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Research on Co-phase Power Supply Test System

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ABSTRACT

Co-phase power supply system can solve the problems of power quality of heavy unbalanced three phase, large harmonics and reactive power and cancel neutral section in electric railway power supply system. In order to do further research, a co-phase power supply test system is proposed. By mean of analyzing on structures and principles of YNvd transformer, integrated power flow controller (IPFC) and simulation load, establishing control strategy on IPFC and simulation load, the system is simulated dynamically. The results illustrate that the scheme can well simulate co-phase system, and the negative sequence is eliminated, harmonic and reactive power are real-timely compensated in system.

Keywords: Co-phase Supply System; IPFC; YNvd Balanced Transformor; Simulation Load

1. Introduction

Reactive power current, harmonics and unbalanced active power current are the outstanding problems in traditional traction supply system [1]. These problems directly influence the three-phase industrial grid through traction substations. With the rapid development of high-speed and heavy-loading railway, these problems are gradual prominence, and the neutral section also restricts the speedpromotion of high-speed train, which influence the safety, reliability and economy of railway operation. As locomotives based on PWM converter are widely used, the distortion of reactive power and harmonics is decreased partially [2], but the unbalance becomes more significant than before. The co-phase system can solve unbalance problem, at the same time, compensate reactive power currents and filter harmonics. And the co-phase power supply system based on passive symmetrical compensation is proposed [2, 3]. With the wide application of power electronic devices in railway system, the co-phase scheme based on active power compensator which is called IPFC is designed [4, 5]. Using real-time detection, strategy control, and distribution algorithms on IPFC, this system can compensate harmonics, reactive power and negative sequence current real-timely and accurately.

As shown in **Figure 1**, In co-phase system, the balanced transformer transformers power from three-phase of public supply grid to two-phase. (YNvd balanced transformer is proposed and used in system.) One phase is connected directly with feeders to supply electric locomotives, and another is connected with phase a by IPFC, which can transfer active power from β-phase to α-phase, compensate the loads' reactive power and filter the harmonic. So there is single-phase power in supply area of one traction substation (SS), so that the neutral section in the substation can be cancelled.

2. Co-phase Power Supply Test System

There are many specific details of co-phase system needing to be studied, but it is impossible to do lots of project tests in the railway system. In order to further research co-phase system, a co-phase system test scheme is proposed which could be operated and tested in the public grid of laboratory. As illustrated in **Figure 2**, test scheme is composition of YNvd balanced transformer, IPFC and simulated load. YNvd transformer simulates traction transformer, simulated load simulates the characteristics of the traction load, IPFC realizes power transmission and compensation dynamically.

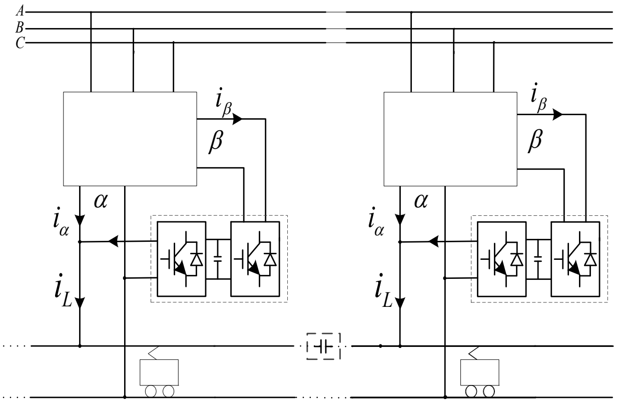

Figure 1. Co-phase power supply system.

2.1. YNvd Balanced Transformer

YNvd balanced transformer is new kind of three-phase to two-phase balance transformer, which adopts three-phase three-column iron core and has the characteristics of high utilization of iron core, simple structure, easy manufacturing and maintenance; the primary side has neutral point and can be grounded directly, so the reliability of system protection can be improved. YNvd transformer connection type is shown in **Figure 3**. The primary side of YNvd transformer connects the grid utility, the windings ω_A, ω_B and ω_B are connected in Y-form. The secondary side composes two phases, ω_{a1} and ω_{c1} compose α-phase in V-form connection which supplies the traction load, and ω_{a2}, ω_{b2} and ω_{c2} compose β-phase in Delta-form connection which only connects IPFC as shown in **Figure 3**.

