Protection Method of Traction Power Supply System for Low and Medium Speed Maglev Traffic Based on Fault Traveling Wave Features

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Abstract

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busbars. Secondly, the direction of the current difference between stations is compared to locate the faulty section. Finally, the fault distance is calculated from the frequency difference of the fault voltage at the double-ended station. Through simulation, the method is validated to be unaffected by fault location, fault transition resistance, noise interference, and is applicable to short circuit faults caused by lightning strikes, and the ranging error always remains within 20m. The method has strong robustness, can effectively solve the problem of protection misoperation and accurately locate the fault point. It is suitable for low and medium speed magnetic levitation transportation power supply rail ground fault.

Introduction

Low and medium speed magnetic levitation is a new type of urban rail transit operation, operating at speeds between 100-120km/h [1]. The advantages of low operating costs, strong climbing ability and small turning radius compared with high-speed magnetic levitation [2]. Compared with subway and light rail, it has the advantages of safety and environmental protection, low noise, high speed and low construction cost [3]. It is suitable for intercity traffic linkage and can effectively relieve the traffic pressure in cities without affecting the environment. At present, low and medium speed magnetic levitation transportation has been vigorously developed at home and abroad [4].

The low and medium speed magnetic levitation uses the positive rail for power supply and the negative rail for return, and the power supply rail and return rail are installed on both sides of the track beam through insulators, so the possibility of short circuit faults between the positive and negative poles is low [5] - [6]. However, due to aging insulators and track fouling, there is an increased possibility of ground faults in the supply rails during train operation [7]. Therefore, when an earth short circuit fault occurs in the power supply system, it is important to quickly determine the fault occurrence section, activate the corresponding fault protection device to cut off the fault, accurately locate the fault occurrence location and then eliminate the fault to improve the train operation efficiency [8] - [9].

In 2015, the Changsha Maglev Express occurred in a 5.12 blackout, which was caused by a protection device malfunctioning due to a positive rail grounding fault during train operation, and the overvoltage grounding protection devices (hereinafter referred to as 64D) at all traction power stations on the line detected the fault current and tripped, which eventually led to the blackout of the entire line. Moreover, the short power supply distance between low and medium speed magnetic levitation traffic stations and the complex structure of the grounding network make it difficult to locate the fault point accurately after a DC ground fault occurs [10] - [11].

At present, the low and medium speed magnetic levitation traction power supply protection system mainly includes DC equipment frame protection, earth leakage protection and train frame protection [12]. The ground leakage protection system mainly uses 64D protection devices. For the problem of 64D misoperation, Woyang Li et al. [13] proposed to change the overvoltage protection to high current protection, and the protection action current value is set to 6000A, which can narrow the accident range and achieve trip selectivity. However, at this point the 64D becomes a single conductor device, requiring a device with a very high resistance to flow.

Fault location in DC systems is mainly based on the fault analysis method and the travelling wave method [14]. The fault analysis method, which is mainly used in traction power supply systems, is a method of analysing and calculating the relevant parameters of the system and the electrical quantities at the measurement points, and thus finding the fault distance [15]. Carlos A. Platero et al. [16] proposes an improved impedance ranging method based on the traditional line current relationship between the two ends considering the effect of high and low voltage at both ends. Abdelhamid Bendjabeura. et al. [17] proposes a double-ended asynchronous ranging method based on solving differential equations. Zhengqing Han et al. [18] presents an improved single-end fault location algorithm solved by genetic algorithm. Xincui Tian et al. [19] proposes a double-ended steady-state fault ranging algorithm that takes into account the distributed parameters of the rail-ground loop. The above method is improved on the basis of the original method of solving differential equations, which is less affected by the transition resistance of the fault point and can significantly reduce the distance measurement error. However, after a ground fault occurs in the supply rail, the fault current flows into the grounding network, the impedance distribution of the grounding network is very complex, and the idealised circuit model is difficult to apply in engineering practice.

