RESEARCH ARTICLE

Research on the performance of heavy-haul rail breakage detection using track circuit

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Abstract

Rail breakage is one of the major safety risks in railway transportation. Because of the large axle weight, high density and large capacity of the heavy-haul railway, the damage to rail caused by heavy-haul train wheels will be more serious than that caused by ordinary passenger and cargo trains, resulting in a higher frequency of rail breakage. Taking the Daqin Railway Line as the research object, this paper analyses and discusses rail breakages occurring in interstation tracks and in-station tracks by establishing the ZPW-2000A track circuit calculation model considering the land leakage resistance between the rail line tracks; introduces the defining standards and measurement index of the broken rail coefficient to quantitatively analyse the influence of various influencing factors on the rail breakage inspection performance under the most unfavourable working conditions; and compares the model simulation data, the laboratory model data and the field test results to verify its effectiveness, so as to provide a reference and theoretical basis for the subsequent improvement and solution of the heavy-haul railway rail breakage problem.

Keywords: heavy-haul railway; track circuit; rail breakage real-time detection; rail breakage on-line detection

1. Introduction

The rail is the main component of railway tracks. It is used to guide the locomotives and the vehicle wheels forward, but also to withstand the huge pressure from the wheels and transfer it to the crosstie. The rail is a continuous and smooth rolling surface with minimal resistance to the wheel, and the occurrence of rail breakage will seriously threaten a train's operation safety, and is also the direct cause of multiple passenger and...
cargo train derailment accidents [1]. Rail breakage can be instantaneous in a particular environment or due to the accumulation of continuous fatigue from year-round operations. The high tonnage and high density of heavy-haul transportation makes the influence of rail fatigue more important. The rail of heavy-haul freight railways is under high load for a long time, and the working environment is complex and diverse. Compared with the rail of a passenger-dedicated railway, it is more prone to fracture. If a failure of the rail track is not discovered in time, there will be major safety hazards to railway operation. At present, the common rail breakage detection means can be divided into two categories: off-line detection and on-line detection [2, 3]. Off-line detection mainly includes inspection by patrol workers, ultrasonic inspection cars etc, and online detection mainly includes track circuit, monitoring technology based on acoustic emission, etc. The track circuit uses the rail as a current path, and when structural changes of the track circuit—such as the shunt, fracture and so on—take place, the receiver’s receiving voltage will be affected in real time. It is precisely due to this characteristic that the track circuit is the main tool for on-line rail breakage detection at present.

The Daqin Railway Line is the largest dedicated route for heavy-haul coal transportation in China, with a total length of 652 km. The first double-line electrified heavy-haul coal railway line in China and the country’s important strategic channel for coal transport from west to east, it enjoys a reputation as China’s number one heavy-haul transport route. At present, the ZPW-2000A track circuit is used in the Daqin Line, which can employ automatic blocking while conducting the whole process of real-time rail breakage detection. Based on the heavy-haul railway of the Daqin Line, this paper conducts quantitative analysis of various factors influencing rail track breakage inspection performance.

2. Track circuit modelling considering earth leakage

Rail is not only the track on which trains run, but is also an important signal transmission channel of the track circuit in the railway signal system and the signal infrastructure for vehicle and train control. Track circuit is a circuit composed of rail as a conductor, which is used to ensure the driving safety and transportation efficiency of the line through the train wheel-pair short-circuit rail shunt track signal, which causes the receiver signal to be reduced and realizes occupation inspection.

The working conditions of the track circuit are quite undesirable, which is greatly influenced by the external environment. At the same time, the area of the circuit laying is wide, which makes it more difficult for the field test. Therefore, the establishment of an accurate and feasible track circuit model that enables simulation of the field environment has gradually become an important means of rail breakage detection. Among them, the establishment of the rail model is the key to track circuit modelling. The system frame structure of the Daqin Railway Line ZPW-2000A track circuit is shown in Fig. 1 [4]. The track circuit system includes sending end equipment, matching equipment, receiving end equipment, cable and rail, etc [5].