The relationship of the windings of YNvd transformer is given by

$$\begin{aligned}&\omega_A:\omega_B:\omega_C:\omega_{a1}:\omega_{c1}:\omega_{a2}:\omega_{b2}:\omega_{c2}\\&=K:K:K:\frac{1}{\sqrt{3}}:\frac{1}{\sqrt{3}}:1:1:1\end{aligned} \tag{1}$$

where K is the turn ratio of primary/secondary voltage.

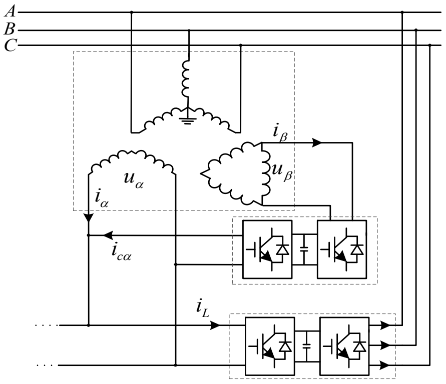

Figure 2. Co-phase system test scheme Co-phase Power Supply System.

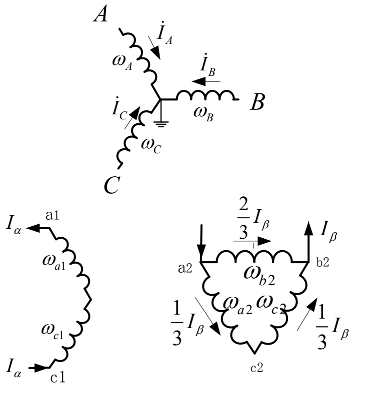

Figure 3. YNvd transformer connection schemes.

So the voltages of primary and secondary windings satisfy the formula:

$$\begin{bmatrix}\dot U_\alpha\\ \dot U_\beta\end{bmatrix}=\frac{1}{K}\begin{bmatrix}\frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}}\\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3}\end{bmatrix}\begin{bmatrix}\dot U_A\\ \dot U_B\\ \dot U_C\end{bmatrix} \tag{2}$$

So that two output voltages of secondary side are mutual perpendicular and has same amplitude.

Current relations between the primary side and secondary side of YNvd transformer is as follow

$$\begin{bmatrix}\dot I_A\\ \dot I_B\\ \dot I_C\end{bmatrix}=\frac{1}{K}\begin{bmatrix}\frac{1}{\sqrt{3}} & -\frac{1}{3}\\ 0 & \frac{2}{3}\\ -\frac{1}{\sqrt{3}} & -\frac{1}{3}\end{bmatrix}\begin{bmatrix}\dot I_\alpha\\ \dot I_\beta\end{bmatrix} \tag{3}$$

According to the symmetrical component principle, the primary side currents can be decomposed as

$$\begin{bmatrix}\dot I_0\\ \dot I_1\\ \dot I_2\end{bmatrix}=\frac{1}{6K}\begin{bmatrix}0 & 0\\ \sqrt{3}+j & -1+j\sqrt{3}\\ \sqrt{3}-j & -1-j\sqrt{3}\end{bmatrix}\begin{bmatrix}\dot I_\alpha\\ \dot I_\beta\end{bmatrix} \tag{4}$$

If $\dot I_\alpha = j\dot I_\beta$, the $\dot I_2$ is equal to zero, and the negative sequence of the primary side is eliminated.

2.2. IPFC

As shown in **Figure 4**, IPFC is a back-to-back single-phase converter which is composed of two fully-bridge converters with one DC-link capacitor, two input AC inductors. The AC ports are respectively connected with α phase and β phase of YNvd transformer. In real system, the output voltage of traction transformer is too high so that isolated step-down transformers must be placed between the converter and traction transformer. In test system, the step-down transformers are canceled because of small output voltage.

The voltages of secondary windings of YNvd Transformer is assumed as

$$\begin{cases}u_\alpha(t)=U\sin\omega t\\ u_\beta(t)=U\sin(\omega t-90^\circ)\end{cases} \tag{5}$$

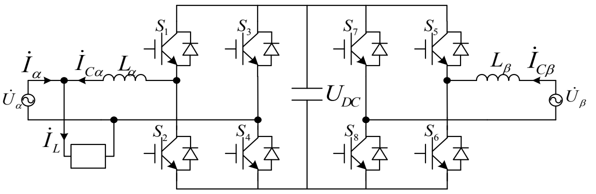

Figure 4. Structure of IPFC.

where U represents the amplitude of voltages of secondary windings.

