Analysis on the influence of tuning area fault on the transmission characteristics of ZPW-2000 track circuit

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Abstract. Based on the operating principle of ZPW-2000 track circuit, the influence of the fault of the tuning area on the transmission characteristics of ZPW-2000 track circuit was analysed. Firstly, the four-terminal network model of the track circuit was established by using the transmission-line theory. Secondly, the transmission characteristic equation from the transmitting end to the receiving end was derived. Finally, the most unfavourable conditions were determined and the voltage at the receiving end of the track circuit and the frequency envelope of the circuit were simulated respectively. The results show that the fault of the tuning area could have a great influence on the transmission characteristics of the track circuit. This mathematical model can provide a theoretical basis for the study of the fault protection capability of the track circuit to the tuning area.

1. Introduction
The jointless track circuit system is an important equipment for checking whether there is a train, whether the track is broken, and the communication between vehicles is realized. Its reliability is directly related to the safety and efficiency of train operation. Tuning area is an important part of the jointless track circuit. Whether it works properly or not directly affects the transmission characteristics of the track circuit. If the tuning equipment fails, the original circuit transmission characteristics are destroyed, resulting in the cross-border transmission of signals in adjacent sections and the formation of neighboring section interference, which seriously affects the safety of driving.

At present, most of the research on the tuning area was based on modeling and simulation using MATLAB software. Most of the research on tuning areas was only fault diagnosis [1], or analysis of neighboring section interference [2] And the circuit shunting current model of ZPW-2000 track circuit was established, and the variation of shunting current to compensate for capacitance failure was studied [3]. The model of ZPW-2000 track circuit is established, and the accuracy of the model was verified by comparing it with that of single circuit [4]. However, this article mainly studies the compensation capacitance failure, and does not analyze the failure of the tuning area. The adjacent section interference model is established to simulate the TCR receiving component, and the model was verified [5]. However, the influence of the fault of tuning area on the transmission characteristics of track circuit was not systematically analyzed.

In view of the above situation, it is necessary to analyze quantitatively and qualitatively the variation of the circuit circuit branch current and the track voltage of the receiving end. In this thesis, a model of the four-end circuit of the track circuit is established, and the influence of the circuit circuit on the circuit
transmission characteristics is simulated. It provides a theoretical basis for the study of fault diagnosis and fault protection capability of the tuning area of the track circuit.

2. Working Principle of ZPW-2000 Track Circuit

The ZPW-2000 track circuit is mainly composed of transmitter, transmission cable, transmitter matching Transformer, transmitter tuning area, rail, receiver tuning area, receiver matching Transformer, receiving cable, damper and receiver parts [6]. The electrical isolation of adjacent sections is vehicle-ried out by means of the electrical insulation node resonator circuit in the tuning area. The basic structure of the ZPW-2000 track circuit is shown in Figure 1.

![Figure 1. Structure of ZPW-2000A track circuit.](image)

The 4G shown in Figure 1 is in an adjusted state. The signals generated by the transmitter are transmitted to the main part of the track circuit via cables and Transformers, and the signal is isolated by the tuning area and transmitted to the receiver. The electrical insulation node makes the signals of adjacent different frequency vehicles unable to cross the area, which guarantees the good transmission of the signals in this section. II G is in a split state. At this time, the signal emitted by the transmitter is returned to the transmitter.

![Figure 2. Principle diagram of electrical insulation joints (tuning area).](image)
3. Construction of a four-terminal network model

In this thesis, the four-terminal network model of track circuit is established by hierarchical modeling method. The equivalent circuit model of train track circuit is shown in Figure 3.

![Figure 3](image.png)

**Figure 3.** Model of track circuit transmission by circuit.

3.1. Tuning area modeling

According to the transmission line theory, $\gamma$ and $Z_c$ are the transmission coefficients and characteristic impedance of the rails, respectively. The expressions of $\gamma$ and $Z_c$ are as shown in equation (1):

$$
\begin{align*}
\gamma &= \sqrt{(R + jwL) \times (G + jwC)} \\
Z_c &= \frac{R + jwL}{\sqrt{G + jwC}}
\end{align*}
$$

In formula (1), $R$ represents the rail resistance value, $L$ represents the inductance value of the rail, $G$ represents the conductivity value of the road bed between the two rails, is the reciprocal of the road resistance value, and $C$ represents the capacitance value between the two rails.

The tuning area acts as a small track to isolate the signals of the two-segment track circuit and is generally installed at the end of a segment of the track circuit. As shown in Figure 2, the tuning area consists of the tuning unit BA1, the hollow coil unit, and the tuning unit BA2. The installation spacing between the components is $ls/2$. The hollow coil and the steel rail units on both sides of which are $ls/2$ are treated as a hollow coil unit. The impedance of each component is calculated as shown in equation (2):

$$
\begin{align*}
Z_{BA2} &= j \frac{\omega^2 L_2 C_2 - 1}{\omega C_2 + \omega^2 C_3 - \omega^3 L_2 C_2 C_3} \\
Z_{SV} &= -j \frac{1}{\omega L_{SV}} \\
Z_{BA1} &= \frac{1 - \omega^2 L_1 C_1}{j \omega C_1}
\end{align*}
$$
In Figure 3, $Z_{BA1}$ represents the impedance of the sending end BA1, $Z_{j1}$ represents the visual impedance of the receiving end BA1 to the receiving end, and $T_{jBA1}$ represents the equivalent four-terminal network of the transmitting end BA1 transmission characteristics. The receiving end BA1 transmission equation can be expressed as formula (3):

$$T_{jBA1} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{BA1} + Z_{j1}} & 1 \end{bmatrix}$$

