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Power supply arm protection scheme of high-speed railway based on wide-area current differential

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Abstract
When fault occurs on cross-coupling autotransformer (AT) power supply traction network, the up-line and down-line feeder circuit breakers in the traction substation trip at the same time without selectivity, which leads to an extended power failure. Based on equivalent circuit and Kirchhoff's current law, the feeder current characteristic in the substation, AT station and sectioning post when T–R fault, F–R fault, and T–F fault occur are analyzed and their expressions are obtained. When the traction power supply system is equipped with wide-area protection measurement and control system, the feeder protection device in each station collects the feeder currents in other two stations through the wide-area protection channel and a wide-area current differential protection scheme based on the feeder current characteristic is proposed. When a short-circuit fault occurs in the power supply arm, all the feeder protection devices in each station receive the feeder currents with time stamp in other two stations. After data synchronous processing and logic judgment, the fault line of the power supply arm can be identified and isolated quickly. The simulation result based on MATLAB/Simulink shows that the power supply arm protection scheme based on wide-area current differential has good fault discrimination ability under different fault positions, transition resistances, and fault types. The verification of measured data shows that the novel protection scheme will not be affected by the special working conditions of the electrical multiple unit (EMU), and reliability, selectivity, and rapidity of relay protection are all improved.

Keywords Cross-coupling AT power supply · Wide-area current differential · Power supply arm protection · Equivalent circuit · High-Speed railway

1 Introduction

The cross-coupling autotransformer (AT) power supply mode is wholly applied to the traction power supply system of China's high-speed railway. The up line and down line of power traction network are connected through cross-line through busbars and circuit breakers in the substation (SS), autotransformer station (ATS) and sectioning post (SP). When a fault occurs on the traction network, the up-line and down-line feeder protection in the SS act and then the up-line and down-line circuit breakers trip at the same time. After the power failure of the traction network, the under-voltage protection of feeder protection device in the ATS and SP act and the feeder circuit breakers trip. Thus, the up and down line of traction power supply arm is separate. After reclosing delay (generally 2 s), the up-line and down-line feeder circuit breakers in the SS reclose, the nonfault line circuit breaker recloses successfully. Then, the up-line and down-line feeder protection devices in the ATS and SP detect the voltage on the traction network and the circuit breakers reclose successfully, so that up and down line of traction network returns to normal cross-coupling AT power supply mode. Obviously, as long as there is a fault on traction network, the feeder protection devices of fault line and nonfault line of the traction network will trip without selectivity, which leads to an extended power failure. Moreover, the circuit breaker of the nonfault line in the SS will be

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impacted by the fault current, which will affect the service life of the circuit breaker.

The real-time interaction of fault information among the protection devices in the SS, ATS and SP through generic object-oriented substation event (GOOSE) communication function based on IEC61850 standard is realized in reference [1]. The feeder protection devices and the fault location system of the power supply arm exchange the fault data and realize the selective tripping of fault line. However, for the multiple information interaction between all stations in the power supply arm, the fault removal will be delayed, and the stability and reliability of the protection also should be verified. Under the condition of wide-area measurement and control system, the traction power supply system, references [2, 3] adopt the high-speed railway power supply arm selective-tripping protection scheme based on the impedance and/or current characteristics of feeders in the SS, ATS and SP. When a metallic fault occurs near the installation station of the voltage transformer, especially near the ATS and SP, very low voltage leads to systematic error in the impedance angle and current direction, which may lead to misjudgment of the relay protection device. Reference [4] proposed a selective-tripping scheme of the power supply arm based on the calculation of the correlation coefficient of the feeder current. By analyzing the correlation coefficient characteristics of the feeder currents in all stations under typical short-circuit conditions, the fault identification and judgment can be realized, and the fault line can be isolated within 83 ms with selectivity and rapidity. In this scheme, it is necessary to transmit the complete fault current waveform between the feeder protection devices of the whole power supply arm for calculation, so it is relatively difficult to achieve higher requirements for feeder protection devices.

The wide-area protection measurement and control system are gradually applied in the traction power supply system of high-speed railway [5–7] in China. It is possible to apply the new power supply arm protection scheme to the traction power supply system, avoid misjudgment caused by the systematic error of voltage transformer in the existing scheme, shorten the data exchange time between the stations and improve the reliability, selectivity and rapidity of the power supply arm protection.

Wide-area protection has been widely used in the line protection of power systems, such as the pilot protection scheme based on the current phase change [8, 9], longitudinal differential protection scheme applied to transmission lines [10, 11], transmission lines protection based on the phasor measurement unit (PMU) [12, 13], the wide-area differential protection scheme realized by the differential ring [14], and the application in the distribution network [15, 16]. In this paper, a new protection scheme based on wide-area current differential for the power supply arm of high-speed railway traction power supply system is proposed, and the current sampling value (SV) collected by the merging unit (MU) in the SS, ATS and SP is transmitted to each station through the wide-area protection measurement and control channel. The current differential protection scheme is adopted by the feeder protection devices of each station to independently judge the fault line of power supply traction network, so as to isolated fault line rapidly. The validity of the proposed protection scheme is verified by the simulation results based on MATLAB/Simulink.

2 Fault current analysis of cross-coupling AT power supply traction network

The typical structure of the cross-coupling AT power supply traction network is shown in Fig. 1. CB1 and CB2 are the down-line and up-line feeder circuit breakers in the SS, respectively; CB3 and CB4 are the down-line and up-line feeder circuit breakers in the ATS, respectively; CB5 and CB6 are the down-line and up-line feeder circuit breakers of the SP, respectively. T1, R1, and F1 are the trolley wire, rail and negative wire on the down line of traction network, respectively; T2, R2, and F2 are the trolley wire, rail and negative wire on the up line of traction network, respectively. $\dot{I}_{t1}$, $\dot{I}_{f1}$, $\dot{I}_{t3}$, $\dot{I}_{f3}$, $\dot{I}_{t5}$, and $\dot{I}_{f5}$ are the trolley wire and negative wire currents on the down-line feeder in the SS, ATS and SP, respectively; $\dot{I}_{t2}$, $\dot{I}_{f2}$, $\dot{I}_{t4}$, $\dot{I}_{f4}$, $\dot{I}_{t6}$, and $\dot{I}_{f6}$ are the trolley wire and negative wire currents on the up-line feeder in the SS, ATS and SP, respectively; $\dot{I}_{r1}$, $\dot{I}_{r2}$, $\dot{I}_{r3}$, $\dot{I}_{r4}$, $\dot{I}_{r5}$, and $\dot{I}_{r6}$ are the rail currents in the SS, ATS and SP, respectively; the positive direction of all the above currents is from the station to the traction network. $\dot{I}_{at1}$, and $\dot{I}_{at2}$ are the AT neutral current in the ATS and SP, respectively. D_1 is the distance from the SS to the ATS, and D_2 is the distance from the ATS to SP in km; x_1 is the distance from the fault point k_1 to the SS, and x_2 is the distance from the fault point k_2 to the SP.