The traction load current is discussed and written as:

$$\begin{aligned} i_L(t) &= i_1(t)+i_h(t) = I_1\sin(\omega t+\varphi_1)+i_h(t) \\ &= I_{1p}\sin\omega t + I_{1q}\cos\omega t + i_h(t) \end{aligned} \tag{6}$$

where i_1 is the fundamental current, i_h is harmonic current. I_p, I_q represent amplitudes of active power, reactive power, φ_1 is the phase difference between i_1 and u_α.

In co-phase traction power supply system, the α-phase of IPFC outputs half active power and compensates the all reactive power and harmonic currents of traction load, the b-phase of IPFC inputs half active power of traction load, and active power is transfer between two ports by DC-link capacitor. The compensated currents of IPFC are expected as:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}I_{1p}\sin\omega t + I_{1q}\cos\omega t + i_h \\ -\frac{1}{2}I_{1p}\sin(\omega t - 90^\circ) \end{bmatrix} \tag{7}$$

The output currents of secondary side of YNvd transformer is obtained as

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_L \\ 0 \end{bmatrix} - \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}I_{1p}\sin\omega t \\ \frac{1}{2}I_{1p}\sin(\omega t - 90^\circ) \end{bmatrix} \tag{8}$$

Taking (8) into (3), it yields

$$\begin{aligned} \begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} &= \frac{1}{K}\begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{1}{3} \\ 0 & \frac{2}{3} \\ -\frac{1}{\sqrt{3}} & -\frac{1}{3} \end{bmatrix} \begin{bmatrix} \frac{1}{2}I_1\cos\varphi_1\sin\omega t \\ \frac{1}{2}I_1\cos\varphi_1\sin(\omega t - 90^\circ) \end{bmatrix} \\ &= \frac{I_1\cos\varphi_1}{3K}\begin{bmatrix} \sin(\omega t + 30^\circ) \\ \sin(\omega t - 90^\circ) \\ \sin(\omega t + 150^\circ) \end{bmatrix} \end{aligned} \tag{9}$$

Obviously, the two output currents of YNvd transformer are same amplitude and in-phase with respective port voltage in (8), and the three-phase currents of primary side are also same amplitude in (9). So negative sequence, harmonics and reactive power can be thoroughly compensated by IPFC and YNvd transformer in co-phase traction power supply system.

2.3. Simulated Load

Simulated load is composition of traction current simulation unit and energy feedback unit, which are back-to-back connected with dc capacitor. The traction current simulation unit (TCSU) as traction load absorbs power from α phase of YNvd transformer. Energy feedback unit feedbacks active power to public grid (EFU). So that the active power is transferred from single-phase through dc link to three-phase.

As shown in **Figure 5**, the main circuit is composed of input inductor, dc capacitor, output inductor. Converter unit and inverter unit exchange energy through the dc link.

Assuming the port voltage of TCSU is

$$u_\alpha(t) = U\sin\omega t \tag{10}$$

where u_α is also α-phase voltage of YNvd transformer.

By means of reasonable control strategy on traction current simulation unit, anticipant load current can be obtained as

$$\begin{aligned} i_L(t) &= i_1(t)+i_h(t) \\ &= I_1\sin(\omega t+\varphi_1)+i_h(t) \\ &= I_{1p}\sin\omega t + I_{1q}\cos\omega t + i_h(t) \end{aligned} \tag{11}$$

So instantaneous power of simulated load is

$$p_L = u_\alpha(t)i_L(t) \tag{12}$$

The A-phase voltage of EFU output side (three-phase side) is:

$$u_A(t) = U_2\sin(\omega t + 30^\circ) \tag{13}$$

where U is the peak value of three-phase voltage.

The three-phase currents of inverter unit are controlled to output same amplitude currents and feedback power to grid with unity power factor, the phase A current is assumed as

$$i_{AF}(t) = I_F\sin(\omega t + 30^\circ) \tag{14}$$

where I_F is effective value of three-phase current that the inverter unit feedbacks to public grid.

Then the instantaneous power of phase A is defined as

$$p_A = u_A(t)i_{AF}(t) \tag{15}$$

During one periodic, the two ports of simulated load have same active power ignoring system loss, so we can obtain:

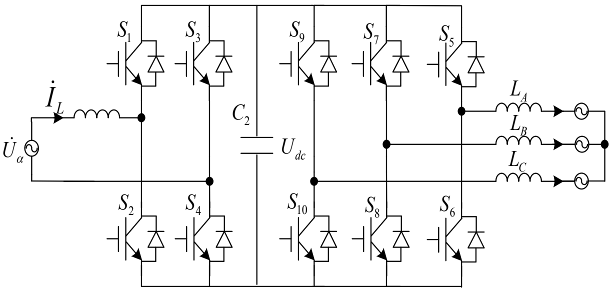

Figure 5. Structure of simulated load.