The traveling wave method is mainly applied to high-voltage DC transmission line faults [20], where the fault distance is calculated by identifying the fault traveling wave head through the reflection of the fault traveling wave back and forth between the measurement end and the fault point [21] - [22]. Zewen Li et al. [23] proposes an improved single-ended traveling wave ranging method based on current detection at the midpoint of the line, where a current sensor is installed at the midpoint of the line to improve the single-ended traveling wave ranging system. Hongchun Shu et al. [24] proposes a method for fault ranging on high-voltage DC transmission lines using a two-terminal traveling wave frequency difference ratio. The traveling wave method is a hot research topic in the field of fault ranging, with the advantages of high fault ranging accuracy, independence from fault point transition resistance and low fault ranging cost. However, the current traveling wave method of fault ranging mostly studies ground faults in high-voltage DC transmission systems and has rarely been applied in low and medium-speed magnetic levitation traffic.

This paper proposes a method to protect the traction power supply system of low and medium speed magnetic levitation traffic based on the fault traveling wave characteristics. Firstly, a dynamic simulation model of the low and medium speed magnetic levitation power supply rail is built to simulate a DC earth fault on the power supply rail. Secondly, the fault section is identified by the difference between the positive and negative bus fault currents, and the corresponding station protection device is tripped to cut off the power supply. Finally, the frequency domain distribution of the line wave of the fault voltage variation at the double-ended fault station is extracted and the fault distance is calculated by the frequency difference. The proposed method is unaffected by fault location, fault transition resistance and noise interference and is suitable for short-circuit faults caused by lightning surge voltage breakdown, with a range error always within 20m. Compared to traditional fault location methods for DC traction power supply systems, the measurement accuracy is higher and the problem of protection malfunctions is effectively solved, making it suitable for low and medium speed magnetic levitation traffic power supply rail earth faults.

Simulation of low and medium speed magnetic levitation traction power supply system

2.1 Model of the traction power supply system

The low and medium speed Maglev traction power supply system converts three-phase AC high voltage power from the city grid to 1500V low voltage DC power through transformers and rectifiers, and uses a contact rail traction network to grant current. The traction network consists of positive and negative rails, with the positive rail supplying power and the negative rail returning current. The positive and negative rails supply power to the train devices through the receiver installed on the train, as shown in Fig. 1.

FIGURE. 1. Low and medium speed magnetic levitation traction power supply system

2.2 Dynamic resistance of supply rails

A centralised variable resistor is used to simulate the dynamic resistance of the power supply rails during train movement, based on the track changes during train operation. The external current bidirectional function is implemented in the form of a rectifier bridge, as shown in Fig. 2, and the module equivalent resistance is changed by controlling the magnitude of the duty cycle of the switching tube S.

FIGURE. 2. Supply rail equivalent variable resistance

2.3 Negative rail dc protection device

FIGURE. 3. Negative rail DC protection device

64D is provided between the negative DC bus and ground for each traction substation of the medium and low speed maglev trains, as shown in Fig. 3. In the event of a positive earth fault, the fault current flows through the fault point into the earth network and finally into 64D of the station's negative rail. The protection device trips when the negative rail-to-ground voltage reaches the rectified value and the power supply to the station is interrupted.

The station negative rail-to-ground voltage is calculated as:

As shown in (1), I is the fault current at the fault point of the train, L is the total running distance of the train, x is the distance of the train from the left traction substation, y is the distance of the train from the right traction substation, U_{xm} and U_{ym} is the negative rail-to-ground potential of the station on the left and right sides of the fault point.

The existing 64D rectification voltage is generally set to 200V, due to the parallel operation of each traction substation. After a positive ground fault occurred in a section, the negative voltage to ground in each traction substation all rose simultaneously, with voltage values exceeding 200V, resulting in 64D action on the entire line and eventually leading to a loss of power on the entire supply track.

Method for determining the fault area

3.1 Determining the occurrence of an earth fault

During normal train operation, the load current flows from the positive terminal of the rectifier, through the positive busbar, the positive supply rail, the train, the negative return rail and the negative busbar, back to the negative terminal of the rectifier, as shown in Fig. 4. During normal operation, the currents in the positive and negative buses in the traction substation are approximately equal in magnitude, with the currents shown as the solid blue line in Fig. 4. When a positive earth fault happens, the positive earth fault current is shown as the solid red line in Fig. 4. Under fault conditions, the fault current does not pass through the negative busbar, resulting in an unequal current amplitude between the positive and negative busbars when a positive earth fault occurs and producing a large current difference.

