Analysis and Research of Networked Traction Power Supply System

Qi Zhuo, Zhengqing Han, and Shibin Gao

Abstract In order to solve the shortcomings of the existing traction power supply system and further optimize the operation quality of the AC traction power supply system, scholars have proposed a networked traction power supply system. This paper analyzes the system structure and operation principle of the networked traction power supply system, constructs a simulation model of the networked traction power supply system, and explores the performance and application prospects of the networked traction power supply system. The analysis shows that the established model can reflect the operating characteristics of the networked traction power supply system. The simulation analysis shows that the networked traction power supply system has enhanced power supply capacity compared with the traditional single-sided traction power supply system, and the system has performance advantages and feasibility, which provides a theoretical basis for further research and practice of the networked traction power supply system.

Keywords Networked Traction Power Supply System · Traction Substation · Converter

1 Introduction

The traction power supply system of Chinese electric railway adopts single-phase power frequency AC system, which has the advantages of simple structure and strong power supply capacity, but it will cause power quality problems in industrial three-phase power supply systems, such as increased line loss and undervoltage at the end of the contact line, grid current imbalance and so on [1]. At present, the traction power supply system is usually connected to the three-phase power supply system by commutation connection, receiving current from the three phases A, B, and C in turn, and setting an electrical split between the ends of two adjacent power supply

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arms to prevent short-circuit between phases. In order to avoid the interphase short circuit caused by live running and phase splitting, the pantograph must be lowered and the power must be cut off when the train passes through the phase splitting. Therefore, the phase splitting will form a power supply dead zone in the traction power supply system, causing the train speed loss, increasing energy consumption, reducing the performance of high-speed railway, affecting the ability of heavy haul freight trains to grow up the slope, and even causing parking in serious cases. At the same time, the existence of electric phase separation makes it impossible to fuse the power between power supply arms, and the traction power cannot be transferred and mutually supported between different power supply arms. In addition, when the train passes through the electric phase separation, it will also produce voltage impact, current impact, pantograph catenary arc, etc., endangering the normal and safe operation of the catenary and electric locomotive [2, 3].

In order to solve the shortcomings of the existing traction power supply system, relevant scholars have proposed the in-phase power supply technology, which can be divided into two categories [4, 5]. The first is to use symmetrical compensation technology to achieve in-phase power supply, and the second is to form the in-phase power supply system based on the power flow controller [6–9]. However, the current technical scheme may generate balanced current and electromagnetic loop network in the traction power supply system. Therefore, some scholars put forward the concept of networked traction power supply system, and optimized the structure of traction power supply system with the help of power electronics technology to solve the problem of phase insulator of traction power supply system and improve the power quality of the system [10, 11].

The networked traction power supply system is based on power electronics technology, with reference to flexible transmission and energy interconnection technologies, and integrates railway regenerative braking energy utilization technology to realize the power controllability and transmissibility of the traction power supply system and improve the power supply quality.

Based on the networked traction power supply system proposed by scholars, this paper analyzes the system structure and operation principle of the networked traction power supply system, establishes the system simulation model using MATLAB/Simulink simulation platform, and studies the performance of the networked traction power supply system.

2 Networked Traction Power Supply System

2.1 System Structure

In the networked traction power supply system, the structure of the traction substation is shown in Fig. 1. The traction substation adopts a fully controlled structure, and its three-phase/single-phase voltage transformation part includes Scott transformer

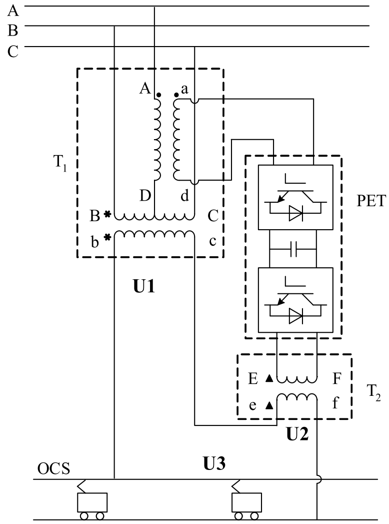


Fig. 1 The structure of traction substation of networked traction power supply system

and power electronic transformer (PET). The incoming lines of the power system are connected to the primary side of the substation in the same phase sequence. The output end of the PET matching transformer is connected with the direct secondary output of the traction transformer through the traction network to supply power to the traction network. At the same time, the intermediate DC link of PET can also be connected to the energy storage device and the new energy power generation device to realize the interconnection of the electrical network and the new energy.