$$\frac{1}{T}\int_0^{2\pi} p_L dt = \frac{1}{T}\int_0^{2\pi}(p_A + p_B + p_C)dt \qquad (16)$$
$$= \frac{3}{T}\int_0^{2\pi} p_A dt$$

so,

$$UI_1 \cos\varphi = 3U_2 I_F \qquad (17)$$

$$I_F = \frac{UI_1\cos\varphi}{3U_2} = \frac{I_1\cos\varphi}{3K} \qquad (18)$$

The three-phase currents feedback by energy feedback unit are followed as

$$\begin{bmatrix} \dot{I}_{AF} \\ \dot{I}_{BF} \\ \dot{I}_{CF} \end{bmatrix} = \frac{1}{3K} I_1 \cos\varphi_1 \begin{bmatrix} \sin(\omega t + 30^{\circ}) \\ \sin(\omega t - 90^{\circ}) \\ \sin(\omega t + 150^{\circ}) \end{bmatrix} \qquad (19)$$

According to energy conservation, the two sides have same active current without considering system loss.

However, compared with (9) and (19), the input three-phase currents of YNvd transformer are equal to the output three-phase currents of simulated load, so that the energy can be recycled.

3. Control Algorithm

3.1. Control Algorithm of IPFC

The detection, control algorithms of IPFC is analyzed to ensure IPFC real-time achieving comprehensive compensation accurately and real-timely. The dc capacitor link needs stable dc voltage to make sure IPFC operation and power transmission. **Figure 6** illustrates that the double-loop control with the inductance current inner loop and capacitor voltage outer loop is introduced.

By detecting and calculating simulated load current, the compensation currents are obtained, which are the parts of command currents of IPFC. The voltage outer loop is to achieve the constant dc voltage control. The compensation currents plus the steady-voltage current which is obtained by voltage outer loop are the compensation command current $i^*_{c\alpha}$ and $i^*_{c\beta}$. The current inner loop controls the IPFC actual compensation currents to follow the command currents. The PWM signals are generated by tuning the difference of the actual current and the command current in PI controller by modulating.

3.2. Control Algorithm of TCSU

TCSU is single-phase rectifier, as shows in **Figure 7**, the current control method is used in order to control the rectifier follow the command current accurately.

Compared with command current i_L* and real traction current i_L, the difference is regulated to be modulating voltage by PI controller and pulse signals for rectifier are generated by PWM generator.

3.3. EFU

EFU is three-phase inverter, and it is required to output currents in the unity power factor and control the dc voltage stabilized on setting value. As shown in **Figure 8**, the double-loop control with the inductance current inner loop and capacitor voltage outer loop is used to control this unit to achieve these functions.

In the α–β reference frame, instantaneous active and reactive currents are respectively controlled with a PI regulator and then the true compensating currents can track the command signals well.

4. Simulation Verification

To verify feasibility and effect of this system, simulation models of YNvd transformer, IPFC, simulated load were built by using the Matlab/SIMULINK. The primary side of YNvd balanced transformer accessed the three-phase public gird, and voltage of primary side was 220 V, the voltage of secondary side was 660V. The power factor of

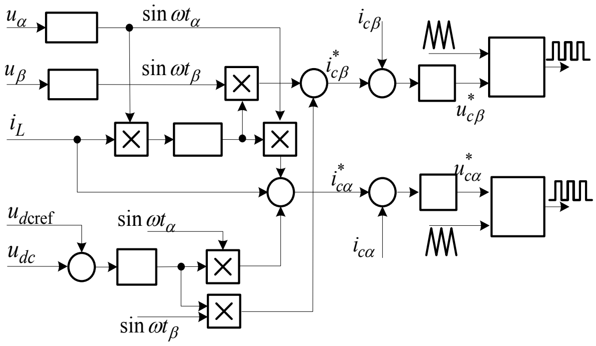

Figure 6. Control diagram of IPFC.

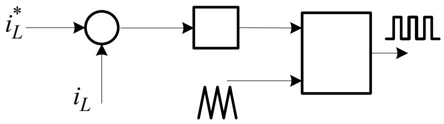

Figure 7. Control diagram of TCSU.

