Modelling and simulation for the network-locomotive coupling of the co-phase continuous power supply and high speed railway

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Abstract

Co-phase continuous power supply system (CCPSS) can completely eliminate electric phase break to realize the co-phase continuous power supply in the traction substation, thus the impact on the power quality of the utility grid can be greatly reduced. In this paper, double-loop control strategy, which involves the load current feedback for three-phase pulse width modification (PWM) rectifier and single-phase inverter in the traction substation were proposed. Also, the control strategy with neutral-point-potential balance for three-level rectifier as well as the constant V/f control for asynchronous motor of electric locomotive was proposed. A network-locomotive coupling model of an AC-DC-AC traction substation and electric locomotive was built in this paper using PSCAD/EMTDC. Thorough simulations were conducted to demonstrate the effectiveness of the proposed control strategies.

Keywords: CCPSS, AC-DC-AC electric locomotive of CRH2, control strategy, PSCAD/EMTDC

1 Introduction

In order to reduce the impact of traction power supply system on utility grid imbalance, the traction substation needs to be connected to the utility grid in turns; therefore an electric phase break section should be set at the output interface of a traction substation. Because of the existing of the electric phase break, the locomotive speed and traction power supply capacity were restricted seriously. To solve these technical problems, literature [1-3] put forward the scheme of co-phase power supply which based on active power filter and different connection forms of transformer. The method balanced the transform from three-phase AC to single-phase AC, and could compensate the harmonics and reactive power. However, these schemes could not realize the inter-connection of the power grid in a traction substation. Thus, it cannot cancel the electric phase break completely.

Literature [4-11] proposed a full transformation structure of the three-phase AC to DC to single-phase AC of the traction substation. In this way, there is no need of the electric phase break, so the electrified railway can be achieved to CCPSS. This structure reduced the impact of traction power supply system on utility grid power quality greatly. At the same time, the electric locomotives can be driven stable and safe high-speed.

In this paper, the network-locomotive coupling model of AC-DC-AC traction substation and electric locomotive was established using PSCAD/EMTDC.

Research the control strategies of traction substations and AC-DC-AC electric locomotives based on PWM.

2 The main structure of CCPSS

Compared with the original traction power supply system, the voltage magnitude, phase and frequency of traction network side of the CCPSS were the same, so the electrical phase break could be abolished completely, and it was suitable for high-speed rail operation. Since the substation used PWM symmetric transformation technology of three-phase rectifier to single inverter [12-16], this method could eliminate the interference between the utility grid and traction power supply system in the power quality. When the circuit breaker of the section post was closed, the substations could reach co-phase continuous power supply. The main structure was showed in Figure 1.

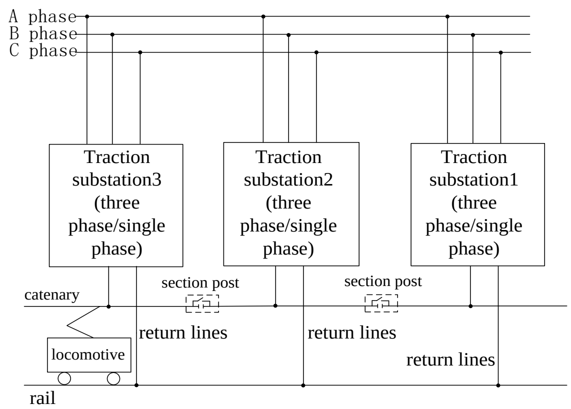

FIGURE 1 The main structure of the CCPSS

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3 The power converter's main circuit structure of the traction substation

This traction substation was based on the power converter of three-phase PWM rectifier and single-phase PWM inverter. Three-phase PWM rectifier was connected with the step-down transformer. When the DC voltage of rectifier was stable, the unity power factor should be achieved at the same time. Single-phase PWM inverter connected step-up transformer, on the one hand, the output voltage magnitude and frequency were stable; on the other hand, the reactive power, harmonics of the traction load should be compensated real-time. Due to the power supply mode of the traction substations was the AC-DC-AC symmetrical full transformation, traction power supply system and the utility grid were independent, and the three-phase load was balanced, so there was no negative sequence problems.