The two adjacent traction substations all adopt the fully controlled structure, and the electric sections are still retained at the exit of the traction substation, and the power supply arms between the substations adopt the bilateral power supply mode, with the upstream and downstream running in parallel.

2.2 System Operation Principle

As shown in Fig. 1, in the traction substation of the networked traction power supply system, the T-block winding of the Scott transformer supplies the 110 kV (or 220 kV) level voltage of the bus bar to the AC/DC converter, the rectifier unit of the converter turns the AC power into DC power, and then the inverter unit of the converter turns the DC power into single-phase AC power, so that the output voltage of the converter can match the frequency and phase of the output voltage of the M-block of the Scott transformer. The output voltage of the converter is stepped up by the transformer and then connected in series with the M block of Scott transformer to provide 27.5 kV/ 50 Hz for the traction load.

When the system is working normally, the converter tracks the secondary voltage of Scott transformer M block to adjust its own output voltage, and then controls the secondary voltage of the matching transformer to ensure that the feeder outlet voltage between traction substation groups remains stable, and also adjusts the power tide between traction substations to realize the power controllability and transferability of the traction power supply system, improve the quality of power supply, and enhance the adaptability of power supply capacity and traffic organization.

As the inverter unit of the converter is mainly composed of power electronics, which is expensive, the normal operating current of the traction load, overcurrent and short-circuit current of the feeder all have to pass through the inverter unit of the converter. Therefore, when a short-circuit fault occurs in the traction network, the converter should adopt the current limiting mode to avoid the short-circuit current from damaging the power electronics, and at the same time make the protection sense the occurrence of the fault, discover the fault and remove it in time.

3 The Working Principle of PET

3.1 Basic Structure of PET

In the networked traction power supply system, the power electronic transformer of the traction substation is mainly composed of power switching tubes, as shown in Fig. 2. The grid-side inductor L_1 of the rectifier unit plays the role of transferring and storing energy and suppressing high harmonics, while the filter capacitor C_d plays the role of suppressing high harmonics and reducing DC voltage ripple; the inductor L and capacitor C of the inverter unit form a series resonant circuit for filtering the harmonic components of the output voltage.

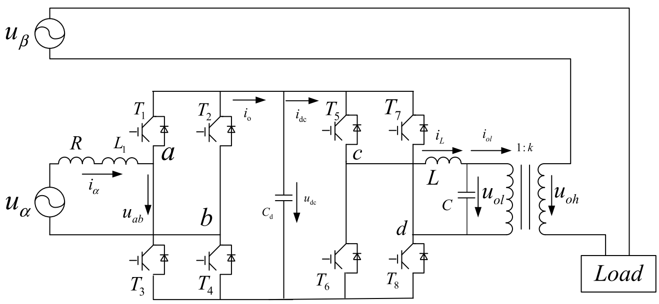


Fig. 2 The working principle circuit diagram of PET

3.2 Control Strategy for PET

As shown in Fig. 1, the secondary voltage vector of Block M of Scott transformer T1 and the secondary voltage vector of transformer T2 are combined to form the output voltage vector of the traction substation of the networked traction power supply system, and the secondary voltage vector of transformer T2 is changed by changing the output voltage of PET to make the output voltage of different traction substations consistent, so as to realize the bilateral power supply of the inter-station arm.