Normally, short-circuit fault types of cross-coupling AT power supply traction network include trolley wire to rail fault (T–R), negative wire to rail fault (F–R), and trolley wire to negative wire fault (T–F).

2.1 T–R short-circuit fault

As shown in Fig. 1, when T–R short-circuit fault k_1 occurs on the down line in the section SS-ATS, the equivalent circuit of cross-coupling AT power supply mode [17] can be obtained as shown in Fig. 2.

In Fig. 2, $\dot{I}_k$ is the short-circuit current at fault point in the equivalent circuit; $\dot{I}'_{t1}$ and $\dot{I}'_{t2}$ are the currents of the down-line and up-line trolley wires in the equivalent circuit. $\dot{I}'_{H1}$ and $\dot{I}'_{H2}$ are the cross-line currents flowing from the up line to the down line, respectively, in the ATS and the SP. T'_1, F'_1, R'_1 and T'_2, F'_2, R'_2 are the trolley wire, negative wire and rail on the down line

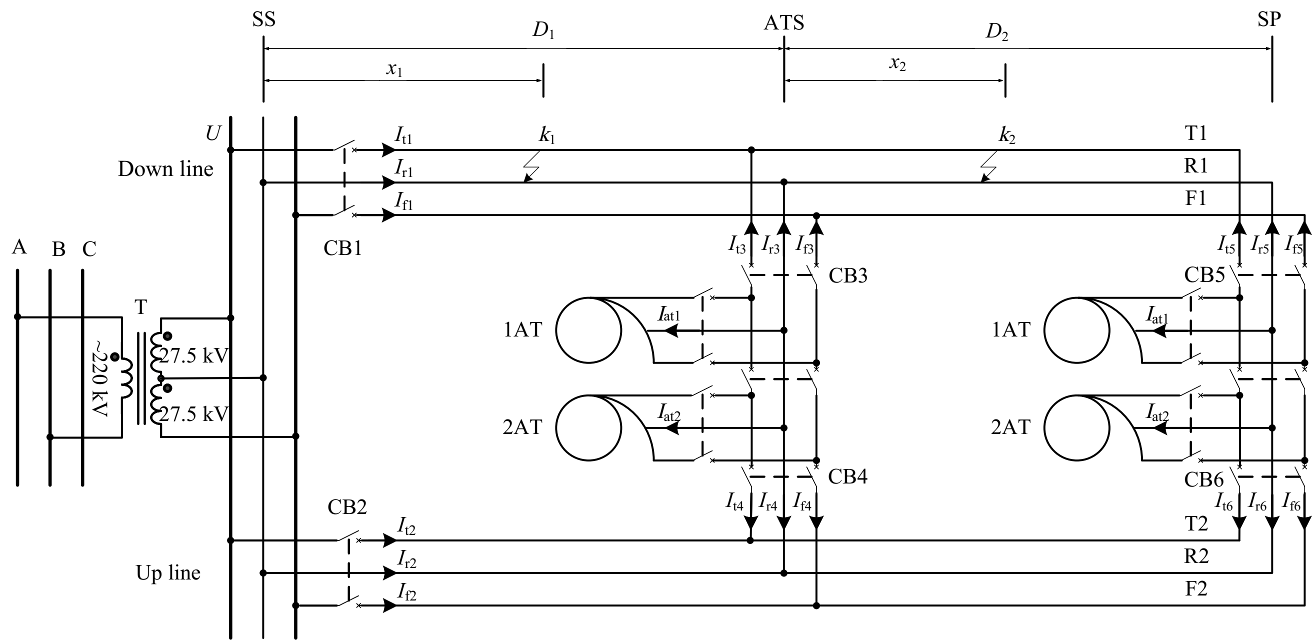

Fig. 1 Diagram of cross-coupling AT power supply traction network

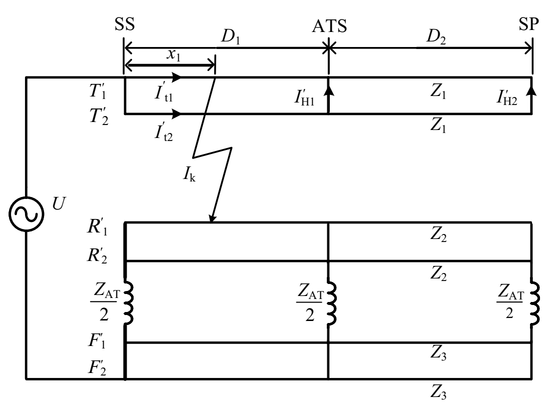

Fig. 2 Equivalent circuit when T–R fault occurs in the section SS-ATS

and up line of equivalent circuit, respectively. Z_{AT} is the leakage reactance of each auto-transformer, ideally 0 Ω. Z_1, Z_2, and Z_3, respectively, represent the equivalent impedance of the trolley wire, rail and negative wire in the equivalent circuit [17], and their values can be expressed as

$$\begin{cases} Z_1 = \dfrac{1}{2}(Z_T + Z_{FR} - Z_{TR} - Z_{TF}) \\ Z_2 = Z_R + \dfrac{1}{2}(Z_T - 3Z_{TR} - Z_{FR} + Z_{TF}) \\ Z_3 = \dfrac{1}{4}(Z_F - Z_T) + \dfrac{1}{2}(Z_{TR} - Z_{FR}) \end{cases}, \tag{1}$$

where Z_T, Z_F, and Z_R respectively, represent the self-impedance of the actual trolley wire, rail, and negative wire and Z_{TR}, Z_{TF}, and Z_{FR} the mutual impedance between each conductor.

