1=\left(\frac{R_1}{R_1^2+X_1^2}E_1\cos\theta_1-\frac{R_1}{R_1^2+X_1^2}E_0+\frac{X_1}{R_1^2+X_1^2}E_1\sin\theta_1\right)+ j\left(\frac{R_1}{R_1^2+X_1^2}E_1\sin\theta_1-\frac{X_1}{R_1^2+X_1^2}E_0\cos\theta_1+\frac{X_1}{R_1^2+X_1^2}E_0\right) \quad (14)$$

So the output active power and reactive power are:

$$P_1=\frac{R_1}{R_1^2+X_1^2}E_0E_1\cos\theta_1-\frac{R_1}{R_1^2+X_1^2}E_0^2+\frac{X_1}{R_1^2+X_1^2}E_0E_1\sin\theta_1 \quad (15)$$

$$Q_1=-\frac{R_1}{R_1^2+X_1^2}E_0E_1\sin\theta_1+\frac{X_1}{R_1^2+X_1^2}E_0E_1\cos\theta_1-\frac{X_1}{R_1^2+X_1^2}E_0^2 \quad (16)$$

When the inverter is connected to the grid, the phase angle of the output voltage is relatively small compared to the voltage phase angle at the load port, which is approximately:

$$\begin{cases}\sin\theta_1=\theta_1\\ \cos\theta_1=1\end{cases} \quad (17)$$

$$\begin{cases}\sin\theta_2=\theta_2\\ \cos\theta_2=1\end{cases} \quad (18)$$

Then equations (17) and (18) can be simplified as:

$$P_1=\frac{E_0(R_1E_1-R_1E_0+X_1E_1\theta_1)}{R_1^2+X_1^2} \quad (19)$$

$$Q_1=-\frac{E_0(R_1E_1\theta_1-X_1E_1+X_1E_0)}{R_1^2+X_1^2} \quad (20)$$

Generally in the power grid, it is considered that the line resistance is much smaller than the line reactance, so the above two formulas are simplified as:

$$P_1=\frac{E_0E_1\theta_1}{X_1} \quad (21)$$

$$Q_1=-\frac{E_0(-E_1+E_0)}{X_1} \quad (22)$$

It can be seen from (21) and (22) that the inverter output power is approximately inversely proportional to the impedance and proportional to the voltage phase angle difference or amplitude difference. The droop characteristic expression of the first inverter in the parallel system is shown in equation (23):

$$\begin{cases} V_i = V_{0i} - m_i P_i \\ f_i = f_{0i} - n_i Q_i \end{cases} \quad (23)$$

Where m_i and n_i are the amplitude and frequency droop coefficients of the i-th inverter. Its control block diagram is shown in Figure 9. u_{ref} is the reference voltage signal and u_0^* is the reference voltage signal.

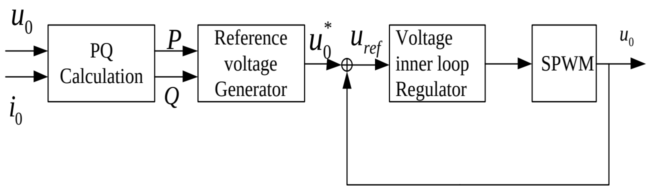
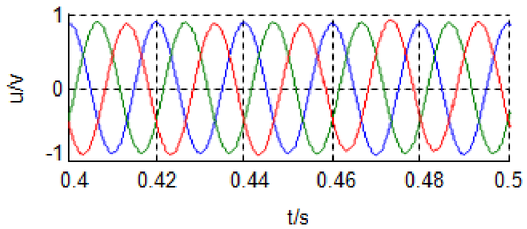


Fig.9 Sag Control Block Diagram

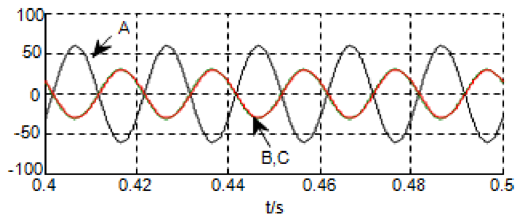
5. Simulation Verification

5.1 Simulation Analysis of a Single Substation

The simulation model of the current traction power supply system is set up under the Matlab / Simulink simulation platform. The three-phase traction transformer has a transformer ratio of 110kV / 27.5kV, the load power of the locomotive is selected to be 4MW, and the load is connected to the transformer secondary ac port. Figure 10 shows the simulation results. It can be seen from the figure that the three-phase current in the system is severely asymmetric, the current imbalance is 1, and the system has a negative sequence component.