2.1 Selection of rail parameter model

According to the electrical characteristics of rail, the electrical model of the track circuit can be divided into two types: the lumped parameter model and the distributed parameter model. Among them, the lumped parameter model is the most widely used, and it is still a common method for designing and simulating track circuits in many scientific research and production units in China. In the actual circuit, the rail of the track circuit is divided into several basic units by the compensating capacitances. The rail can be divided into several equivalent basic units using the theoretical analysis method of the rail circuit of A. M. Bryleev [6]. The electrical parameters of each unit are represented by the resistance R, inductance L, conductance G and capacitance C of the lumped parameters, and its equivalent circuit is shown in Fig. 2.

The series branch resistance R and the inductance L, the parallel branch conductance G and the capacitance C are all equivalent by the primary parameters of the rail. Because the rail impedance of the actual line laying is inductive, in order to compensate the transmission decay of the effective signal it is necessary to add the parallel compensation capacitance C0 at equal intervals of the rail.

Values per km of the electrical parameters (R, L, C, G) are indicated in Table 1.

Finally, several equivalent electrical unit models are cascaded to form a lumped rail parameter model in a track circuit system.
Under the actual working conditions, the rail line has two asymmetric leakage currents. One leaks into the earth; the other, through the track ballast surface and crosstie, leaks from one rail to another. Therefore, when calculating the basic working state of rail signal transmission in a track circuit, the track circuit system model should be built as a circuit composed of three conductors, that is, two rails and the earth [7,8].

The basic hypothetical premise of the model calculation is [9]: the rail has uniform self-impedance and mutual impedance; the earth is a wire with a large cross-sectional area and the impedance is zero; and the three conductors are connected to each other by a uniformly distributed leakage conductance. Take a small length of the rail and, considering its sinusoidal stable state solution, its equivalent circuit can be drawn, as shown in Fig. 3.

**Table 1:** Values per km of the electrical parameters (R, L, C, G)

| Parameter | R       | L       | C       | G       |
|-----------|---------|---------|---------|---------|
| Frequency |         |         |         |         |
| 1700 hz   | 1.117 mΩ| 1.314 μH| 0.3 μF  | 1 x 10^{-6} S |
| 2000 hz   | 1.306 mΩ| 1.304 μH| 0.3 μF  | 1 x 10^{-6} S |
| 2300 hz   | 1.435 mΩ| 1.297 μH| 0.3 μF  | 1 x 10^{-6} S |
| 2600 hz   | 1.550 mΩ| 1.291 μH| 0.3 μF  | 1 x 10^{-6} S |
The circuit equation is shown in formula (1), according to Kirchhoff's law.

\[
\begin{align*}
\frac{dU_{1x}}{dx} &= -(z_1 I_{1x} + z_M I_{2x}) \\
\frac{dU_{2x}}{dx} &= -(g_1 + g_{12}) U_{1x} + g_{12} U_{2x} \\
\frac{dI_{1x}}{dx} &= -(z_2 I_{2x} + z_M I_{1x}) \\
\frac{dI_{2x}}{dx} &= -(g_2 + g_{12}) U_{2x} + g_{12} U_{1x}
\end{align*}
\]

(1)

For the simultaneous solution, the differential equation of \( U_{1x} \) is obtained from the simplification, as is shown in formula (2).

\[
\frac{d^4 U_{1x}}{dx^4} - \left[(z_1 (g_1 + g_{12}) + z_2 (g_2 + g_{12}) - 2z_M g_{12}) \frac{d^2 U_{1x}}{dx^2}ight] + (z_1 z_2 - z_M^2) (g_1 + g_{12} + g_2 + g_{12}) U_{2x} = 0
\]

(2)

The characteristic equation and the characteristic solution are as follows:

\[
\lambda^4 - a \lambda^2 + b = 0
\]

\[
\lambda_{1,2,3,4} = \pm \left( \frac{1}{2} a \pm \left( \frac{1}{4} a^2 - b \right)^{1/2} \right)^{1/2}
\]

(3)

of which, \( a = (z_1 (g_1 + g_{12}) + z_2 (g_2 + g_{12}) - 2z_M g_{12}) \), \( b = (z_1 z_2 - z_M^2) (g_1 + g_{12} + g_2 + g_{12}) \).

