Study on Short-Circuit Impedance Characteristics in DN Traction Electric Lines

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Abstract. The fault location accuracy of traction electric lines protection device based on impedance characteristics is usually over thousands of meters. To find out the reasons that affect the accuracy of fault location, this paper studies some the key factors including rail potential, feedback current through ground and fault point impedance characteristics of traction electric lines. Then the calculation method of impedance increment and the reason of the location error are found. It is of great significance for the setting calculation and fault location error analysis of the protection system.

1. Introduction
The DN-style traction power supply system is generally adopted in the ordinary speed electrical railway. The traction electric line is more easily to happen many type of short-circuit fault, and the only auxiliary engineering tool is the protection device in finding fault location of the traction electric lines. Unfortunately, there is a big deviation between the measurement value and the actual value, which is caused by imperfect calculation method of short-circuit impedance. Engineering experience shows that the measurement errors of existing protective devices often reach thousands of meters, far beyond the industry standards and the endurance of staff. Therefore, it is vital to improve the location accuracy of the device by the detailed theoretical research and the engineering requirements.

It is concluded that there are three typical cases of short circuit in the traction electric lines, namely the line to track fault, the line to return line fault and the line to ground fault, which aren’t the specific proportion. After the ground impedance characteristic of the traction electric lines is analysed, this paper presents a new calculation method of short-circuit impedance, which is helpful to improve the fault location precision of the traction electric line.

2. Analysis of rail potential and backflow in short-circuit state

2.1. The rail potential and current
Fig.1 is equivalent circuit diagram during the short-circuit state of the AC traction electric lines. It is shown by in Fig.1that the digital label 1, 3 and 7 represent respectively the substation, the catenary and the ground zero potential. Similarly, the label 2, 4, 5 and 6 represents respectively the grounding resistance $R_g$, the mutual impedance $Z_{TR}$ between the catenary and the rail, the self-impedance $Z_R$ of the rail and the leakage impedance of the rail to the ground.
Figure 1. Equivalent circuit diagram during the short-circuit state of the traction electric lines

In figure 1, the distance between the substation A and short-circuit point B is \( L \), and the short-circuit current is \( I \), which is injected into the ground through the grounding resistance \( R_g \). The mutual impedance \( Z_{TR} \) between the catenary and the rail generates an induction potential and current on the rail between the traction substation A and the short-circuit point B. When \( L \) is large enough, the rail current eventually reach the induction current \( I_{Rm} \) (substation rail induction backflow), through the return line back to the substation, and the backflow \( I_{ex} \) (substation ground backflow) is mainly composed of ground net. Through directly back into the substation, the backflow generally does not affect the rail potential and current near the substation. When \( Z_{R} \), \( Z_n \) and \( Z_{TR} \) are constant, the rail potential and current are mainly determined by \( Z_{TR} \) and backflow near short-circuit point. The rail potential distribution of the traction electric lines short-circuit is shown in figure 2.

![Diagram of short-circuit state](image)

Figure 2. The rail potential distribution of the traction electric line short-circuit

If the rail potential and current at the distance \( x \) (km) from the short-circuit point are \( U_{RX} \) and \( I_{RX} \) respectively, then

\[
\frac{dU_{RX}}{dx} = -I_{RX}Z_R \frac{dx}{dx} + IZ_{TR} \frac{dx}{dx}
\]

\[
\frac{dI_{RX}}{dx} = -(U_{RX} / Z_n) \frac{dx}{dx}
\]

Take the deformation and derivative of formula (1).

\[
\frac{d^2U_{RX}}{dx^2} = -\frac{dI_{RX}Z_R}{dx}
\]

In combination with formula (2) and (3),

\[
\frac{d^2U_{RX}}{dx^2} - \frac{U_{RX}Z_R}{Z_n} = 0
\]
\[ Z_R / Z_n = \gamma^2, \gamma \] is the transmission coefficient of the loop between the traction electric lines and the rail, and the above formula becomes

\[ \frac{d^2 U_{RX}}{dx^2} - \gamma^2 U_{RX} = 0 \]  \hspace{1cm} (5)

The general solution of formula (5) is

\[ U_{RX} = Ae^{\gamma x} + Be^{-\gamma x} \]  \hspace{1cm} (6)

\[ I_{RX} = (IZ_{TR} dx - dU_{RX}) / Z_R dx \]  \hspace{1cm} (7)

Where, A and B are undetermined coefficients.