In Fig. 2, according to the current relationship [17, 18] between the equivalent circuit and the actual circuit, the down-line feeder current $\dot{I}_{tf1}$ and the up-line feeder current $\dot{I}_{tf2}$ in the SS are expressed:

$$\begin{cases} \dot{I}_{tf1} = \dot{I}_{t1} - \dot{I}_{f1} = \dot{I}'_{t1} \\ \dot{I}_{tf2} = \dot{I}_{t2} - \dot{I}_{f2} = \dot{I}'_{t2} \end{cases}. \tag{2}$$

In Fig. 2, according to Ref. [18], the down-line feeder current $\dot{I}_{tf3}$ and the up-line feeder current $\dot{I}_{tf4}$ in the ATS are expressed in Eq. (3), and the down-line feeder current $\dot{I}_{tf5}$ and the up-line feeder current $\dot{I}_{tf6}$ in the SP are expressed in Eq. (4).

$$\begin{cases} \dot{I}_{tf3} = \dot{I}_{t3} - \dot{I}_{f3} = \dot{I}_{H1} \\ \dot{I}_{tf4} = \dot{I}_{t4} - \dot{I}_{f4} = -\dot{I}_{H1} \end{cases}, \tag{3}$$

$$\begin{cases} \dot{I}_{tf5} = \dot{I}_{t5} - \dot{I}_{f5} = \dot{I}_{H2} \\ \dot{I}_{tf6} = \dot{I}_{t6} - \dot{I}_{f6} = -\dot{I}_{H2} \end{cases}. \tag{4}$$

In the circuit of the T'_1 and T'_2 of the equivalent circuit in Fig. 2, there is cross-line in the SS and ATS, which connects down line and up line of power supply arm, with symmetry in parameters. According to Eq. (2) and Fig. 2, the following equation can be obtained:

$$\begin{cases} \dot{I}_{\text{tf1}} = \dot{I}'_{\text{t1}} = \dfrac{2D_1 - x_1}{2D_1}\dot{I}_{\text{k}} \\ \dot{I}_{\text{tf2}} = \dot{I}'_{\text{t2}} = \dfrac{x_1}{2D_1}\dot{I}_{\text{k}} \end{cases}. \tag{5}$$

According to the equivalent circuit in Fig. 2, $\dot{I}'_{t2}$ only flows on the cross-line between T'_1 and T'_2 where ATS is not in the SP, so that the cross-line current $\dot{I}_{H1} = \dot{I}'_{t2}$ in the ATS and the cross-line current $\dot{I}_{H2} = 0$ in the SP. According to Eqs. (3)–(5), the feeder currents in ATS and SP can be obtained:

$$\begin{cases} \dot{I}_{\text{tf3}} = -\dot{I}_{\text{tf4}} = \dfrac{x_1}{2D_1}\dot{I}_{\text{k}} \\ \dot{I}_{\text{tf5}} = -\dot{I}_{\text{tf6}} = 0 \end{cases}. \tag{6}$$

As shown in Fig. 1, T–R fault k_2 occurs on the down line in the section ATS-SP, and the equivalent circuit of the cross-coupling AT power supply mode traction network can be obtained as shown in Fig. 3:

In Fig. 3, $\dot{I}'_{t1}$ and $\dot{I}'_{t2}$ represent the down-line and up-line traction network currents in the section ATS-SP in the equivalent circuit, and Eq. (7) can be easily obtained according to Fig. 3:

$$\begin{cases} \dot{I}'_{\text{t1}} = \dfrac{2D_2 - x_2}{2D_2}\dot{I}_{\text{k}} \\ \dot{I}'_{\text{t2}} = \dfrac{x_2}{2D_2}\dot{I}_{\text{k}} \end{cases}. \tag{7}$$

In Fig. 3, there is a cross-line in the ATS, and the down line and up line are symmetrical in parameters, so Eq. (8) can be easily obtained:

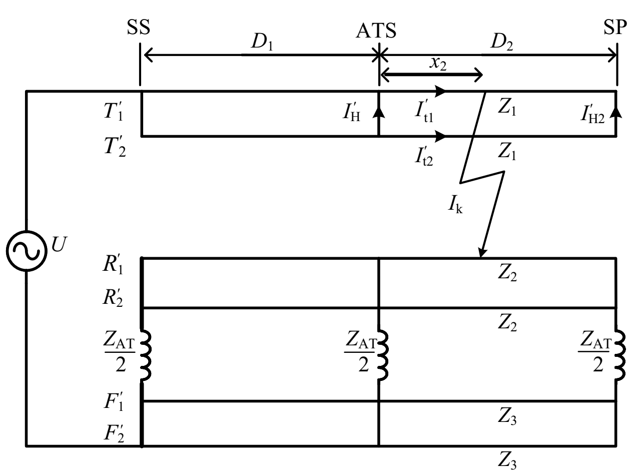

Fig. 3 Equivalent circuit when T–R fault occurs in the section ATS-SP

$$\dot{I}_{\text{tf1}} = \dot{I}_{\text{tf2}} = \frac{\dot{I}'_{\text{t1}} + \dot{I}'_{\text{t2}}}{2} = \frac{1}{2}\dot{I}_{\text{k}} \quad . \tag{8}$$

According to Fig. 3 and Eq. (7), the cross-line currents in the ATS and SP [19] can be obtained as:

$$\begin{cases} \dot{I}_{\text{H1}} = \dfrac{\dot{I}'_{\text{t1}} - \dot{I}'_{\text{t2}}}{2} = \dfrac{D_2 - x_2}{2D_2}\dot{I}_{\text{k}} \\ \dot{I}_{\text{H2}} = \dot{I}'_{\text{t2}} = \dfrac{x_2}{2D_2}\dot{I}_{\text{k}} \end{cases}. \tag{9}$$

Therefore, according to Eqs. (3) and (9), Eq. (10) can be obtained:

$$\begin{cases} \dot{I}_{\text{tf3}} = \dot{I}_{\text{H1}} = \dfrac{D_2 - x_2}{2D_2}\dot{I}_{\text{k}} \\ \dot{I}_{\text{tf4}} = -\dot{I}_{\text{H1}} = -\dfrac{D_2 - x_2}{2D_2}\dot{I}_{\text{k}} \end{cases}. \tag{10}$$

According to Eqs. (4) and (9), Eq. 11 can be obtained:

$$\begin{cases} \dot{I}_{\text{tf5}} = \dot{I}_{\text{H2}} = \dfrac{x_2}{2D_2}\dot{I}_{\text{k}} \\ \dot{I}_{\text{tf6}} = -\dot{I}_{\text{H2}} = -\dfrac{x_2}{2D_2}\dot{I}_{\text{k}} \end{cases}. \tag{11}$$

According to the calculated results that have been obtained, when T–R fault occurs on the down line, whether it is in the section SS-ATS or in the section ATS-SP, Eq. (12) is obtained. It shows that the sum of the feeder currents in all stations can be used as the criterion for judging the down-line fault.

$$\begin{cases} \dot{I}_{\text{tf1}} + \dot{I}_{\text{tf3}} + \dot{I}_{\text{tf5}} = \dot{I}_{\text{k}} \\ \dot{I}_{\text{tf2}} + \dot{I}_{\text{tf4}} + \dot{I}_{\text{tf6}} = 0 \end{cases}. \tag{12}$$

Similarly, when T–R fault occurs on the up line, whether it is in the section SS-ATS or in the section ATS–SP, Eq. (13) can be obtained. It shows that the sum of the feeder currents in all stations can be used as the criterion for judging the up-line fault.

$$\begin{cases} \dot{I}_{\text{tf1}} + \dot{I}_{\text{tf3}} + \dot{I}_{\text{tf5}} = 0 \\ \dot{I}_{\text{tf2}} + \dot{I}_{\text{tf4}} + \dot{I}_{\text{tf6}} = \dot{I}_{\text{k}} \end{cases}. \tag{13}$$

2.2 F–R short-circuit fault

Similar to T–R short-circuit fault, the same feeder current expressions can be obtained when F–R short-circuit fault occurs except for the difference in impedance parameters of equivalent circuit. Equation (12) is true in case of down-line fault, and Eq. (13) is true in case of up-line fault.