In the same way, the solution of the voltage and current along the rail with integral constant can be obtained, as shown in equation (4).

\[
\begin{align*}
U_{1x} &= A_1 \cosh \lambda_1 x + A_2 \sinh \lambda_1 x + A_3 \cosh \lambda_2 x + A_4 \sinh \lambda_2 x \\
U_{2x} &= M A_1 \cosh \lambda_1 x + A_2 \sinh \lambda_1 x + N A_3 \cosh \lambda_2 x + A_4 \sinh \lambda_2 x \\
I_{1x} &= y_{11} A_1 \sinh \lambda_1 x + A_2 \cosh \lambda_1 x + y_{12} A_3 \sinh \lambda_2 x + A_4 \cosh \lambda_2 x \\
I_{2x} &= y_{21} A_1 \sinh \lambda_1 x + A_2 \cosh \lambda_1 x + y_{22} A_3 \sinh \lambda_2 x + A_4 \cosh \lambda_2 x
\end{align*}
\]

(4)

of which, \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, A_1, A_2, A_3, A_4, M = \frac{z_1 z_2 - z_M^2}{z_1 (g_1 + g_{12}) + z_2 (g_2 + g_{12}) - 2z_M g_{12}}, N = \frac{z_1 z_2 - z_M^2}{z_1 (g_1 + g_{12}) + z_2 (g_2 + g_{12}) - 2z_M g_{12}}, y_{11} = \lambda_1^2, y_{12} = \lambda_2^2, y_{21} = \lambda_1^2, y_{22} = \lambda_2^2 \) are constants.

2.2 Solving the coefficients of the four-terminal network of the rail

The four-terminal network of the rail of the track circuit [10, 11] is shown in Fig. 4.

If the integral constants \( A_1, A_2, A_3 \) and \( A_4 \) are defined as unknowns, then the basic equation (4) can be transformed into the form of matrix (5):

\[
\begin{bmatrix}
U_{1x} \\
U_{2x} \\
I_{1x} \\
I_{2x}
\end{bmatrix} = \mathbf{M}(x) \begin{bmatrix} A_1 \\
A_2 \\
A_3 \\
A_4 \end{bmatrix}
\]

(5)

Where, matrix \( \mathbf{M}(x) \) is a matrix function about the distance \( x \) along the line, whose expression is shown in formula (6).

\[
\mathbf{M}(x) = \begin{bmatrix}
\cosh \lambda_1 x & \sinh \lambda_1 x & \cosh \lambda_2 x & \sinh \lambda_2 x \\
M \cosh \lambda_1 x & M \sinh \lambda_1 x & N \cosh \lambda_2 x & N \sinh \lambda_2 x \\
y_{11} \sinh \lambda_1 x & y_{11} \cosh \lambda_1 x & y_{12} \sinh \lambda_2 x & y_{12} \cosh \lambda_2 x \\
y_{21} \sinh \lambda_1 x & y_{21} \cosh \lambda_1 x & y_{22} \sinh \lambda_2 x & y_{22} \cosh \lambda_2 x
\end{bmatrix}
\]

(6)

The following steps are taken to determine the voltage and the current relations between both ends of the four-terminal network:

(a) It is known that the rail voltage and current at the distance \( x = 0 \) can be obtained by formula (4) as definite values \( U_{10}, U_{20}, I_{10} \) and \( I_{20} \); then the unknown variable in equation (5) is only the integral constant \( A_1, A_2, A_3 \) and \( A_4 \).

\[
\begin{bmatrix}
U_{10} \\
U_{20} \\
I_{10} \\
I_{20}
\end{bmatrix} = \mathbf{M}(0) \begin{bmatrix} A_1 \\
A_2 \\
A_3 \\
A_4 \end{bmatrix}
\]

(7)
Based on formula (7), the integral constants $A_1$, $A_2$, $A_3$ and $A_4$ are obtained as follows:

$$
\begin{bmatrix}
A_1 \\
A_2 \\
A_3 \\
A_4
\end{bmatrix} = M_u^{-1}(0)
\begin{bmatrix}
U_{10} \\
U_{20} \\
I_{10} \\
I_{20}
\end{bmatrix}
$$