4 The power converter control strategy of the traction substation

4.1 THE CONTROL STRATEGY OF THE THREE-PHASE PWM RECTIFIER

Since the voltage mode of three-phase PWM rectifier [17] has several advantages, such as: adjustable power factor, low harmonics injected of AC side, DC side voltage stability and to work with the four-quadrant and two-way flow of energy, this control strategy was used in this article.

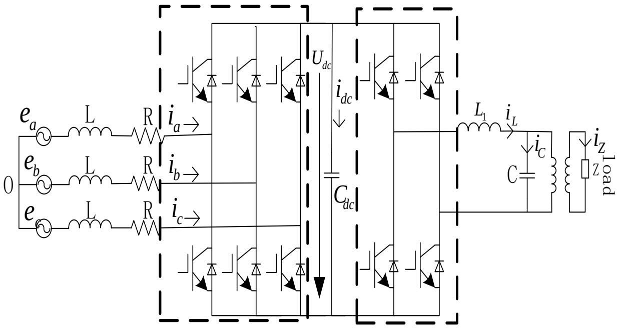


FIGURE 2 The main circuit configuration diagram of the power converter

This control of rectifier mainly included hysteresis current control, predictive current control, resonance control and linear PI controller [18]. Its control method had fast current response and robustness; by comparison, the voltage and current double closed loop PI controller [19] were used in this paper. Meanwhile, in order to improve the anti-jamming capability of rectifier side DC voltage, the paper increased the load current feedback compensation control, so that the power of three-phase PWM rectifier input and output could be balanced, the modulation method using SPWM. Figure 2 shown the equations of three-phase PWM rectifier circuit in ABC coordinates:

$$\begin{cases} C_{dc}\dfrac{du_{dc}}{dt} = i_a S_a + i_b S_b + i_c S_c - i_{dc} \\ L\dfrac{di_a}{dt} + Ri_a = e_a - u_{dc}S_a - u_{NO} \\ L\dfrac{di_b}{dt} + Ri_b = e_b - u_{dc}S_b - u_{NO} \\ L\dfrac{di_c}{dt} + Ri_c = e_c - u_{dc}S_c - u_{NO} \\ u_{NO} = -\dfrac{1}{3}u_{dc}(S_a + S_b + S_c) \end{cases}. \quad (1)$$

(S_a, S_b, S_c - Continuity and shutdown of the upper and lower bridge arm, u_{dc} - the rectifier side DC voltage i_a, i_b, i_c, e_a, e_b, e_c - the current and voltage of AC side; u_{NO} - the neutral point voltage). Through the stationary coordinate ABC to dq0 rotating coordinate transform, the equation of three-phase PWM rectifier under dq0 coordinates could be achieved as follows:

$$\begin{cases} L\dfrac{di_d}{dt} + Ri_d = e_d - U_{dc}S_d + \omega L i_q \\ L\dfrac{di_q}{dt} + Ri_q = e_q - U_{dc}S_q - \omega L i_d \\ C_{dc}\dfrac{du_{dc}}{dt} = \dfrac{3}{2}\left(i_d S_d + i_q S_q\right) - i_{dc} \end{cases}. \quad (2)$$

Let $U_d = U_{dc}S_d, U_q = U_{dc}S_q$, the following equation:

$$\begin{cases} U_d = e_d - L\dfrac{di_d}{dt} - Ri_d + \omega L i_q \\ U_q = e_q - L\dfrac{di_q}{dt} - Ri_q - \omega L i_d \end{cases} \quad (3)$$

In the Equations (2) and (3), i_d, i_q, e_d, e_q, respectively represented the current and voltage under the dq0 coordinate; where ω was the Angular frequency; S_d, S_q respectively represented continuity and shutdown function under the dq0 coordinate. i_{dc} isyhe rectifier side current.