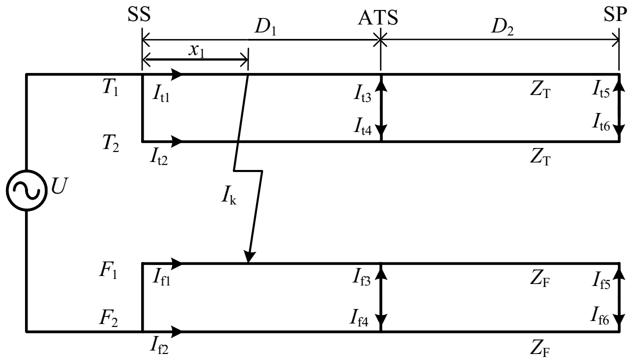

Fig. 4 Simplified circuit when T–F fault occurs on the down line in the section SS–ATS

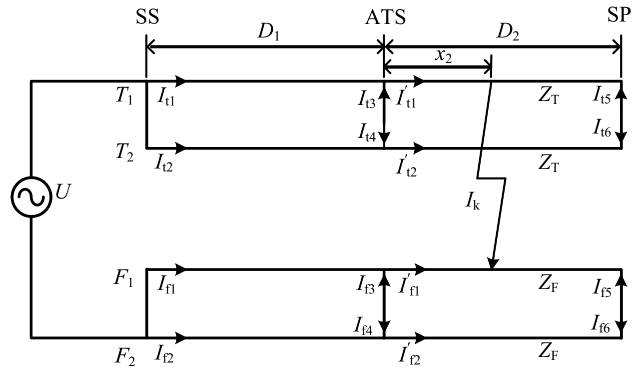

Fig. 5 Simplified circuit when T–F fault occurs on the down line in the section ATS–SP

2.3 T–F short-circuit fault

In an ideal case, for the symmetry in parameters of trolley wire and negative wire, when T–F fault k_1 occurs on the down line in the section SS-ATS, it is considered that the auto-transformers of ATS and SP are bypassed. The simplified fault circuit, rather than equivalent circuit, of the cross-coupling AT power supply traction network is shown in Fig. 4. Where T_1, F_1 and T_2, F_2 are the trolley wire, negative wire on the down line and up line of simplified circuit, respectively.

According to Fig. 4, Eq. (14) can be easily obtained:

$$\begin{cases} \dot{I}_{t1} = -\dot{I}_{f1} = \dfrac{2D_1 - x_1}{2D_1}\dot{I}_k \\ \dot{I}_{t2} = -\dot{I}_{f2} = \dfrac{x_1}{2D_1}\dot{I}_k \end{cases}. \tag{14}$$

According to Fig. 4, Eqs. (3), (4) and (14), the feeder currents of each station can be obtained:

$$\begin{cases} \dot{I}_{tf1} = \dfrac{2D_1 - x_1}{D_1}\dot{I}_k \\ \dot{I}_{tf2} = \dot{I}_{tf3} = -\dot{I}_{tf4} = \dfrac{x_1}{D_1}\dot{I}_k \\ \dot{I}_{tf6} = \dot{I}_{tf5} = 0 \end{cases}. \tag{15}$$

Similarly, when T–F fault k_2 occurs on the down line in the section ATS-SP, the simplified fault circuit of the cross-coupling AT power supply traction network is obtained as shown in Fig. 5.

According to Fig. 5, Eq. (16) can be easily obtained:

$$\begin{cases} \dot{I}'_{t1} = -\dot{I}'_{f1} = \dfrac{2D_2 - x_2}{2D_2}\dot{I}_k \\ \dot{I}'_{t2} = -\dot{I}'_{f2} = \dfrac{x_2}{2D_2}\dot{I}_k \end{cases}. \tag{16}$$

According to Fig. 5, Eqs. (3), (4) and (16), the feeder currents at each station can be obtained:

$$\begin{cases} \dot{I}_{tf1} = \dot{I}_{tf2} = \dot{I}_k \\ \dot{I}_{tf3} = -\dot{I}_{tf4} = \dfrac{D_2 - x_2}{D_2}\dot{I}_k \\ \dot{I}_{tf5} = -\dot{I}_{tf6} = \dfrac{x_2}{D_2}\dot{I}_k \end{cases}. \tag{17}$$

According to Eqs. (15) and (16), when T–F fault occurs on the down line, the sum of feeder currents of all stations can be obtained:

$$\begin{cases} \dot{I}_{tf1} + \dot{I}_{tf3} + \dot{I}_{tf5} = 2\dot{I}_k \\ \dot{I}_{tf2} + \dot{I}_{tf4} + \dot{I}_{tf6} = 0 \end{cases}. \tag{18}$$

Similarly, according to the symmetry of the up line and down line of the traction network, when T–F fault occurs on the up line, the sum of the feeder currents of all stations can be obtained:

$$\begin{cases} \dot{I}_{tf2} + \dot{I}_{tf4} + \dot{I}_{tf6} = 0 \\ \dot{I}_{tf2} + \dot{I}_{tf4} + \dot{I}_{tf6} = 2\dot{I}_k \end{cases}. \tag{19}$$

According to the current distribution characteristics of short-circuit faults of various types, it can be seen that when T–R and F–R short-circuit faults occur on the up line, the sum of up-line feeder currents of all stations is equal to the fault current; when T–F fault feeder occurs on the up line, the sum of up-line feeder currents of all stations is twice the fault current; no matter which type of fault, the sum of down-line feeder currents of all stations is zero, as shown in Eqs. (13) and (19); when T–R and F–R short-circuit fault on the down line, the sum of down-line feeder currents of all stations is equal to the fault current; when T–F fault occurs on the down line, the sum of feeder currents of all stations is twice the fault current; no matter which type of fault, the sum of up-line feeder currents of all stations is zero, as shown in

Eqs. (12) and (18). By applying the wide-area protection measurement and control system, according to the feeder current characteristics when fault occurs, the power supply arm protection scheme based on wide-area current differential can be constructed.