Based on this, this paper proposes to use the current difference between positive and negative busbars to determine the positive earth fault, calculate the current difference between positive and negative busbars, and determine the occurrence of an earth fault when the current difference is not 0A.

FIGURE. 4. Positive train ground fault current

3.2 Determining the fault area

When a positive supply rail earth fault occurs on a train, each power point supplies a short circuit current to the fault point. For faulty areas, the fault current supplied by the rectifier in the traction station at both ends of the area flows through the positive busbar in the station to the fault point. For non-faulty areas, the fault current supplied by the rectifier at the traction station within the area flows across the positive busbar at both ends of the non-faulty area into the adjacent area.

To this end, this paper proposes a method for identifying fault segments using the positive bus current direction, with current flowing from the positive bus into the positive contact rail as the positive direction and current flowing from the positive contact rail into the positive bus as the negative direction. When the protection element detects that the difference between the positive and negative bus currents is greater than the set threshold for determining a positive earth fault, the protection unit initiates a determination of the positive bus current direction. If the protection unit detects the positive direction of the positive bus current and the same direction as the positive feeder current at its opposite end, the zone is determined to be a fault area. If the protection unit detects that the positive feeder current is in the opposite direction to the positive feeder current at its opposite end, the zone is determined to be a non-faulty area.

3.3 Algorithm flow for determining the fault area

When a positive earth fault occurs, the fault point resistance and the fault voltage can be different from the fault current generated by the fault resistance under the type of fault resistance. Current measuring devices are set up on the positive and negative supply rails to detect changes in current. When the difference in current between the positive and negative buses ΔI[?]0, it is judged that a supply rail earth fault has occurred. Then, the current direction determination is activated to collect information on the current direction of the positive supply rails at each station and, based on the current direction at each station, the faulty station zone is determined.

FIGURE. 5. Algorithm process 1

At the same time the positive earth fault protection operates, cutting off the power supply to the faulty station and issuing an alarm signal to inform the staff. The fault ranging device is further activated to accurately locate the fault point. The algorithm flow is shown in Fig. 5

Fault location methods

4.1 Time domain and frequency domain methods

(a) Time domain waveforms

(b) Frequency domain waveforms

FIGURE. 6. Fault voltage time domain and frequency domain waveforms

When a DC earth fault occurs on the supply rail, the fault traveling wave is reflected between the fault point and the stations on the two sides, and the fault voltage traveling wave measured at the station fluctuates in a certain time sequence, as shown in Fig. 6(a).

The fault voltage traveling waves obtained at both stations have the same time-domain attenuation characteristics. The fft transform is performed on the station fault voltage traveling wave at both ends and the frequency distribution is shown in Fig. 6(b). Where $\Delta f=1/2\tau$and τ is the time required for the fault traveling wave to propagate from the fault point to the station.

Due to the short power supply range of low and medium speed magnetic levitation traffic, when a positive ground fault occurs, it is not easy for the measuring devices set up at both sides of the traction power supply station to capture the wave head of the fault traveling wave, and there are difficulties in using the traveling wave method for fault location. At the same time, low and medium speed magnetic levitation transportation has the advantages of low noise and smooth operation compared with other rail transportation. Therefore, the frequency amplitude is more easily identified in the event of a fault grounding. Based on this, this paper proposes a fault location method based on the frequency variation characteristics of double-ended stations.

4.2 Mechanisms for the generation of faulty traveling wave spectra

In the case of an earth fault on the supply rail between stations A and B, the fault line wave will be reflected several times between the two stations and the fault point. In the frequency domain this can be expressed as the sum of an infinite number of harmonics of a particular frequency, which is the spectral distribution of the fault wave.