The Equations (2) and (3) show that, when the current i_{dc} changed, the u_{dc} deviated firstly, then the system was adjusted, because the PI regulator delayed, the adjustment process of DC voltage u_{dc} resulted in large errors. In order to strengthen the stability of the DC voltage of three-phase PWM rectifier, a load current feedback compensation link was added. If we ignored line losses and switching losses, the Equation was:

$$\frac{3}{2}\left(e_d i_d + e_q i_q\right) = U_{dc}\left(C_{dc}\frac{du_{dc}}{dt} + i_{dc}\right), \quad (4)$$

when the system was stable, $i_q = 0$, $C_{dc}\dfrac{d_{uc}}{dt} = 0$ the equation was:

$$\frac{3}{2}e_d i_d = U_{dc} i_{dc} . \quad (5)$$

Because of the PI regulator, the current loop without static error tracking could be achieved, if we ignored the adjustment process of the current loop, front feed control variables of the load current was:

$$\overset{*}{i}_d = \frac{2}{3} \times \frac{U_{dc}}{e_d} \times i_{dc} . \quad (6)$$

Figure 3 showed the three-phase PWM rectifier joined the double-loop control system of the load current feedback loop:

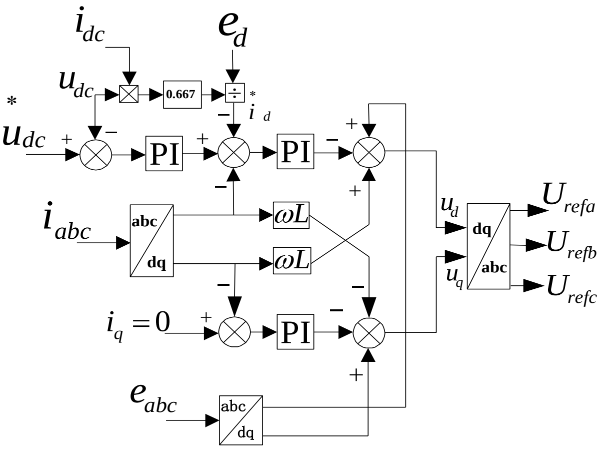


FIGURE 3 Joined the load current feedback loop of the double-loop control system

Double-loop PI control of three-phase PWM rectifier generated three-phase voltage as the reference signal was compared with the triangular carrier, and each switch action pulses to drive each switch-off and switch-on were got.

4.2 THE CONTROL STRATEGY OF SINGLE-PHASE PWM INVERTER

Because the double-loop controller had several characteristics [20, 21], such as: design simple, the output voltage waveform distortion small, fast dynamic response, and it required the power converter accurate tracking given traction load current, this control method was used in this article for the control of single-phase PWM inverter. The control system was shown in Figure 4.

The mathematical model of single-phase PWM inverter circuit was:

$$\begin{pmatrix} L_1 \dfrac{di_L}{dt} \\ L_1 \dfrac{du_c}{dt} \end{pmatrix} = \begin{pmatrix} u_{dc} \\ i_L \end{pmatrix} - \begin{pmatrix} u_C \\ i_Z \end{pmatrix} , \quad (7)$$

where i_L was the current of filter inductor; u_{dc} was the voltage of filter capacitor; i_z was the load current.

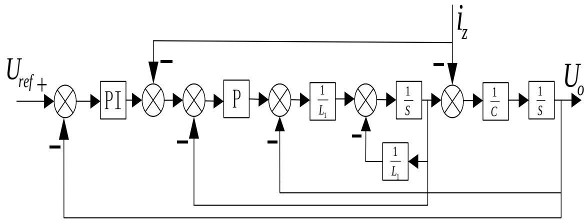


FIGURE 4 Single phase inverter control block

5 The converter main circuit structure of the AC-DC-AC electric locomotive traction

Currently, there are mainly two types of the traction converters，the one is the AC-AC converter, the other one is the AC-DC-AC converter.