(a)



(b)

Fig.10 Current Three-Phase Ac side Voltage Waveform and Three-Phase Ac side Input Current Waveform

Build a simulation model of AC-DC-AC power converter through power supply through Matlab / Simulink. In order to be close to the actual situation, step-up and step-down transformers are added to the AC-DC device. The DC voltage is given by U_{dc}=5kV, the step-up transformer ratio is 3.5kV/27.5kV, the load power locomotive power is selected as 4MW, and the simulation model parameters of the AC-DC-AC device are:

Three-phase input bus voltage Ea=3.5kV; single-phase output voltage Uc=3.5kV; input inductanceL_a=L_b= L_c =2mH;DC support capacitance C_{dc}=8mF; output inductance L_1=1mH.

The simulation results are shown in Figure 11. From the simulation results, it can be seen that the AC-DC power supply device can well realize the conversion of three-phase and single-phase power supply systems, the output voltage and current are stable, and the three-phase side currents are symmetrical.

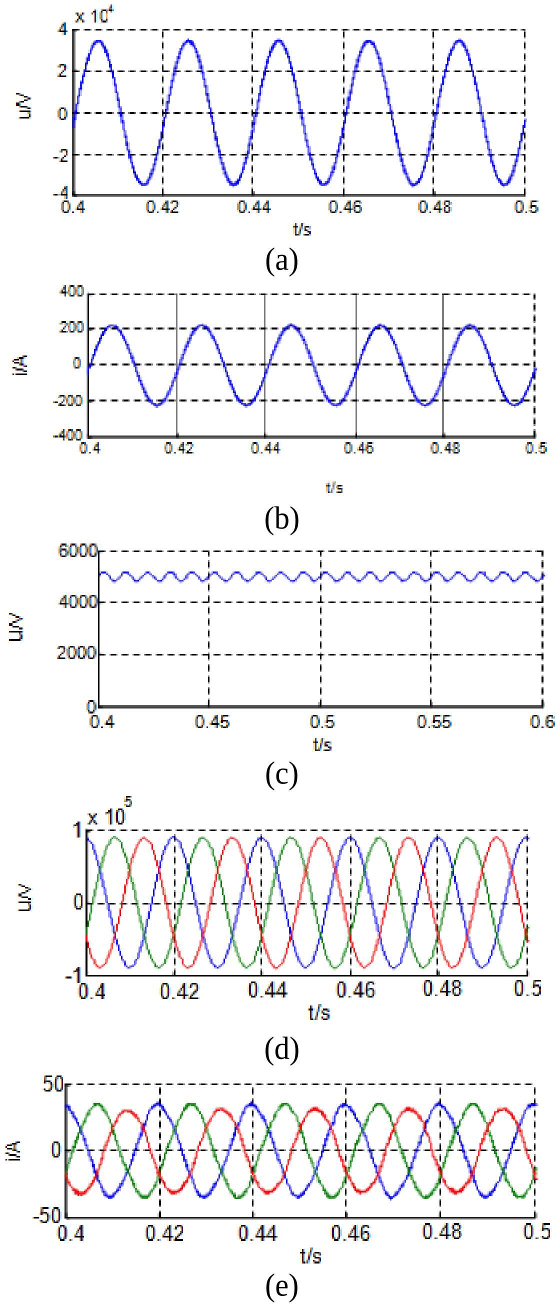
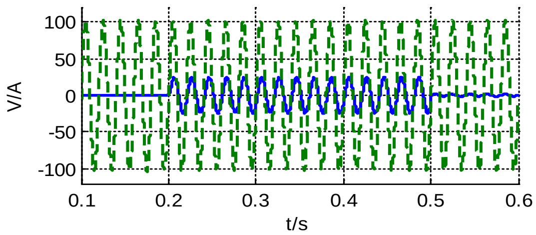


Fig.11 Simulation Results of a through-in-Phase Power Supply Unit

5.2 Substation Interconnection Simulation Analysis

In order to simplify the analysis, the simulation model ignores the three-phase rectification unit, and establishes the interconnection power distribution between the inverter sides of the two substations. The rated output voltage peak of each voltage is 100 V, and the line impedance Z_1, Z_2 is $0.05 + j1.88\Omega$ and $0.1 + j3.76\Omega$, The simulation results are shown in Figure 12. It can be seen from the figure that the output power of the inverter E1 is half less than the output power of the inverter E2 under the interconnection condition of the substation, which is in line with the theory of droop control power distribution.