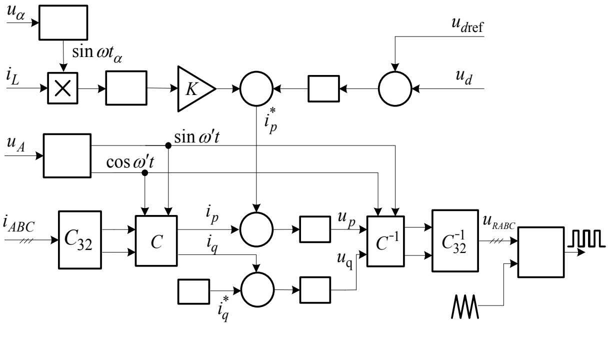

Figure 8. Control diagram of EFU.

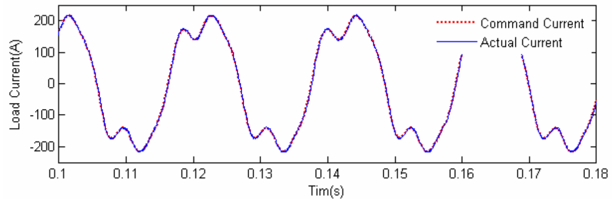

Figure 9. Command current and actual traction current of the TCSU.

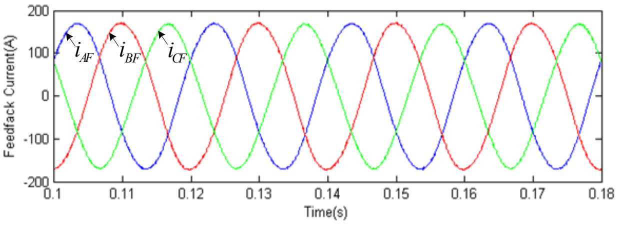

Figure 10. Three-phase feedback currents of EFU.

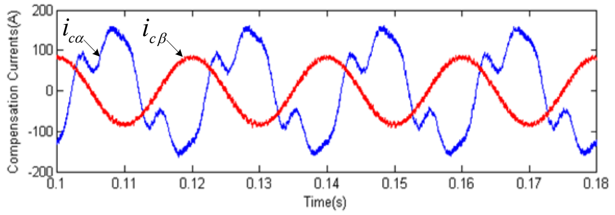

Figure 11. Compensation currents of IPFC.

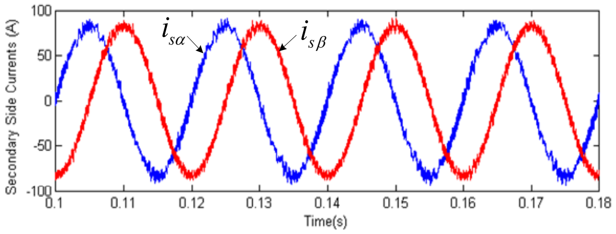

Figure 12. Secondary side output currents of YNvd transformer.

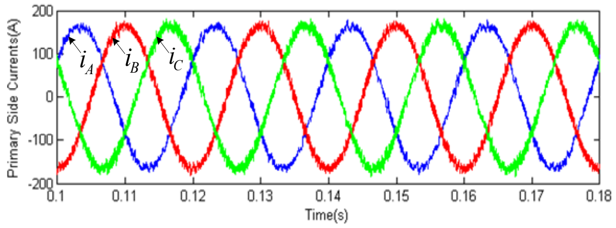

Figure 13. Primary side input currents of YNvd transformer.

the traction current was assumed as 0.866(lagged), the occupancy of the third and fifth harmonic currents were 20% and 10% respectively, so the simulated load command current was followed as

$$i_L^* = 200\sin(\omega t - 30^\circ) + 40\sin(3\omega t - 60^\circ) + 20\sin(5\omega t + 150^\circ)$$

The **Figure 9** shows the command current and actual traction current of TCSU, and he **Figure 10** shows the three phase currents fed back to grid by feedback unit. The simulation results of simulated load illustrated that the traction current could follow the command current precisely, and as shown in **Figure 10**, the three-phase currents were all active currents with same amplitude, the input active power of single-phase was equal to the output.

The simulated load is to be traction load, and the simulation results of the other units were shown in **Figures 11-13**.

As shown in **Figure 12**, the two output currents of the secondary side of YNvd transformer were totally active currents with same amplitude and a phase difference of 90° by the compensation of IPFC, so the traction supply system was resistance load relative to public grid.

Figure 13 illustrates that the input currents of primary side were equal and negative sequence was eliminated by YNvd transformer and IPFC. The feedback currents of simulated load were nearly equal to the inputs currents of primary side of YNvd transformer, which means that power energy was used circularly and effectively.

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