The AC traction drive system generally adopted the following basic structure of AC-DC-AC electric locomotive:

The traction supply system of asynchronous motor power supply used voltage type AC-DC-AC converter; the traction supply system of synchronous motor power supply used current type AC-DC-AC converter, the traction supply system of synchronous motor power supply used AC-AC converter [22].

Compared with current type converter, the output current waveform of the voltage type converter contained less harmonic components [23]. Its performance was superior, the current waveform were closer sine. In summary, this paper adopted voltage type AC-DC-AC converter as the electric locomotive traction converters [24]. The main circuit configuration was shown in Figure 5.

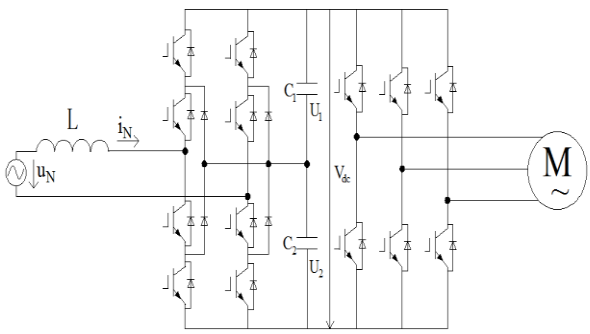


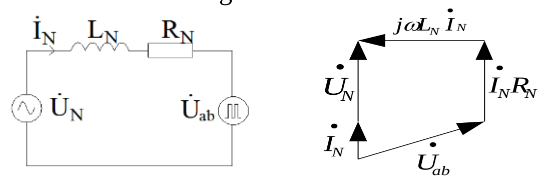
FIGURE 5 Traction converter main circuit diagram

The traction substation of decreasing from single-phase AC 27.5KV to 1.5KV single-phase AC; through three-level PWM rectifier to 2.6kV~3kV DC for the three-phase PWM inverter, three-phase PWM inverter and motor control as a whole, using the control mode of VVVF (variable voltage variable frequency).

5.1 THE CONTROL STRATEGY OF TRACTION CONVERTER

5.1.1 The control strategy of the single phase three-level PWM rectifier

Analysing rectifier side of Figure 5，the equivalent circuit diagram of the AC side of the rectifier and its control vector were shown in Figure 6.



a) Equivalent circuit diagram b) Control vector

FIGURE 6 Equivalent circuit and control vector of rectifier

In the Figure 6, where $\dot{U}_N$ was the voltage of the secondary winding of vehicle transformer, R_N , L_N ,were converted to resistance and leakage inductance of secondary side of the transformer windings respectively; $\dot{U}_{ab}$ was the fundamental vector of modulation voltage. Figure 6b showed the voltage vector equation of vehicle transformer secondary AC circuit:

$$\dot{U}_N = \dot{U}_{ab} + (R_N + j\omega L_N)\dot{I}_N . \quad (8)$$

The literature [25, 26] proposed an improved balance control with a midpoint voltage of transient current control method was used in the rectifier of the CRH2 locomotive. On the basis of Equation (8), when the compensated was increased the control Equation as follows:

$$\overset{*}{I}_{N1} = K_p(\overset{*}{U}_{dc} - U_{dc}) + \frac{1}{T_i}\int(\overset{*}{U}_{dc} - U_{dc})dt , \quad (9)$$

$$\overset{*}{I}_{N2} = \frac{I_{dc}U_{dc}}{U_N} , \quad (10)$$

$$\overset{*}{I}_N = \overset{*}{I}_{N1} + \overset{*}{I}_{N2} , \quad (11)$$

$$\overset{*}{U}_{ab}(t) = u_N(t) - (\overset{*}{I}_N R_N \sin\omega t + \overset{*}{I}_N \omega L_N \cos\omega t) - K[\overset{*}{I}_N \sin\omega t - i_N(t)] . \quad (12)$$

K_p, T_i were the proportional integral constant of PI regulator; K was the constant of PI regulator, i_N was the input current of AC side, other variables could be seen from Figure 7.