FIGURE. 7. Supply rail short circuit diagram

In Fig. 7, $\mathrm{Z_L}$ is the wave impedance of the supply rail, $\mathrm{Z_A}$ and $\mathrm{Z_B}$ are the equivalent impedances of the traction power stations of the stations on both sides respectively, $\mathrm{R_f}$ is the transition resistance at the point of failure, l_f is the distance from the point of failure to station A, v is the wave speed, $e_{\mathrm{A}}(t)$ and $e_{\mathrm{B}}(t)$ are the equivalent power supplies at stations A and B, and U_f is the equivalent fault voltage at fault point f.

The refraction and reflection of the fault travelling wave at station A and fault point f is analysed. The equivalent fault resistance Z_f is shown in (2), and the refraction and reflection coefficients of the travelling wave at the fault point f are shown in (3) and (4).

The refraction and reflection coefficients of the traveling wave at station A are shown in (5) and (6).

By Davinan's equivalence theorem, the supply system is equated when a DC earth fault occurs in the supply rail. The supply rail is equated to a wave impedance $\mathrm{Z_L}$ in series with a controlled voltage source $f_{\mathrm{A}}(t)$. Station A is equivalent to the system impedance $\mathrm{Z_A}$ with an independent voltage source $\mathrm{e_A}(t)$. The fault is equated to the controlled voltage source $f_{\mathrm{f}}(t)$ as shown in Fig. 8.

FIGURE. 8. Davinan equivalent circuit for traction power supply system after failure

The voltage at station A, $u_{\mathrm{A}}(t)$, and the voltage at the fault point f, $u_{\mathrm{f}}(t)$, are shown in (7) and (8).

The controlled power supplies $f_{\mathrm{A}}(t)$ and $f_{\mathrm{f}}(t)$ are shown in (9) and (10).

The Laplace transform of (9) and (10) leads to (11) and (12).

In (11) and (12), $f_{\mathrm{A}}(s)$ and $f_{\mathrm{f}}(s)$ are the controlled sources $f_{\mathrm{A}}(t)$ and $f_{\mathrm{f}}(t)$, $\beta_{\mathrm{A}}(s)$ and $\beta_\varphi(s)$ are the pull domain transforms of the reflection coefficients β_{A} and β_φ, $P(s) = \exp(\text{-}\sigma\tau)$ is the pull-domain operator for the propagation delay of the faulted traveling wave; $E_1(s)$ is the pull-domain transform of the ideal DC source on the system side with frequency 0.

Combining (11) and (12), it can be concluded that the natural frequency of the fault traveling wave obtained at the traction power supply station A is the root of the characteristic equation as (13).

The natural frequency equation obtained by solving is (14).

In (14), the f_n is the nth component of the natural frequency; v_n is the wave speed at that frequency, is the angle of reflection of the traveling wave at the traction power supply station A, is the angle of reflection of the traveling wave at the fault point f.

4.3 Line wave frequency difference ratio and fault ranging

A traveling wave measurement device is set up at the location of the traction power supply station to extract the fault traveling wave frequency, and from (14) the nth traveling wave frequency can be expressed as (15).

The (n+1)th frequency is shown in (16).

In (16), ϑ_1 and ϑ_2 denote the reflection angles of traction power supply stations A and B respectively; L is the full length of the line.

According to equations (15) and (16) can be derived from the double-end frequency difference as shown in (17).

Because the reflexion coefficients are all less than 1 in absolute value, when the fault traveling wave is refracted through the fault point and reaches the opposite side, it is then reflected back to the voltage through the station. The voltage reflected back from the fault point directly is small compared to the fault voltage, so the frequency difference can be determined by taking the extreme points of the change in the frequency domain waveform, as shown in (18).

The fault distances calculated from the frequency differences of the stations on both sides of A and B (both being the distance of the fault point from the station on the A side) are shown in (19).

From the above formula can be learned, the frequency distribution of the fault line wave is not affected by the traction power supply station impedance, transition resistance, only with the location of the fault point and the fault line wave arrives at both ends of the line related to the time. That is to say, the fault line wave frequency difference obtained at both ends of the line and the fault location has a clear mathematical relationship. The location of the fault point can therefore be calculated from the fault frequency difference and the speed of the fault travel wave.