3 Power supply arm protection scheme based on wide-area current differential

3.1 Existing protection scheme for power supply arm

At present, the traction power supply system is equipped with wide-area protection measurement and control system with power supply arm as unit on Beijing–Shenyang, Beijing–Zhangjiakou and Nanchang–Shenzhen high-speed railway in China [7]. As shown in Fig. 6, the smart traction substation [6] based on IEC61850 protocol is equipped with wide-area protection channel connecting with protection intelligent electronic device (IED), where the abbreviations that have not been mentioned are as follows:

- High voltage (HV),
- Online monitoring (OM),
- Overhead contact system (OCS),
- Protection, measurement and control intelligent electronic device (P, M&C),
- Wide-area measurement, protection and control (WAM P&C),
- Station area measurement, protection and control (SAM P&C),
- Manufacturing message specification recording and analysis (MMS R&A).

According to the communication connection of all stations, the wide-area protection channel in existing power supply arm protection scheme is shown in Fig. 7. Based on the GOOSE function of IEC61850 protocol [20], the feeder protection devices of the traction substation receive the judgment result of the distance protection element and/or overcurrent protection element of the feeder protection device on the same line in the ATS and SP. Through comprehensive analysis of the feeder protection devices in traction substation, fault line can be identified. The feeder protection device (FPD) on the fault line in traction substation

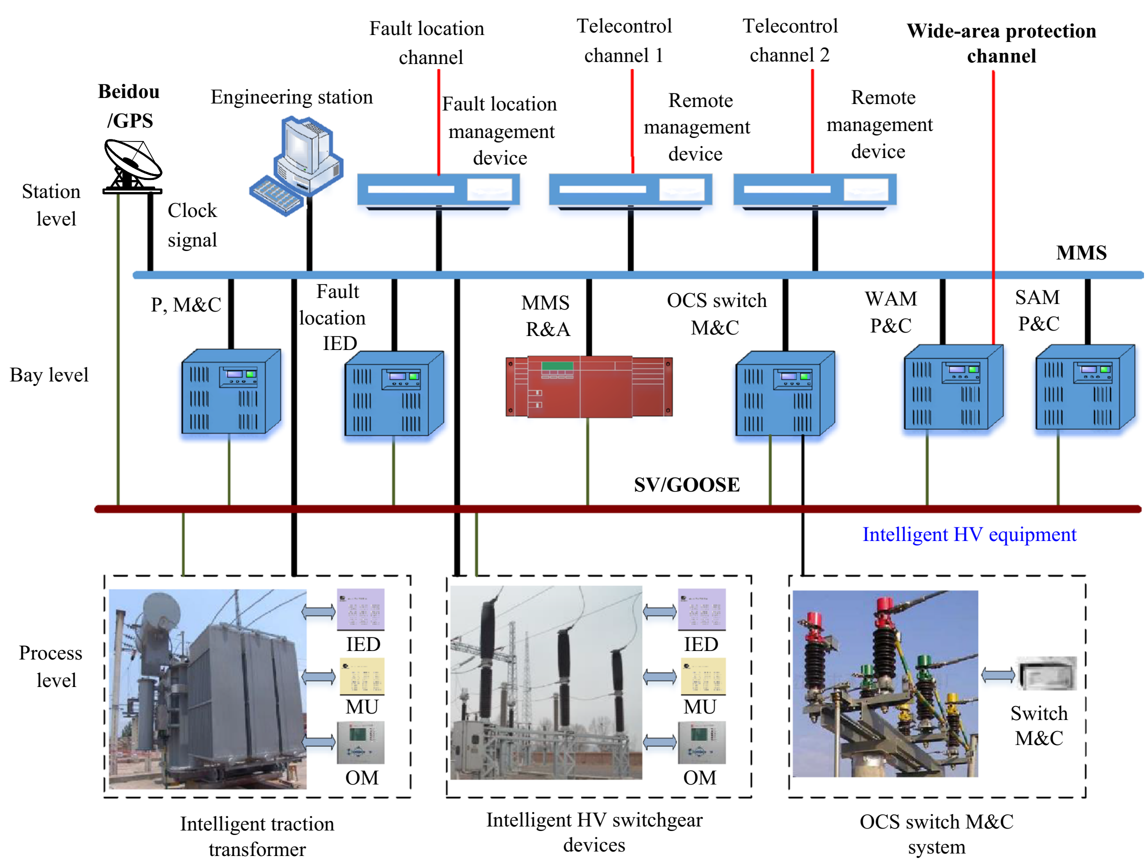

Fig. 6 Architecture of smart traction substation based on IEC61850

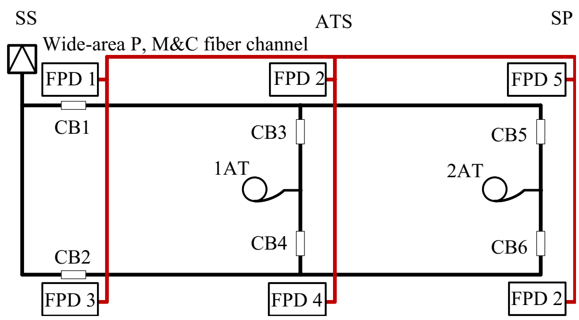

Fig. 7 Wide-area protection channel scheme for power supply arm protection

trips its own circuit breaker and sends tripping command to the feeder protection devices on the same line in the ATS and SP. Thus, the fault line can be identified and isolated selectively.

3.2 Novel principle of wide-area current differential protection

Because of the natural selectivity of current differential protection, it is widely used in transformer protection, line protection and bus protection of power systems. With the development of modern communication technology [21], current differential protection is basically unaffected by distance between stations [11, 22]. Based on the dedicated communication channel or wide-area network channel, the exchange of current data with time stamp can be realized by the transmission protection devices at double terminals or multiple terminals [23], and the wide-area protection of long-distance transmission lines can be realized.

Based on the principle of multi-terminal current longitudinal differential protection of transmission lines, the traction power supply wide-area protection measurement and control channel are used to exchange feeder current data sampled synchronously with each other every ms. Based on the same current synchronous data with time stamp and criterion, a novel power supply arm protection scheme based on wide-area current differential is proposed.

According to Eqs. (12) and (18), the criterion of wide-area current differential protection scheme for down line is obtained.

$$\begin{cases} I_1 = |\dot{I}_{\mathrm{tf1}} + \dot{I}_{\mathrm{tf3}} + \dot{I}_{\mathrm{tf5}}| \ge k \cdot I_{\mathrm{ml.d}} \\ t_1 \ge t_{\mathrm{set}} \end{cases} . \tag{20}$$

According to Eqs. (13) and (19), the criterion of wide-area current differential protection scheme for up line is obtained.

$$\begin{cases} I_2 = |\dot{I}_{\mathrm{tf2}} + \dot{I}_{\mathrm{tf4}} + \dot{I}_{\mathrm{tf6}}| \ge k \cdot I_{\mathrm{ml.u}} \\ t_2 \ge t_{\mathrm{set}} \end{cases} , \tag{21}$$

where k is the reliability coefficient, normally 1.2; $I_{\mathrm{ml.d}}$ and $I_{\mathrm{ml.u}}$ are the maximum load current of the down line and up line, respectively; t_{set} is the setting delay, normally 20 ms, which should avoid the isolation time of internal fault of the EMU.