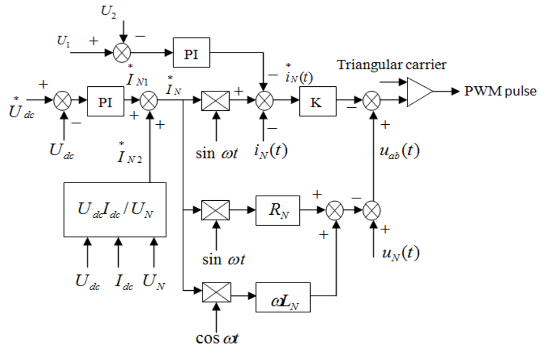


FIGURE 7 The control system block diagram of rectifier

The AC side current for a given value:

$$\overset{*}{i}_N(t) = \overset{*}{I}_N \sin\omega t - [K_{p1}(u_1 - u_2) + \frac{1}{T_{i1}}\int(u_1 - u_2)dt] - i_N(t) . \quad (13)$$

The traction converter rectifier control system block diagram was shown in Figure7.

5.1.2 The control strategies of the three-phase PWM inverter and motor

According to the knowledge about motor, electromagnetic torque *M* and *U/f* had a positive correlation.If the frequency *f* was adjusted, the voltage *U* should also be adjusted. So that the ratio $(U/f)^2$ could remained constant, and the flux ϕ remained unchanged, as well as the value of the torque *M* [27]. Control block diagram was shown in Figure 8.

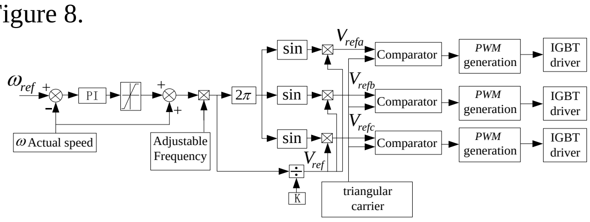


FIGURE 8 The control block diagram of the VVVF motor speed

6 Simulation results and analysis

Based on the PSCAD/EMTDC, the network-locomotive coupling model of AC-DC-AC traction substation and electric locomotive was established.

The main parameters were shown in Table 1.The other parameters of CRH2 according to the literature [28].

TABLE 1 The main parameters of the model

Three-phase power system	Three-phase rectifier side	Single-phase inverter side	Electric locomotive rectifier side
Fundamental frequency $f = 50Hz$	DC voltage set point $U_{dc} = 5KV$	Filter inductance $L_1 = 0.25mH$	Filter capacitance $C_1 = C_2 = 2200uF$
Source voltage $V_S = 110KV$	DC capacitor capacitance $C_{dc} = 9000uF$	filter capacitance $C = 130uF$	DC voltage set point $V_{dc} = 3KV$
three-phase step-down transformer ratio $110KV/3.5KV$	triangular carrier frequency $f_C = 1000Hz$	triangular carrier frequency $f_{C1} = 1200Hz$	triangular carrier frequency $f_{C2} = 1000Hz$

In this study, the pole-placement method was utilised [20], adjustment them through a lot of simulation experiments, to achieve the desired requirements.

The simulation results were as follows:

1) In this model, the co-phase continuous power supply system consisted of three traction substation, and three traction substations acquire power in the same utility grid together.

2) Traction substation output interface and rectifier of the waveform was shown in Figure 9 to Figure 13.