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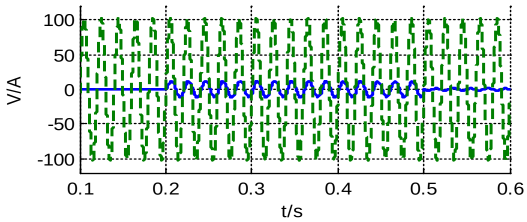

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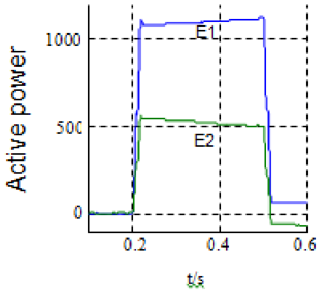
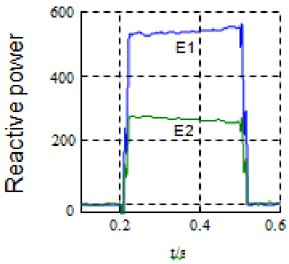


(c)



(d)

Fig.12 Simulation Results of the Interconnection of the through-Phase Power Supply Substation

6. Discussion on System Solution Implementation

The main factors affecting the implementation of the system are economy and reliability. This can be addressed in a number of ways:

Reliability: The operation and maintenance of the in-phase power supply system based on three-phase single-phase variable current is similar to the main circuit of the power system's high-voltage DC transmission and AC-DC electric locomotive. Real-time monitoring and periodic maintenance are required to enhance system reliability.

Economic aspects: First, the price of high-power power electronic devices has dropped significantly, especially IGBTs have now been domesticated, and the application of high-power converter products will be more popular in the future; Second, the in-phase power supply scheme improves the power factor of the traction power supply system 2. Eliminate the negative sequence, realize the good coupling of the traction power supply system and the power system, and reduce the fines caused by problems such as power quality.

7. Conclusion

Based on the existing theory of in-phase power supply, this paper proposes a new type of through-in-phase power supply based on three-phase-single-phase conversion. The variable side uses an SPWM inverter with double closed-loop control of voltage rms and instantaneous value. The simulation verification was performed on the Matlab simulation platform. The research shows that the conversion device can achieve three-phase-single-symmetric conversion, the output side voltage and current are stable, and the input side three-phase current waveforms are symmetrical. Good coupling between power supply systems. In the case of multiple grid connection, connectionless peer-to-peer connection can be achieved, and the power distribution satisfies the droop distribution principle.

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References

[1] ZHOU Mo, WANG Guo, CHANG Wenhuan, et al. Study on hybrid active compensation based on three-phase two-leg inverter for electrification railway[J]. Power System Protection and Control, 2015, 43(13): 100-104.

[2] LUO Pei, CHEN Yuehui, LUO Longfu, et al. Railway power quality manage system capacity optimization design [J]. Transactions of China Electrotechnical Society 2016, 31(8): 181-188.

[3] ZHANG Chenmeng, CHEN Baichao, YUAN Jiaxin, et al. Research on a hybrid compensation system for V/V co-phase railway power supply system [J]. Transactions of China Electrotechnical Society, 2015, 30(12): 496-504.

[4] LI Qunzhan, HE Jianmin. Electrified railway feeding system without phase exchange and symmetrical compensation technology [J]. Automation of Electric Power Systems, 1996, 20(4): 9-11.

[5] Zhang Rui. Research on power converter of penetrating non-phase power supply system [J]. Electrified Railway, 2012 (4): 19-22.

[6] Hu Jingyu. Research on power flow control strategy of penetrating non-inverting power supply system [D]. Master's thesis, Southwest Jiaotong University, 2013.

[7] Wang Yuan. Research on penetrating co-phase power supply system based on three-phase-single-phase converter [D]. Chengdu: Southwest Jiaotong University, 2013.

[8] Wu Ping. Research on co-phase power supply technology for electrified railways [D]. Chengdu: Southwest Jiaotong University, 2008.

[9] He Xiaoqiong, Peng Xu, Zhou Yingying, etc. Research on Current Sharing Performance of a New Cophase Traction Power Supply System [J]. Electric Power Automation Equipment, 2014, 34 (4): 53-58.

[10] Xia Yankun. Multi-level single-phase cascaded active filter carrier modulation and capacitor voltage balance method [J]. Chinese Journal of Power Systems and Automatic Chemistry, 2017, 29 (3): 79-82, 109.

[11] Xie Shaofeng, Li Qunzhan, He Jianmin, et al. Symmetric compensation for in-phase power supply system Research on Device Control Strategy [J]. Journal of the China Railway Society, 2002, (24).

[12] Sun Yifeng, Ruan Xinbo. Power balance control of cascaded multilevel inverterControl Strategy [J]. Proceedings of the CSEE, 2006, 26 (4): 126-133.

[13] CHEN Minwu, GONG Yansheng, LI Qunzhan, et al. Assessment of power quality of electrified railway and the research on the new control scheme [J]. Power System Protection and Control, 2012, 40(16): 141-147.