(8)

where,

$$
M_u(0) = \begin{bmatrix}
1 & 0 & 1 & 0 \\
M & 0 & N & 0 \\
0 & y_{11} & 0 & y_{12} \\
0 & y_{21} & 0 & y_{22}
\end{bmatrix}
$$

(9)

(b) After obtaining the integral constants $A_1$, $A_2$, $A_3$ and $A_4$, the relations between voltages and the currents at both ends of the four-terminal network can be established by substituting them into the basic matrix equation (5). In addition, by substituting formula (9) into the basic matrix equation (5), the voltage and the current relations between the starting end and the point $x$ distant from the starting end can also be obtained, as shown in formula (10).

$$
\begin{bmatrix}
U_{1x} \\
U_{2x} \\
I_{1x} \\
I_{2x}
\end{bmatrix} = M_u(x)\begin{bmatrix}
A_1 \\
A_2 \\
A_3 \\
A_4
\end{bmatrix} = M_u(x)M_u^{-1}(0)
\begin{bmatrix}
U_{10} \\
U_{20} \\
I_{10} \\
I_{20}
\end{bmatrix}
$$

(10)

Where, $M_u(x)M_u^{-1}(0)$ is called the relation matrix of the track circuit. Thus, the relations of voltages and currents between the railhead and the end positions are established, that is, the rail distribution parameter model of the track circuit considering the earth is established, which is also the basis of the real-time model for rail breakage.

3. Model analysis of rail breakage detection of the track circuit

3.1 Definition of broken rail coefficient

When an electrical break occurs somewhere in the rail, the current flowing through the rail will be discontinued. At this point, the current output from the track circuit transmitter can only bypass the rail broken point and reach the receiver via the ‘third rail’ [12], as shown in Fig. 5. In the figure, after the rail break occurs, the current will flow through the path of the rail—ballast resistance—the earth—ballast resistance—the rail, as shown in the purple channel (2). However, compared to passing through the rail as a good conductor, the impedance of the current bypass path will increase substantially, and the current to the receiver will also decrease substantially. As a result, the receiving voltage of the track circuit falls. Under the most unfavourable working conditions, the effectiveness of broken rail detection depends on whether the track circuit receiver voltage is less than the track relay’s reliable drop threshold of 153 mv under the most unfavourable operating conditions [13].

For the convenience of the quantitative description and analysis of the degree of rail breakage, the broken rail coefficient $K_d$ is introduced here to evaluate the margin of the receiver residual voltage and its threshold limits when the rail is broken, as shown in formula (11).

$$
K_d = \frac{K_Hu_T}{K_{BH}u_R}
$$

(11)

In the formula, $K_H$ is the voltage fluctuation coefficient and is the modulus value of the ratio of the highest voltage of the generator fluctuation to the lowest voltage. $K_{BH}$ is the reliable return coefficient of the receiver; $u_R$ is the broken rail residual voltage value of the signal continuing to pass through the outer loop and the track bed resistance to the receiver end when the rail breaks under certain circumstances. $u_T$ is the minimum adjusted voltage value under the condition of the lowest track bed. $u_T$ and $u_R$ are affected by the operating conditions of the track circuit. The minimum adjustment value of track circuit $u_T$ is related to the track bed resistance, transmitter voltage level, main rail section length (with or without compensation capacitance), carrier frequency and the primary parameters of the station rail. In addition to the above factors, $u_R$ is also influenced by the impedance of the outer loop. Among them, the voltage fluctuation coefficient $K_H$ and the reliable return coefficient $K_{BH}$ of the receiver are the inherent coefficients of the equipment itself, and the reduction of $K_H$ and the increase of $K_{BH}$ can reduce $K_d$, thus increasing the residual of the reliable fall of the track relay.

As for the ZPW-2000A track circuit, $K_H = 1.1$, $K_{BH} = \frac{153}{200}$.
Quantitative analysis indicators: when $K_d \geq 1$, the rail breakage detection cannot be guaranteed; when $K_d < 1$, the rail breakage detection can be guaranteed if the rail electrical break occurs, that is, the track circuit receiver voltage is less than the reliable drop threshold of 153 mv of track relay.