From formulas (6) and (7), formulas (8) and (9) can be concluded.

\[ dU_{RX} / dx = \gamma (Ae^{\gamma x} + Be^{-\gamma x}) \]  \hspace{1cm} (8)

\[ I_{RX} = \frac{IZ_{TR}}{Z_R} - \frac{(Ae^{\gamma x} + Be^{-\gamma x})}{\sqrt{Z_R Z_n}} \]  \hspace{1cm} (9)

\[ Z_0 = \sqrt{Z_R Z_n}, \]  \hspace{0.5cm} \text{is the characteristic impedance of the loop between the traction electric lines and the rail, then formula (9) becomes}

\[ I_{RX} = \frac{IZ_{TR}}{Z_R} - \frac{(Ae^{\gamma x} + Be^{-\gamma x})}{Z_0} \]  \hspace{1cm} (10)

Where, A and B are determined by the boundary conditions. When \( x \to \infty \), \( U_{RX} \to 0, I_{RX} \to IZ_{TR} / Z_R \). That is \( A = 0 \).

\[ U_{RX} = Be^{-\gamma x} \]  \hspace{1cm} (11)

\[ I_{RX} = \frac{IZ_{TR}}{Z_R} + \frac{Be^{-\gamma x}}{Z_0} \]  \hspace{1cm} (12)

If the rail on both sides of the short-circuit point is infinitely long, the current transiting to the rail is \( IZ_{TR} / (2Z_R) \). When \( x=0 \), \( I_{RX} = IZ_{TR} / (2Z_R) \). Formula (13) can be obtained from formula (12).

\[ B = -IZ_0Z_{TR} / (2Z_R) \]  \hspace{1cm} (13)

\[ n_0 = Z_{TR} / Z_R, \]  \hspace{0.5cm} \text{n}_0 \text{ is the rail induction current coefficient of the traction electric lines. Therefore, the potential and current of the rail are obtained as follows.}

\[ U_{RX} = -\frac{n_0}{2} IZ_0 e^{-\gamma x} \]  \hspace{1cm} (14)

\[ I_{RX} = n_0 I \left(1 - \frac{e^{-\gamma x}}{2}\right) \]  \hspace{1cm} (15)

The rail potential and current on both sides of the short-circuit point change exponentially, and the transition current between the rail and the ground flows from the ground to the rail. So the rail potential is negative. While the rail current flows to the power supply, the rail current is positive. The rail potential and current distribution are shown in figure 3.
Figure 3. The rail potential and current distribution

When the traction electric line is short-circuited, the short-circuit current is recirculated by the rail and return line at the same time. In the section of multiple lines, $Z_R$ is the integrated self-impedance of the rail and return line. $Z_n$ is the integrated leakage reactance of the rail to the ground. $Z_{TR}$ is the integrated mutual impedance between the catenary and the rail-return line.

2.2. Key factors affecting the rail potential and current

According to formulas (14) and (15), the key factors affecting the rail potential and current are the rail induction current coefficient $n_0$, short-circuit current $I$, characteristic impedance $Z_0$ of the rail loop and transmission constant $\gamma$ of the loop between the traction electric lines and the rail. Among them, $n_0$ is related to the relative position among the rail, catenary and return line. $I$ is related to the system impedance and short-circuit point distance $L$. $Z_0$ and $\gamma$ are mainly related to the self-impedance of the rail and return line, and the leakage reactance of the rail to the ground $Z_n$. In double track section of the ordinary speed, $Z_n$ is generally $0.1\Omega/km$-$10\Omega/km$. $Z_R$ is $0.38\Omega/km$. $Z_n$, $Z_0$ and $\gamma$ are shown in table 1. The relationship curves of the three are shown in figure 4.

| $Z_n/(\Omega/km)$ | $Z_0/(\Omega/km)$ | $\gamma$  |
|-------------------|-------------------|-----------|
| 0.1               | 0.195             | 1.949     |
| 0.2               | 0.276             | 1.378     |
| 0.5               | 0.436             | 0.872     |
| 1.0               | 0.616             | 0.616     |
| 2.0               | 0.872             | 0.436     |
| 4.0               | 1.233             | 0.308     |
| 6.0               | 1.510             | 0.252     |
| 8.0               | 1.744             | 0.218     |
| 10.0              | 1.949             | 0.195     |