In the traction substation of the networked traction power supply system, the schematic circuit diagram of the PET operation is shown in Fig. 2, $u\alpha$ and u_β are the low voltage side voltages of the traction transformer M block and T block, u_{ol} is the AC output voltage of the PET, u_{oh} is the load side output voltage of the converter matching transformer, and k is the ratio of the matching transformer.

According to the working principle of the traction substation of the networked traction power supply system, let u_{set} be the desired output voltage of the traction substation, then the voltage relationship between Scott transformer and PET is shown as follows:

$$\begin{cases} u_\alpha(t) = \sqrt{2}U_\alpha \sin \omega t \\ u_\beta(t) = \sqrt{2}U_\beta \sin(\omega t - 90^\circ) \\ u_{ol}(t) = u_{oh}(t)\big/ k \\ u_{set}(t) = u_\beta(t) + u_{oh}(t) \end{cases} \quad (1)$$

During the normal operation of the networked traction power supply system, the output voltage of the low voltage side of the Scott transformer's M block is detected, and the output voltage of the PET is calculated according to the set output voltage of the traction substation, and the PET uses this as the control target of the output voltage, and the voltage of the low voltage side of the T block of the Scott transformer is AC/DC transformed so that the traction substation can steadily output 27.5 kV/50 Hz to provide power to the traction load. Hz to provide power to the traction load.

As a grid-side converter of PET, the rectifier unit is essentially an intermediate medium for energy exchange between the AC grid and the DC intermediate circuit. The rectifier unit converts the input AC energy into DC energy for the inverter unit. In the process of energy exchange, the rectifier unit uses algorithms to achieve control characteristics such as stable DC intermediate voltage, grid power factor close to 1, and grid current waveform close to sinusoidal, so as to improve the power quality of the traction power supply system as much as possible.

The inverter unit adjusts the output of AC voltage according to the output voltage of the low voltage side of Scott transformer M block, and inverts the intermediate DC voltage to AC voltage that meets the demand, so that the traction substation can steadily output 27.5 kV/50 Hz voltage.

For the inverter unit of the converter, in order to keep the output voltage of the traction substation stable, the output voltage of the inverter unit requires high steady-state accuracy and fast dynamic response, therefore, the dual-loop control scheme of voltage outer loop and current inner loop is selected. The current inner loop of the dual-loop control scheme expands the bandwidth of the inverter control system, which makes the dynamic response of the inverter faster and reduces the harmonic content of the output voltage, and improves the adaptability to nonlinear loads. The current inner loop of the dual-loop control scheme expands the bandwidth of the inverter control system.

Meanwhile, since the Scott transformer and PET are connected in series, both traction load current and short-circuit fault current have to pass through the converter. Therefore, when a short-circuit fault occurs in the traction network and the short-circuit current will exceed the capacity of the PET devices, in order to avoid the damage of the power electronics of the PET due to the high current, the PET should enter the current limiting and voltage reduction mode to control the current within the capacity of the devices.

4 Simulation Model Analysis

4.1 Simulation Model

According to the analysis of traction substation topology and PET control strategy of networked traction power supply system, the model of PET in MATLAB and the simulation model of networked traction power supply system are shown in Fig. 3.

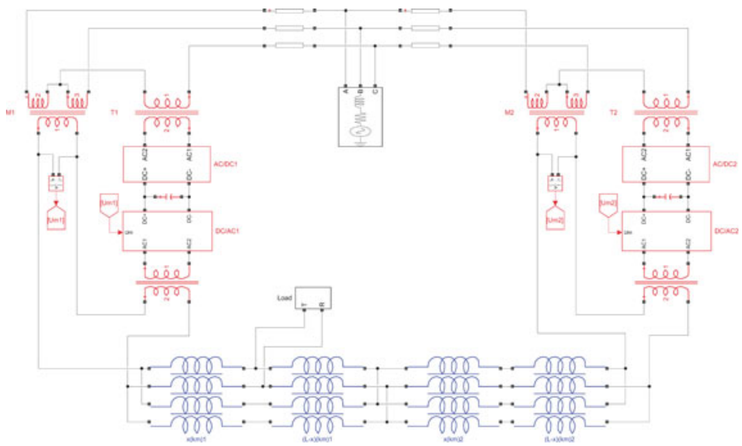


Fig. 3 Simulation model of traction substation for networked traction power supply system