Based on the cases of ZPW-2000A track circuit in interstation and in-station tracks, the effectiveness of rail breakage detection is discussed in what follows.

### 3.2 Model analysis of rail breakage detection of track circuit in interstation tracks

The ZPW-2000A track circuit on the seamless interstation tracks of the Daqin Railway Line adopts the electrical insulation joint configuration. To ensure the safety of rail and track bed maintenance personnel, rail will be provided with grounding measures to reduce the rail voltage rise brought by traction current. This grounding measure is achieved by connecting the centre point of the air-core coil or choke transformer in the track circuit system to the ground wire beside the rail, also known as the transverse connection.

The transverse connection has an important effect on the rail breakage detection of track circuits. After the rail breaks, the signal current can continue to flow to the receiver through the sending end and the transverse connection with the rail side ground wire, as shown in yellow channel ③ in Fig. 5. In order to avoid this kind of situation in real lines, the impedance of circuitous circuit must meet certain requirements, that is, the length of transverse connection line should be more than 1.2 km, otherwise the current path connected by transverse circuit may make the track breaker residual voltage increase.

In recent years, the traction current of heavy-haul trains is increasing. In order to reduce the potential danger caused by the rail voltage uplift, the distance between the two transverse connections should be reduced; thus, the rail break check margin of the track circuit is further compressed. The calculated model of the rail state required for quantitative analysis is shown in Fig. 6.

According to the interstation rail basic circuit unit and the start-end component relation matrix of the four-terminal network of the rail, the matrix variables $M_{left}$ and $M_{right}$ represent the relation matrices of the left track and the right track respectively, as shown in formula (12).

$$
M_{left} = M_{UI}(x)M^{-1}_{UI}(0) \\
M_{right} = M_{UI}(y)M^{-1}_{UI}(0) 
$$

The boundary conditions of the relation matrix at the broken point are shown in formula (13).

$$
\begin{align*}
\dot{I}_1 &= \dot{I}_{10} = 0 \\
\dot{U}_2 &= \dot{U}_{20} \\
\dot{I}_2 &= \dot{I}_{20}
\end{align*} 
$$

Considering the power equation of the starting and the end point impedance equation of the track circuit, it is possible to solve the broken rail residual voltage of the track circuit receiving end in the
Fig. 7: The circuitous circuit of a track circuit in Daqin Line Station

interstation tracks. This paper, however, focuses on analysis of the in-station tracks.

3.3 Model analysis of rail breakage detection of the in-station track circuit

Because of the large number of in-station tracks and the variety of traction current backflow channels, the insulation joint of the track circuit usually cuts off the external loop by adopting the ‘one-end blocking’ method, so as to ensure rail breakage detection. However, when high-power locomotives pass through the station with high density, the high traction current can easily lead to breakage of the insulation joint. Therefore, the station can realize a ‘double-end reflux’ through the central point connection of the rail choke transformer beside the rail. It is therefore necessary to place a series of unsaturated reflux reactors on the external circuitous circuit of the station to compensate for the impedance of the external circuit, thus ensuring the rail breakage detection of the track [14, 15]. Taking the track section of a station in the Daqin Railway Line as an example, the circuitous circuit that may be produced when the rail break occurs after adopting a ‘double-ended reflux’ is shown in Fig. 7.

Fig. 8: The Matlab model of the ZPW-2000A track circuit and external loop circuit in the station

Based on the transmission line principle and impedance matching relation [16–18], the Matlab model of the ZPW-2000A track circuit and external loop circuit in the station are established, as shown in Fig. 8, BESK_FS1 and BESK_FS2. In Fig. 9, the rail choke transformers along the rail are shown, and DL1 and DL2 are the cable models.

According to the application scene in the station and the characteristics of the ZPW-2000A track circuit, the specific analysis of the most unfavourable conditions for rail break detection is as follows.