According to Eq. (20), the down-line feeder protection device of each station can identify the down-line fault and selectively trip the down-line feeder circuit breakers CB1, CB3 and CB5. According to Eq. (21), the up-line feeder protection device of each station can identify the up-line fault and selectively trip the up-line feeder circuit breakers CB2, CB4 and CB6.

3.3 Advantages of wide-area current differential protection

In the existing power supply arm protection scheme [1–3] described in Sect. 3.1, the feeder protection devices in the ATS and SP must send protection discriminated results of distance protection and/or overcurrent protection to the feeder protection device. The feeder protection devices in the SS judge the fault line and then send the tripping commands to the feeder protection devices on the fault line in the ATS and SP. Therefore, the transmission of fault data and tripping command requires two information back and forth as soon as possible, which delays the fault isolation time. The novel wide-area current differential protection proposed in this paper only needs to send the feeder current data in one direction, and each feeder protection device makes independent decision and tripping, thus saving a GOOSE communication transmission time compared with the existing application of power supply arm protection. According to the field measurement data of the Beijing–Zhangjiakou high-speed railway, the maximum delay of the wide-area protection channel from the SS to the SP is 14 ms. It shows the wide-area differential protection proposed in this paper is 14 ms faster than the existing power supply arm protection scheme. The novel scheme is independent of feeder voltages in all stations, so there is no voltage dead zone problem in existing power supply arm protection scheme.

4 Verification

4.1 Verification by simulation

The simulation model of cross-coupling AT traction power supply system is built based on MATLAB/Simulink. The main simulation parameters are shown in Table 1.

Table 1 Simulation parameter values of AT traction cross-coupling power supply system

Parameter	Value
Power	
Three-phase line voltage (kV)	220
Frequency (Hz)	50
Short-circuit capacity (MVA)	2000
Traction transformer	
Type of transformer wiring	V/v
Transformer capacity (MVA)	50
Transformation ratio (kV)	220/27.5/27.5
Short-circuit voltage percentage	10.5%
AT transformer	
Transformer capacity (MVA)	32
Transformation ratio (kV)	55/27.5
Short-circuit voltage percentage	1.733%
Line parameters	
Length of power supply arm (km)	25
Length of section SS-ATS (km)	12
Length of section ATS-SP (km)	13

The impedance parameters of cross-coupling AT power supply traction network are shown in Eq. (22) [24].

Taking the Beijing–Shanghai high-speed railway as an example, the maximum load current of one EMU in active operation EMUs is 800 A. The minimum tracking interval for EMU is 3 min, and it is up to two EMUs running on one line of the power supply arm. Thus, the maximum load current on one line is twice the maximum load current of one EMU with maximum load current, so the setting values of Eqs. (20) and (21) are all 1920 A.

When different types of short-circuit faults with different transition resistances ($R_g = 0$, 10 Ω) occur at different positions of cross-coupling AT power supply arm, the simulation results are shown in Figs. 8 and 9, in which the horizontal axis is the distance from SS to the fault position. The sum of down-line feeder currents of all stations I1 and the sum of up-line feeder currents of all stations I2 are calculated according to Eqs. (20) and (21), respectively.

The simulation results are also shown in Tables 2, 3, and 4, in which the fault distance of '12(−)' is the end of the section SS-ATS and the fault distance of '12(+)' is the beginning of the section ATS-SP.

As shown in Figs. 8, and 9, and Tables 2, 3, 4, when any type of short-circuit fault with different transition resistance occurs at any position on the down line of the traction network, the sum of down-line feeder currents calculated by the down-line feeder protection device in the SS, ATS

$$Z = \begin{bmatrix} & T_1 & R_1 & F_1 & T_2 & R_2 & F_2 \\ T_1 & 0.1683+j0.5866 & 0.05+j0.314 & 0.05+j0.413 & 0.05+j0.3275 & 0.05+j0.314 & 0.05+j0.292 \\ F_1 & 0.05+j0.314 & 0.212+j0.7463 & 0.05+j0.314 & 0.05+j0.2918 & 0.05+j0.314 & 0.05+j0.2918 \\ R_1 & 0.05+j0.413 & 0.05+j0.314 & 0.1452+j0.7314 & 0.05+j0.292 & 0.05+j0.2918 & 0.05+j0.2629 \\ T_2 & 0.05+j0.3275 & 0.05+j0.317 & 0.05+j0.292 & 0.1683+j0.5866 & 0.05+j0.314 & 0.05+j0.4130 \\ R_2 & 0.05+j0.314 & 0.05+j0.314 & 0.05+j0.2918 & 0.05+j0.314 & 0.212+j0.7463 & 0.05+j0.314 \\ F_2 & 0.05+j0.292 & 0.05+j0.2198 & 0.05+j0.2629 & 0.05+j0.4130 & 0.05+j0.314 & 0.1452+j0.7314 \end{bmatrix}. \quad (22)$$

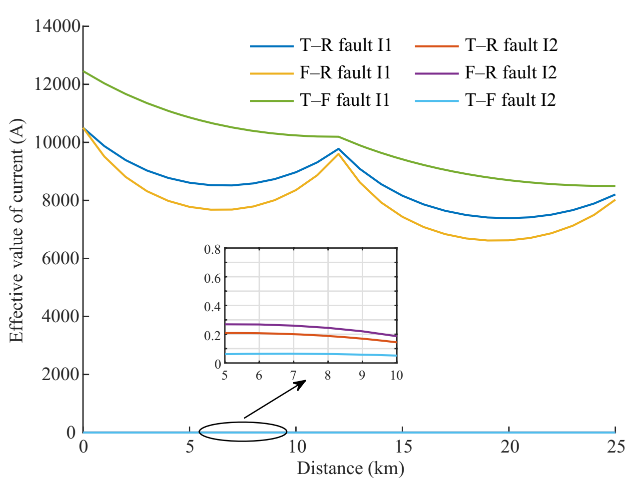

Fig. 8 Simulation results when T–R, F–R, and T–F faults occur on the down-line (R_g=0 Ω)