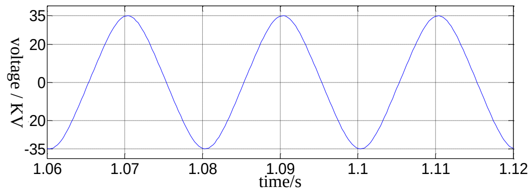


FIGURE 9 The voltage of traction substation 1

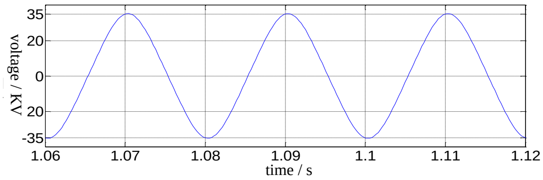


FIGURE 10 The voltage of traction substation 2

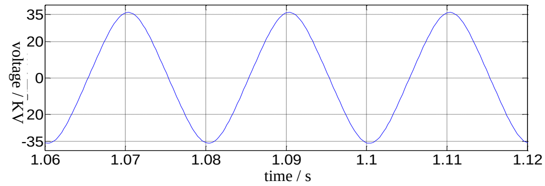


FIGURE 11 The voltage of traction substation 3

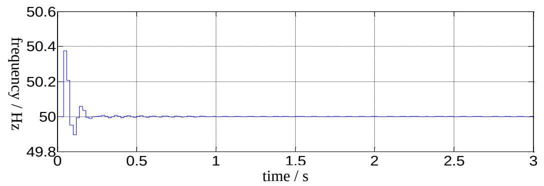


FIGURE 12 The frequency of traction substation

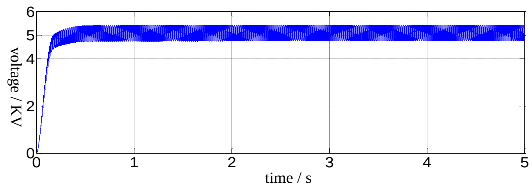


FIGURE 13 The DC voltage of traction substation rectifier side

It could be seen from Figure 9 to Figure 13 that in the case of electric locomotive load conditions, the voltage of traction substation rectifier side and the voltage of the output interface, frequency were stabilized at predetermined 5kV, 27.5kV, 50Hz,and harmonics injected and negative sequence were very low, have a high quality of voltage.

The rectifier side voltage of AC-DC-AC electric locomotive, current of the stator side and the stator flux trajectory waveform were shown in Figures 14-16.

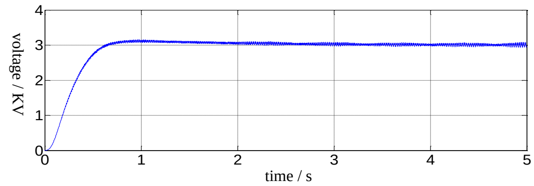


FIGURE 14 the voltage of electric locomotive rectifier side

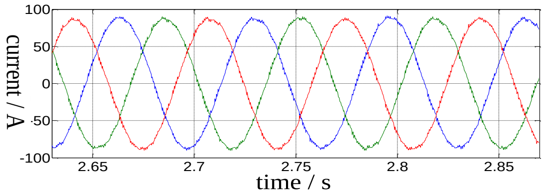


FIGURE 15 The current of the stator side

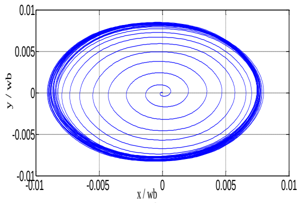


FIGURE 16 The stator flux trajectory waveform

It could be seen from Figure 14 to Figure 16 that, the voltage of electric locomotive rectifier side was stabilized at predetermined 3KV; the three-phase current of the stator side was symmetry. The stator flux trajectory waveform was approximate round.

7 Conclusions

This paper mainly studies the main circuit structure and control strategy of traction substation and AC-DC-AC electric locomotive. Application of electromagnetic transient simulation software PSCAD/EMTDC, it established the network-locomotive coupling model of AC-DC-AC traction substation and electric locomotive.

Through the analysis of this paper and the simulation results, the conclusions were as follows:

1) The voltage magnitude, phase and frequency were the same of three traction substation output interface. The electric phase break is completely cancelled, so the traction substation between the CCPSS is achieved. It reduces the impact of traction substation on the utility grid power quality greatly.

2) The double-loop control strategy of the loaded was suitable, not only the anti-interference ability be improved of DC voltage of three-phase PWM rectifier, but also make the DC voltage to track the command voltage fast.

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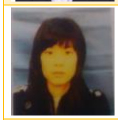

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