Fig. 9: The relation curve between the broken rail coefficient and the broken rail position under different bed resistance
3.3.1 Critical ballast resistance. The critical ballast resistance is the ballast resistance when the receiver voltage is maximum in the track circuit. The Daqin Railway Line in-station track length is designed up to 650 m. Shown in Fig. 9 is the broken rail coefficient \( K_d \) under different bed conditions when the length of the in-station track is 650 m, the track circuit carrier frequency is 1700 Hz and the breakages occur at different positions. The \( K_d \) values are all less than 1.

Through simulation analysis of the broken rail coefficient under different section lengths and frequency configurations, it is concluded that the larger the ballast bed resistance and the \( K_d \), the less favourable they are for rail breakage detection. Therefore, the infinite bed resistance is the most unfavourable condition, which will be presumed in subsequent analysis.

3.3.2 Critical section length. The critical section length is the length of the section when the receiver voltage in the track circuit is maximum. In general, the maximum length of an in-station track is 650 m. The sections with and without compensation capacitance are analysed respectively.

(1) The section with compensation capacitance

In the in-station track design, the compensation capacitance will be set when the section length is more than 300 m and less than or equal to 650 m. Fig. 10 shows the distribution of the broken rail coefficient at different rail breakage positions for the carrier frequency of 1700 Hz and the track length of 300–650 m.

It can be seen from the figure that the most unfavourable position of track breaking is different for different length of track, and the most unfavourable broken rail coefficient decreases gradually with the increase in the length of the track. When the length of the track is 300 m, its maximum \( K_d \) is 0.73; when the length of the track is 650 m, its maximum \( K_d \) is 0.62.

(2) The section with no compensation capacitance

When the section length is less than 300 m, the track does not need compensation capacitance. For short sections with no compensating capacitance, the relation between the broken rail coefficient and the section length is shown in Fig. 11.

When the lengths of the track section are 300 m, 200 m and 100 m, the broken rail coefficient \( K_d \) is 0.73, 0.67 and 0.63 respectively. As the length of the track section decreases, the broken rail coefficient \( K_d \) will decrease gradually.

Therefore, for both the long sections with compensation capacitance and the short sections without compensation capacitance, the maximum broken rail coefficient is \( K_d = 0.73 \), i.e. the most unfavourable section length is 300 m.

3.3.3 Rail minimum impedance. The rail minimum impedance refers to the minimum impedance when the receiver voltage in the track circuit is maximized. There are two types of track bed in in-station sections of the Daqin Line, which are ballast bed and ballastless bed. Usually, the rail primary parameters of ballast bed are smaller than those of ballastless bed.

As shown in Fig. 12, the broken rail coefficient of the ballast track bed is higher than that of the ballastless track bed, so the rail parameters of the ballast bed rail are chosen as the most unfavourable condition.
3.3.4 Highest supply voltage. The highest supply voltage refers to the maximum voltage level of a transmitter when the receiver voltage in the track circuit is maximized. The ZPW-2000A track circuit transmitter has different output signal voltages at different voltage levels, with the highest level at level 1 and the lowest level at level 9. Therefore, under the condition of levels 1, 6 and 9, the broken rail coefficients of a 500 m section in different broken rail positions are compared.

As shown in Fig. 13, the broken rail coefficients $K_d$ of three different voltage levels of level 1, 6 and 9 are selected for comparison. At this time, the broken rail coefficients at three levels in any position basically coincide; therefore, the selection of different voltage levels has no effect on rail breakage detection. At the same time, the broken rail coefficient $K_d$ is less than 1 at any break position, which also proves the validity of rail breakage detection under this condition.

3.3.5 Minimum external loop length. The rail impedance of the outer loop will be close to zero in extreme cases if the track is broken under the condition of two-way backflow, while in-station tracks of the Daqin Railway Line are many and complex. Therefore, for the convenience of analysis, the most unfavourable situation can be considered by 0Ω, that is, there is only a reactor in the outer loop formed by the section circuitous reflux third rail.

3.3.6 Critical rail breaking frequency. When the track length is 300 m and the carrier frequency values are 1700 Hz, 2000 Hz, 2300 Hz and 2600 Hz respectively, the broken rail coefficients at different rail breakage positions are less than 1, that is, the effectiveness of rail breaking detection can be guaranteed at the four track circuit frequencies, as shown in Fig. 14. It can also be concluded that with the increase in frequency, the broken rail coefficient $K_d$ decreases gradually, and the most unfavourable frequency is 1700 Hz.