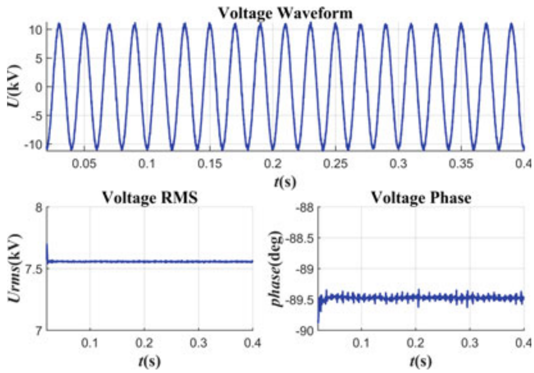


Fig. 4 Transformer output voltage simulation of PET

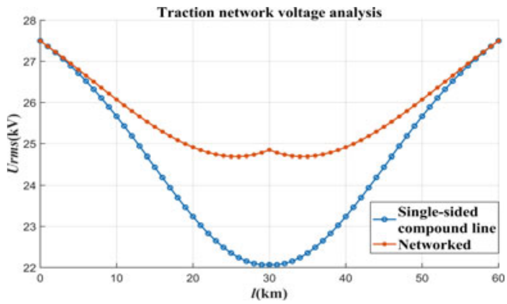
4.2 System Performance Analysis

The desired output voltage of the traction substation has a magnitude of 27.5 kV and a phase angle of -90°; the primary and secondary voltage ratio of Block M of Scott transformer is 110 kV/20 kV, and the simulated output voltage of the secondary output voltage of Block M has a magnitude of 19.9 kV and a phase angle of -90.28°. According to Eq. (1), the output AC voltage from the PET is 7.51 kV with a phase angle of -89.25° after the transformer step-up. The voltage waveform simulation is shown in Fig. 4.

According to Fig. 4, after the PET is stepped up by the transformer, the RMS value of the output voltage is 7.52 kV and the phase angle is -89.31°, which can realize the control of the output voltage of the traction substation. The networked traction power supply system makes the output voltage of adjacent traction substations achieve the same amplitude, frequency and phase through the regulating effect of PET, and thus the system does not produce equalization current and electromagnetic ringing problem.

According to the established system simulation model, comparing the voltage loss of the traditional single-sided complex traction power supply system and the networked traction power supply system, the impedance per unit length of the traction network is taken to be $0.131 + 0.366i$ (Ω/km), the length of the power supply arm of the traction substation is 30 km, and the traction load current is taken to be 1000 A. The change of the traction network voltage with the movement of the traction load position is shown in Fig. 5.

Fig. 5 Traction network voltage analysis of traction power supply system



5 Conclusion

This paper analyzes the system structure and operation principle of the networked traction power supply system, establishes a simulation model based on MATLAB/Simulink simulation platform, verifies the feasibility of the networked traction power supply system, explores the performance advantages of the system, and provides a basis for further research and practice of the networked traction power supply system.

The networked traction power supply system is based on power electronics technology, drawing on flexible transmission and energy interconnection technology, and integrating railroad regenerative braking energy utilization technology. Through the regulation of PET, it can ensure that the feeder outlet voltage between groups of traction substations remains stable and of the same frequency and phase, avoiding the phenomenon of electromagnetic ring network in the system and reducing the impact of the traction power supply system on the power system, while also regulating the power tide between traction substations, improving the power tide characteristics of the traction network, realizing the power controllability and transferability of the traction power supply system, improving the quality of power supply, and increasing the utilization rate of new energy.

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