Figure 4. The relationship curves of $Z_n$, $Z_0$ and $\gamma$
When $x=0$, $Z_n=0.1\Omega/km$, $Z_{TR}=0.30\Omega/km$. When $I=2000A$, $n_0=0.79$ and $U_{RX}=-154V$. When other parameters remain unchanged and $Z_n=10\Omega/km$, $U_{RX}=-1540V$. When $\gamma x \geq 3$, $e^{-\gamma x} < 5\%$, the rail potential can be ignored.

3. Impedance characteristics of short-circuit

When the traction electric lines is short-circuited, there is the transition process of backflow near the short-circuit point, which increases the impedance of the traction electric lines. The impedance characteristics of the traction electric lines short-circuit are analyzed as follows.

3.1. The analysis of impedance increment

Let the equivalent self-impedance of traction electric lines be $Z_e$, the mutual impedance be $Z_{jm}$, and the impedance increment of traction electric lines short-circuit be $Z_z$.

$$Z_z=\int_0^\infty (Z_j-Z_{jm}) \frac{I_{RX} Z_{TR}}{I} dx$$ (16)

Formula (17) can be obtained by arranging and calculating formula (16).

$$Z_z=\frac{Z_{TR}^2}{2Z_R} \left(-\frac{e^{-\gamma x}}{\gamma} + C_0^\infty\right) = \frac{Z_{TR}^2}{2\gamma Z_R}$$ (17)

When $Z_j=0.33\Omega/km$, $Z_{TR}=0.30\Omega/km$, $Z_R=0.38\Omega/km$ and $Z_n=0.1\Omega/km$, $Z_e=0.607\Omega/km$. The location deviation of the device is $0.061/0.33\sim 0.185$ (km). When other parameters remain unchanged and $Z_n=10\Omega/km$, $Z_e=0.607\Omega/km$. The location deviation of the device is $1.839$ km.

3.2. The analysis of impedance device error

According to formula (17), the main factors affecting the impedance increment of traction electric lines short-circuit are the comprehensive self-impedance $Z_{TR}$ between the rail and return line, the comprehensive mutual impedance $Z_R$ of the rail and return line, and the propagation constant $\gamma$.

By analyzing calculation and practice, it is known that the impedance increment of the traction electric lines short-circuit increases the location error of the device. Usually, the grounding resistance $R_l$ is used to judge whether the traction electric lines is short-circuited. $R_l$ is the short-circuit resistance minus the total resistance of the catenary and the arc. When $R_l \geq 1\Omega$, the traction electric lines can be thought of short-circuit. In the scene, the traction electric line is short-circuited through the catenary pole and buildings, mountain, trees and other foreign matter. $R_l$ is commonly $1\Omega-6\Omega$. When the contact wire breaks on the ballast, $R_l$ is commonly $6\Omega$ or more.

The device is generally set according to the rail short-circuit reactance. The practice shows that under this circumstance, the location error of the device is generally $0.5km-2km$ due to the traction electric lines short-circuit, the change of impedance increment and grounding resistance. Considering the setting error of the device and environmental factors, when the traction electric line is short-circuited, the location error of the interval is generally $0-2.5km$, and the location error near the station is generally $0.5km-3km$.

4. Conclusion

There are two main reasons for the location error of the device due to the traction electric lines short-circuit:

- Due to the backflow channel changing, the traction electric lines impedance has a large impedance increment.
- The grounding resistance changing from the large to small increases the measured reactance.

In the power supply section where the rail has less leakage resistance to the ground, the mean reactance of short-circuit can be setting calculation according to three forms. No matter which kind of
short-circuit fault occurs in the traction electric lines, the fault point can be found according to the location value of the device. The device error can be controlled within ±1km.

In the power supply section where the rail has larger leakage resistance to the ground, the setting calculation can be carried out according to reactance of short-circuit to the rail. When the traction electric line short-circuit, according to the size of the grounding resistance and the distance of the fault point to calibrate the location value of the device with a step function, the fault point is found based on the calibrated location value. The device error can also be controlled within ±1km.

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