Based on the analysis of the most unfavourable working conditions in sections 3.3.1–3.3.6, it can be seen that the broken rail coefficients are less than 1 when the outer loop circuit of the ZPW-2000A track circuit in the station connects into the reflux reactor, which can ensure the realization of rail breakage detection.

4. Model test validation based on field data

4.1 Laboratory model validation test

In order to verify the accuracy of the in-station rail breakage detection and simulation model by the reflux reactor, a test environment is built where the ZPW-2000A external loop circuit and the reflux reactor are connected in series. The simulation board in Fig. 15 can be used to set up simulation of different section lengths (300–650 m), different rail parameters (ballast, ballastless) and different...
rail bed resistance values \((0.6–\infty \Omega)\), and eventually simulate the electrical environment of rail signal transmission in the actual line. As shown in Fig. 16, based on the actual track section, the track circuit transmitting end and receiving end equipment and choke transformer are connected in parallel to the rail, and the reflux reactor is connected to the central point of the two choke transformers to test the influence of different outer loop impedance on the rail breakage detection.

By selecting the length and equipment configuration of the different track sections in the field and using the simulation board to simulate rail breakage, the effectiveness of the rail breakage detection function of the track circuit can be tested when the reactor is connected to the circuitous circuit in series. Taking the most unfavourable working conditions when testing, i.e. a 300 m section with and without compensation capacitance, carrier frequency 1700 Hz and track bed resistance infinity (equivalent 1000 \(\Omega\) km), the comparison is made between simulation data under the condition of ballasted bed rail parameters and laboratory test data, as shown in Figs 17 and 18.

From Figs 17 and 18, it can be seen that when the ZPW-2000A track circuit is at 300 m section, in the case of the outer loop-only series reflux reactor, the track circuit receiver voltage is all less than the track relay reliable drop threshold of 153 mV at different rail breakage positions, which can realize the rail break detection.

### 4.2 Field model validation test

Based on the field environment of a station on the Daqin Railway Line, the rail breakage test under various external circuitous circuit conditions is carried out to verify the accuracy of the
simulation analysis model. Normally, after the rail breakage occurs in an in-station track, the signal can be circulated through an external circuitous loop, including a single outer loop, two outer loops and three outer loops, and the verification test schematic of the model is shown in Figs 19–21. Field test schematics simulate separately: (1) single outer loop main rail breakage; (2) two outer loop main rail breakage; (3) three outer loop main rail breakage.

Based on the field environment and test conditions, the schematic diagram of the simulation circuit of circuitous circuit of track circuit is built, as shown in Fig. 22.

Field test results and simulation results are shown in Table 2. The simulated rail breaking residual voltage and the measured residual voltage of the rail breaking receiver are basically consistent, and all of them are less than the reliable drop threshold limit of 153 mv of the
track relay, which can realize the rail-breaking detection.

5. Conclusions

This paper takes the ZPW-2000A track circuit of a station on the Daqin Railway Line as the research object and, based on the rail lumped concentration parameters and the four-terminal network coefficient theory, it establishes the rail breakage detection model of the track circuit system considering the earth leakage. It also defines the broken rail coefficient, formulates the standard to measure the quantitative analysis of the rail breakage detection and further analyses the unfavourable factors that affect the broken rail coefficient. According to the situation of a ‘third rail’ on a circuitous circuit that may appear when the track circuit is broken, the paper quantitatively analyses the influence of compensation capacitance configuration, critical track bed resistance, critical section length, minimum rail impedance, critical rail breaking frequency and transmitter voltage level on the residual voltage of the track circuit receiver after the rail breakage. Finally, the feasibility of the method is verified by comparing the simulated and measured data, and a quantitative calculation method is provided for the rail breakage detection of a heavy-haul railway, which provides a reference and theoretical basis for subsequent research on the rail breakage detection of a heavy-haul railway.

Conflict of interest statement. None declared.

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