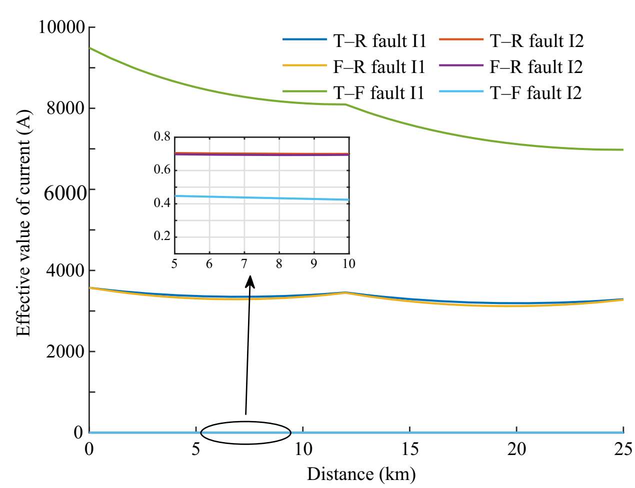

Fig. 9 Simulation results when T–R, F–R, and T–F faults occur on the down-line (R_g = 10 Ω)

Table 2 Simulation results when T–R faults occur on the down line

Fault distance (km)	Transition resistance (Ω)	Sum of the feeder current		Results (T/F)		
		I_1(A)	I_2(A)	Eq. (20)	Eq. (21)	Fault line
0	0	10506	0	T	F	Down
6	0	8524	0	T	F	Down
12(−)	0	9777	0	T	F	Down
12(+)	0	9085	0	T	F	Down
19	0	7384	0	T	F	Down
25	0	8203	0	T	F	Down
0	10	3573	1	T	F	Down
6	10	3355	1	T	F	Down
12(−)	10	3456	1	T	F	Down
12(+)	10	3393	1	T	F	Down
19	10	3192	1	T	F	Down
25	10	3289	1	T	F	Down

Table 3 Simulation results when F–R faults occur on the down line

Fault distance (km)	Transition resistance (Ω)	Sum of the feeder current		Results (T/F)		
		I_1(A)	I_2(A)	Eq. (20)	Eq. (21)	Fault line
0	0	10505	0	T	F	Down
6	0	7679	0	T	F	Down
12(−)	0	9600	0	T	F	Down
12(+)	0	8621	0	T	F	Down
19	0	6622	0	T	F	Down
25	0	8022	0	T	F	Down
0	10	3573	1	T	F	Down
6	10	3293	1	T	F	Down
12(−)	10	3446	1	T	F	Down
12(+)	10	3365	1	T	F	Down
19	10	3121	1	T	F	Down
25	10	3276	1	T	F	Down

and SP can satisfy Eq. (20) and the sum of up-line feeder currents calculated by the up-line feeder protection device in the SS, ATS and SP cannot satisfy Eq. (21). Thus, the fault is judged on the down line, and the faulty down line of the power supply arm is quickly isolated, and the up line of the power supply arm is normally powered.

According to the symmetry of the down line and up line of the traction network, when any type of short-circuit fault with different transition resistances occurs at any position on the up line of the traction network, the sum of up-line feeder currents calculated by the up-line feeder protection device in the SS, ATS and SP can satisfy Eq. (21) and the sum of down-line feeder currents calculated by the down-line feeder protection device in the SS, ATS and SP cannot satisfy Eq. (20). Thus, the fault is judged on the up line, and the faulty up line of the power supply arm is quickly isolated, and the down line of the power supply arm is normally powered.

4.2 Verification by measured data

According to the statistics of the field onboard measured data of the EMU running on the Beijing–Shanghai high-speed railway, the working conditions are as follows: accelerated process, running through the SP, and regenerative braking. The waveform of the maximum current measurement value is shown in Figs. 10, 11, and 12; the models are CR400AF and CRH380BL, respectively. The maximum current RMS (root mean square) statistics for CR400BF and CRH380D are shown in Table 5.

Table 4 Simulation results when T–F faults occur on the down line

Fault distance (km)	Transition resistance (Ω)	Sum of the feeder current		Results (T/F)		
		I_1(A)	I_2(A)	Eq. (20)	Eq. (21)	Fault line
0	0	12455	0	T	F	Down
6	0	10670	0	T	F	Down
12(−)	0	10193	0	T	F	Down
12(+)	0	9896	0	T	F	Down
19	0	8696	0	T	F	Down
25	0	8496	0	T	F	Down
0	10	9493	0	T	F	Down
6	10	8400	0	T	F	Down
12(−)	10	8094	0	T	F	Down
12(+)	10	7905	0	T	F	Down
19	10	7116	0	T	F	Down
25	10	6977	0	T	F	Down

The subordinate complex operating conditions are considered to verify the effectiveness of the proposed protection criterion. When one EMU is operating under the accelerated process, another EMU is running through the SP; and when one EMU operates under accelerated process, the other EMU operates under regenerative braking condition. By analyzing whether the above two cases of EMU running on one line of the power supply arm or distributed on both lines of the power supply arm, the maximum effective value of current obtained by the protection criterion Eqs. (20) and (21) is not greater than the setting value. It shows that the protection criterion is not affected by the special working conditions of EMU.

5 Conclusion

In this paper, the characteristics of feeder currents in the SS, ATS and SP under T–R, F–R and T–F short-circuit faults are obtained based on the equivalent circuit or simplified circuit of cross-coupling AT traction network and Kirchhoff's current law. Through wide-area protection measurement and control channel connecting each station, a novel power supply arm protection scheme based on wide-area current differential is proposed. The novel protection scheme realizes the identification and isolation of the fault line selectively. It is more selective than the traditional protection and tripping scheme and improves the rapidity by saving the communication time between stations, and judging fault line and tripping independently