4.4 Fault location algorithm flow

Each station is equipped with a travelling wave coupling measurement device. After the fault zone has been determined by algorithm process 1, the corresponding station protection device trips and cuts off the power supply. At the same time, the fault traveling waveforms of the stations at both ends are extracted and the fault distance is measured by the fault traveling waveform frequency difference method.

Fast Fourier transform of the station fault voltage signal, extract the double-ended station spectrum $\mathrm{f_A}$ and $\mathrm{f_B}$, take the more regular part of the spectrum distribution, find the amplitude point, calculate the difference between the two ends of the frequency, and take the plural to get $\Delta \mathrm{f_A}$ and $\Delta \mathrm{f_B}$. If $\Delta \mathrm{f_A} << \Delta \mathrm{f_B}$ and $\Delta \mathrm{f_A} >> \Delta \mathrm{f_B}$occur, it proves that a near-station ground fault has occurred and the station on the side with the larger frequency difference is closer to the fault point; to reduce the error, the fault distance $\mathrm{l_f}$ is calculated by substituting $\Delta \mathrm{f_{max}}$into (19). $\mathrm{I_f}$ the above situation does not occur, the fault frequency difference $\Delta \mathrm{f_A}$ and $\Delta \mathrm{f_B}$between the two stations is substituted into (19) to calculate the fault distance $\mathrm{l_{fA}}$ and $\mathrm{l_{fB}}$, and the average of the two is taken as the final fault distance $\mathrm{l_f}$. The flow of the algorithm is shown in Fig. 9.

FIGURE. 9. Algorithm process 2

Simulation verification

A simulation model of the ±1500V DC transmission system is built, the supply rails are equivalent to Π-type conductors, the distance between stations is set to 3km, four stations are set up along the entire line, and each station is equipped with a traveling wave coupling box to measure fault traveling waves. The speed of the travelling wave is calculated as v =33.41km/ms, the unit resistance of the supply rail $\mathrm{R_0}$=0.028Ω/km, the unit inductance $\mathrm{L_0}$=2.6629mH/km, the unit capacitance $\mathrm{C_0}$=0.0211μF/km, the sampling frequency is 10^8Hz, and the equivalent impedance of the station traction power supply $\mathrm{R_Q}$=2.5685, go for simulation verification.

5.1 Determining the fault area

Fig. 10 shows the positive and negative bus currents and their differences at stations A, B, C, and D after a positive earth fault on the supply rail.

From Fig. 10, the train was running normally 0.01s ago and the positive and negative bus currents at stations A, B, C, and D were equal in amplitude and opposite in direction, ΔI=0. After 0.01s the positive bus current is greater than the negative bus current and ΔI[?]0. From this it can be determined that an earth fault occurred on the supply rail at 0.01s. The train sends out an alarm signal to notify the crew of an earth fault and simultaneously initiates a current differential direction determination.

The direction of the current difference between stations A and B is reversed and the A-B section is determined to be a non-faulty section. If the current difference between C and D is in the same direction, the C-D section is judged to be a faulty section and the protection unit on C and D stations operates to remove the faulty section.

FIGURE. 10. Positive and negative buses currents and their differences at each station after a fault

5.2 Fault point location

After identifying the fault zone from the above steps, the station C and D earthing protection device trips and cuts off the power supply, while extracting the fault traveling waves in the 1ms time window before and after the fault. Fig. 10 shows the time domain distribution of the faulty traveling waves in and . As can be seen from the graphs, the waveheads of the fault line waves are not easy to capture and there are difficulties in using the line wave method for fault location.

(a) Station C

(b) Station D

FIGURE. 11. Station fault voltage frequency distribution

Therefore, this paper proposes a fault location method based on frequency variation characteristics, where the extracted fault line wave is subjected to fast Fourier analysis and the fault distance is calculated by the fault line wave frequency difference method.

Fig. 11(a) and Fig. 11(b) shows the frequency distribution of fault voltages at double-ended stations. Δf_{C}=66.2kHz, Δf_{D}=33.2kHz, $\Delta f_{\mathrm{C}}>\Delta f_{\mathrm{D}}$, so the fault point is closer to station C. Calculated by bringing in (19):l_{fC}=1007.63m, l_{fD}=990.81m,l_{f}=999.22m, the fault distance error is 0.78m.