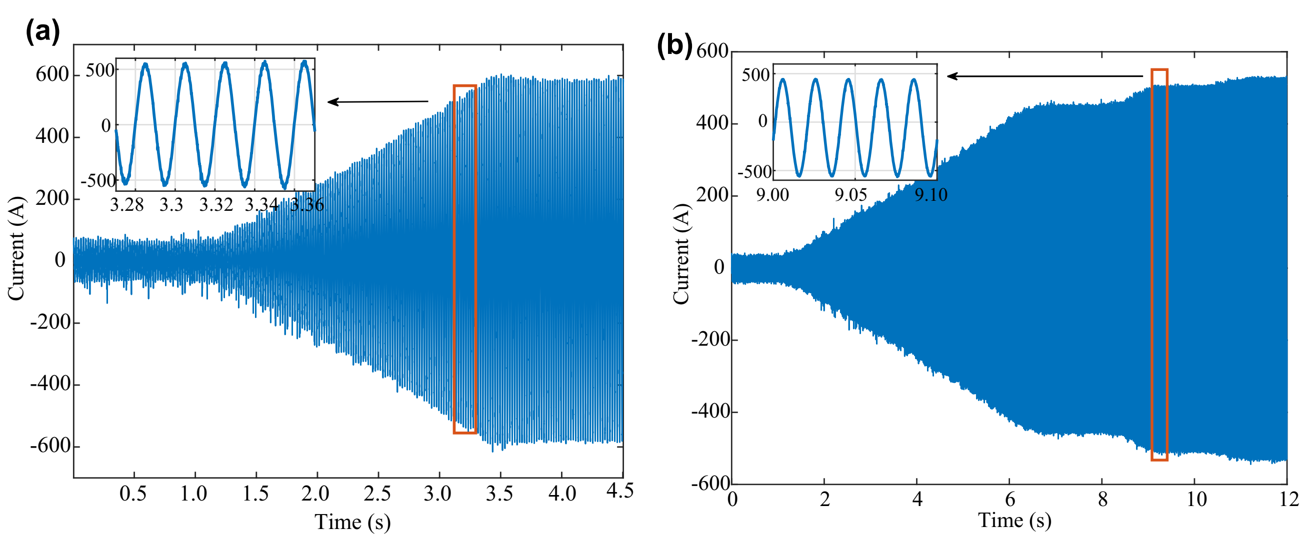

Fig. 10 Current measurement data of EMU under accelerated process: **a** CR400AF; **b** CRH380BL

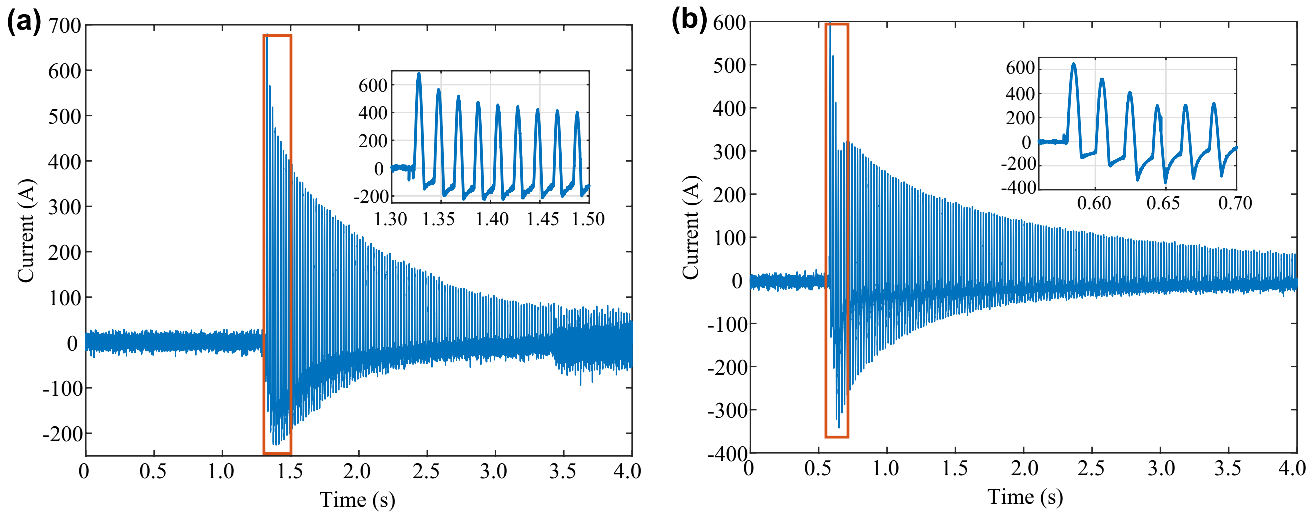

Fig. 11 Current measurement data of EMU running through the SP: **a** CR400AF; **b** CRH380BL

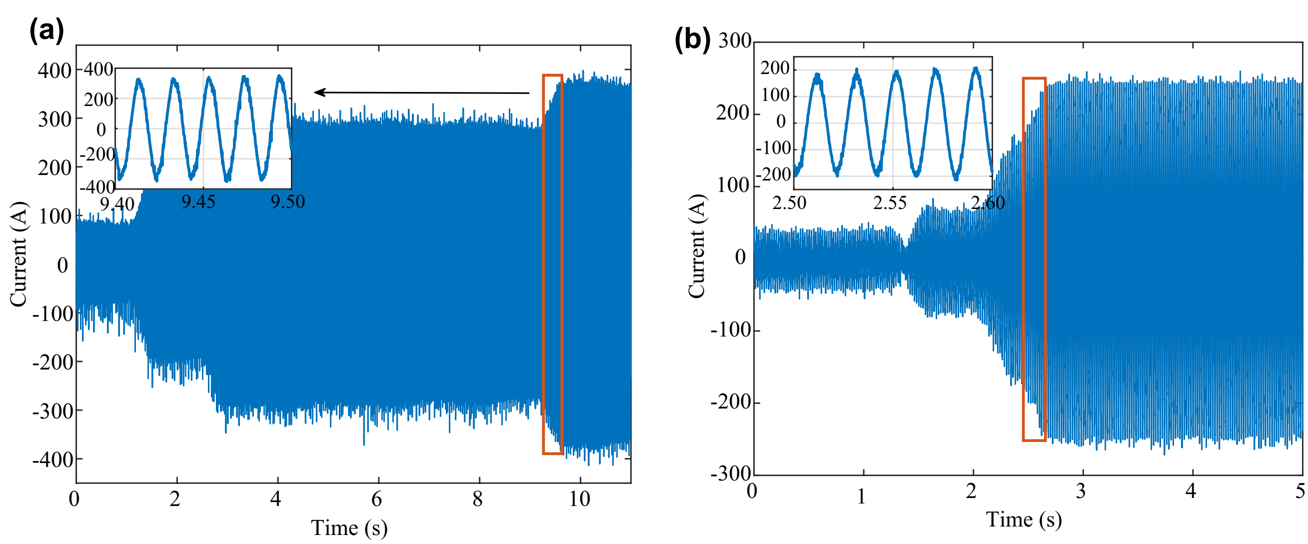

Fig. 12 Current measurement data of EMU under regenerative braking: **a** CR400AF; **b** CRH380BL

Table 5 Maximum current measurement value of EMU under different operating conditions

Operating conditions	CR400BF (A)	CRH380BL (A)
Accelerated process	450.83	334.44
Running through the SP	110.38	305.57
Regenerative braking	294.92	100.55

compared with the existing power supply arm protection schemes. In different fault positions, different transition resistances, and different fault types of short-circuit fault, the simulation results based on MATLAB/Simulink and measured data of various EMU models verify the correctness of novel protection scheme. The novel protection scheme improves the reliability by avoiding the influence of the voltage dead zone when the fault near station occurs.

It is worth pointing out that this protection scheme can utilize existing feeder protection devices and wide-area protection channels without additional hardware, so it is easy to be applied in traction power supply protection system.

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