The above analysis shows that the fault ranging method with frequency distribution characteristics can be used to locate the fault point accurately.

Analysis of methodological adaptability

This paper discusses the adaptability of the simulation model and algorithm in terms of four aspects: fault point location, fault point transition resistance, noise disturbance, and lightning surge voltage effects.

6.1 The effect of fault location

When an earth fault happens on a train, the distance between the fault point and the station measurement point affects the distribution of the fault frequency and the difference in frequency distribution has an impact on the measurement error.

As shown in Fig. 12, single-ended fault ranging at near-fault stations yields a smaller measurement error for near-fault faults, and double-ended fault ranging yields a smaller measurement error for more distant faults. Furthermore, as the fault distance increases, the measurement error increases accordingly.

FIGURE. 12. Error distribution at different fault locations

As can be seen from (18), when a near fault occurs, the frequency difference of the fault line wave is large and the measurement error caused by the frequency difference error is small; when a long distance fault occurs, the frequency difference of the fault line wave is small and the measurement error caused by the frequency difference error is relatively more. Therefore, in the case of close faults, single-ended fault ranging using the station voltage on the side closer to the fault point can effectively reduce the fault ranging error. In the case of longer distance faults, the average of the error distances measured at both ends is chosen as the total error distance, which can effectively reduce the measurement error.

6.2 Effect of transition resistance at the point of failure

6.2.1 Effect of transition resistance on the measurement error

FIGURE. 13. Error distribution at different transition resistances at different fault points

During the operation of low and medium speed magnetic levitation traffic, the types of faults are diverse and high resistance earth faults may occur due to fouling and ageing of insulators. Keeping the above line conditions constant, the transition resistance is set to R_f=0.01Ω and R_f=500Ω respectively to simulate the earth fault in low and high resistance cases.

In Fig. 13, the maximum range error is 10m when a low resistance earth fault occurs, with relatively little change in the range error as the fault location changes. When a high resistance earth fault occurs, the maximum range error is 16.94m, which is greater than the range error caused by a direct earth fault. And when a close high resistance earth fault occurs, the fault error is so large that it is even impossible to calculate the fault point.

6.2.2 Discussion of fault resolution under high resistance earth faults b

Under a high resistance earth fault, the shunt effect at the fault point is small and the current flowing back to the station negative rail through the earth network is small, so the voltage detected by the station 64D is small and may not reach the protection action voltage, resulting in the circuit breaker not being able to act in time to cut off the power supply to the faulty station. This paper uses the positive and negative bus current difference to determine the occurrence of grounding faults. When a high resistance ground fault occurs, the current difference between the positive and negative buses is small but not 0, which can determine the occurrence of grounding faults and avoid the problem that the circuit breaker cannot operate in time.

As can be seen from (6), under the high resistance ground fault, the refraction coefficient of the fault point is larger, the fault line wave is refracted through the fault point to the opposite end of the station, and then reflected back to the local side of the voltage is larger, the frequency domain shows a small difference in the amplitude of the different frequencies, the frequency difference resolution is lower, interfering with the acquisition of the frequency difference, resulting in a larger measurement error.

6.3 Effect of noise interference

(a) Time domain waveforms

(a) Frequency domain waveforms

FIGURE. 14. Time-domain and frequency-domain distribution of faulty traveling waves under noise interference

This paper uses the difference between positive and negative bus currents to determine the occurrence of earth faults. The noise mainly interferes with the time domain distribution of the fault waveform and has less effect on the amplitude of the fault current, so it has less influence on determining whether a fault has occurred.

Keeping the above supply rail fault conditions constant, simulate a ground fault occurring in a train with large Gaussian random noise, and observe the change in the waveform of the fault line wave after adding noise, as shown in Fig. 14(a) and Fig. (b). After adding noise, the time-domain waveform of the faulty line wave is almost always masked by noise and the wavehead signal cannot be distinguished, as shown in in Fig. 14(a). However, the frequency domain waveform is highly resistant to noise, with small fluctuations in frequency distribution, and overall the spectrum distribution is relatively stable and does not affect fault location.

6.4 Lightning surge voltage effects

For low and medium speed magnetic levitation traffic, the power supply and return rails are located on both sides of the track girders and there are no shielding protection facilities such as contact nets above the car body, which makes the car body vulnerable to lightning. The duration of the lightning surge voltage is very short, a non-periodic voltage variation of only a few microseconds to a few tens of microseconds, but the voltage generated is so high that it can seriously damage the insulation of the train's power supply rails and track support devices, or even break through and cause grounding faults in the power supply rails.

Keeping the above line conditions constant, simulate the ground fault caused by lightning surge voltage, where the station C traveling wave measurement device to obtain the fault traveling wave time domain, frequency domain distribution as shown in Fig. 15(a) and Fig. 15(b).

As can be seen from Fig. 15(a), the lightning surge voltage only affects the wavehead steepness and amplitude of the fault line wave, not the overall time-domain distribution of the line wave, which in turn does not affect the distribution of the fault voltage line wave frequency domain, meaning that the frequency difference remains constant. After the supply rail is disturbed by lightning, the station protection device is controlled by the Algorithm 1 process to cut off the power supply to the faulty station. The measurement device extracts the fault travelling wave spectrum, the frequency distribution is consistent with the ground fault except for the amplitude, and the measurement error calculation follows the Algorithm 2 process.

(a) Time domain waveforms

(b) Frequency domain waveforms

FIGURE. 15. Time-domain and frequency-domain distribution of faulted traveling waves under lightning faults

Therefore, lightning strikes resulting in a supply rail fault are consistent with the short-circuit fault ranging algorithm process. However, the high inrush current of lightning for a short period of time requires an increase in the current resistance of the current detection device.

The distance measurement results for different fault conditions are shown in Table I.

TABLE I Units for Magnetic Properties

Type of fault	Fault distance	Fault distance	R_f	R_f	Δf_A/kHz	Δf_B/kHz	l_f/m
Short circuit failure	50	0.01	0.01	1328.8	1328.8	22.9	50.2
		500	500	1910	1910	-	34.92
	1500	0.01	0.01	44.17	44.17	44.17	1510.19
		500	500	44.08	44.08	44.7	1513.44
Noise interference faults	50	0.01	0.01	1328	1328	23	50.23
		500	500	1921	1921	-	34.72
	1500	0.01	0.01	44.1	44.1	44.1	1512.59
		500	500	44.05	44.05	44.1	1513.45
Lightning surge voltage disturbances	50	-	-	-	-	-	-
		500	500	43.8	43.8	44.5	1510.97
	1500	0.01	0.01	44.2	44.2	44.13	1509.85
		500	500	44.1	44.1	42	1531.93

CONCLUSION

In order to solve the problem of false operation of 64D protection device after a ground fault occurs in the power supply track of low and medium speed magnetic levitation, this paper proposes a protection method for the traction power supply system of low and medium speed magnetic levitation transportation based on the fault traveling wave characteristics. The difference between the positive and negative currents of the double-ended stations is used to determine the fault zone and constitute a protection action with the supply station. And on this basis, the double-ended station fault voltage travelling wave frequency distribution is analysed and the fault distance is calculated. The following conclusions can be drawn from theoretical analysis and simulation verification:

The use of the station's positive and negative current difference to locate the fault zone allows the fault point to be accurately located, avoiding the problem of large area outages caused by protection malfunctions.

The frequency of the travelling wave of a fault at a double-ended station is not affected by the impedance within the station, but is only related to the location of the fault point and the time of arrival of the travelling wave at both ends of the line.

The double-ended frequency difference ratio is used to calculate the fault distance, independent of the fault point location, transition resistance and noise interference, and the distance measurement error is always kept within a controllable range of 20m, with strong robustness.

The method proposed in this paper is not only applicable to low and medium speed magnetic levitation traffic power supply rail grounding faults, but also to short circuit faults caused by lightning surge voltage penetrating the air gap of the power supply rail. It is also of reference significance for fault location in urban rail transport such as high-speed magnetic levitation, metro and light rail.

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