In formula (3), $Z_{BA1}$ represents the impedance of the sending end BA1, $Z_{j1}$ represents the visual impedance of the sender to BA1. $T_{SBA1}$ represents the equivalent four-terminal network of the transmitting end BA1 transmission characteristics, and the transmitting end BA1 transmission equation can be expressed as (4):

$$T_{sBA1} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{BA1} + Z_{s1}} & 1 \end{bmatrix}$$

The transmission equation of the small track circuit to the receiving end of the adjacent section is:

$$T_{SVA} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{SVA} + Z_{ca}} & 1 \end{bmatrix}$$

$$T_{tx} = T_S \left( \frac{L_s}{2} \right) \times T_{SVA} \times T_S \left( \frac{L_s}{2} \right)$$

$$Z_{tx} = \frac{T_{tx11}}{T_{tx21}} \left( \frac{Z_{BA2} + Z_{ca}}{Z_{BA2} + Z_{ca}} + \frac{T_{tx12}}{T_{tx22}} \right)$$

$$T_{ip} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{BA1}} & 1 \end{bmatrix} \times \begin{bmatrix} 1 & Z_{ca} \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{tx}} & 1 \end{bmatrix}$$

In formula (5), $T_{SVA}$ represents the transmission equation of the hollow coil element, $T_{tx}$ represents the transmission equation of a hollow coil unit, and $Z_{tx}$ represents the visual impedance of the BA1 at the sending end of the adjacent segment to the receiving end of the segment.

3.2. Modeling of the main track

The compensation capacitor is placed at an equal distance on the rail, so the idle track track surface can be regarded as a cascade of multiple compensation capacitor unit modules. The installation spacing of the compensation capacitor is $l_c$, where the first and last compensation capacitors are separated from the transmitter and receiver $l_c/2$, respectively. The compensation capacitor and its two side’s length $l_c/2$ rail unit are considered as a compensation capacitor unit.

$T_x (l_c/2)$ represents the transmission matrix of the rail four-terminal network with a length of $l_c/2$, $T_c$ represents the transmission matrix of the rail and a single compensation capacitor, and $T_{cc}$ represents the transmission matrix of a compensation capacitor unit. The transmission matrices are shown in equation (6):
When there is no vehicle occupation, the number of compensating capacitors is calculated according to the length of the track circuit. The main track transmission equation is as shown in equation (7):

\[ N = (Tcc)^n \]  

### 3.3. Track Modeling Based on Dial Location

During the process of entering the track circuit section to completely clear the track circuit section, the change trend of the number of road separation wheel pairs is to increase first and then remain unchanged and then gradually decrease. This section establishes a four-terminal network model for the rail part of the rail from the transmitting end to the receiving end of the track circuit. At this time, the number of circuit pairs does not change with the driving distance. Set the position of the wheel pair to \( x \), where the wheel pair has \( m \) compensation capacitance units at the sending end.

From Figure 3, it can be seen that the transmission matrix of the transmitter tuning unit BA1 to the first round pair is \( TR \); \( TL \) is the transmission matrix of the last round pair to the receiving tuning unit BA1;

Obviously, when the first round of the train runs to the \( m \)-compensated capacitor unit, the distance from the wheel pair position to the right of the \( m \)-compensated capacitor module is \( \Delta x \), and the transmission matrix \( TR(x) \) is sent to the first round pair as shown in formula (8):

\[
TR(x) = \begin{cases}
(Tcc)^n \times Tx(\Delta x) & 0 < \Delta x < l_c / 2 \\
(Tcc)^n \times Tx(l_c / 2) \times Tc \times Tx(\Delta x - l_c / 2) l_c / 2 < \Delta x < l_c \\
(Tcc)^n & \Delta x = 0 \\
(Tcc)^n \times Tx(l_c / 2) & \Delta x = l_c / 2
\end{cases}
\]  

Similarly, at this time, the transmission equation for the last round of the train to the receiving end is \( TL \), the distance from the position of the wheel pair to the left of the \( m \)-compensated capacitor module is \( \Delta x_1 \), and the transmission matrix \( TL(x) \) from the sending end to the first round pair is as shown in formula (9):

\[
TL(x) = \begin{cases}
Tx(\Delta x_i - l_c / 2) \times Tc \times Tx(l_c / 2) \times (Tcc)^{n-1-m} l_c / 2 < \Delta x_i < l_c \\
Tx(\Delta x_i) \times (Tcc)^{n-1-m} & 0 < \Delta x_i < l_c / 2 \\
(Tcc)^{n-m} & \Delta x_i = l_c \\
Tx(l_c / 2) \times (Tcc)^{n-1-m} & \Delta x_i = l_c / 2
\end{cases}
\]  

The transmission matrix of the split wheel pair in Figure 3 is \( TR_f \), and its expression is as shown in equation (10):
The transmission matrix $T_{rf}$ from the sending end of this section to the receiving end of this section is as shown in equation (10):

$$
T_{rf} = \begin{bmatrix}
1 & 0 \\
1/R_f & 1
\end{bmatrix}
$$

The transmission matrix $T_{tc}$ from the sending end of this section to the receiving end of this section is as shown in equation (11):

$$
T_{tc} = T_{sBA1} \times T_{ca} \times TR \times T_{rf} \times TL \times T_{ca} \times T_{jBA1}
$$

In equation (11), the lead wiring transmission equation is:

$$
T_{ca} = \begin{bmatrix}
1 & Z_{ca} \\
0 & 1
\end{bmatrix}
$$

In equation (12), $Z_{ca}$ represents the lead impedance, and its impedance value changes with the frequency. Let the frequency shift signal voltage valid value emitted by the transmitter be $U_{se}$, which is shown by the property of the transmission Matrix, as shown by the rail voltage $U_{re}$ at the receiving end, the transmission equation (13) is:

$$
U_{re} = \frac{U_{se}}{|T_{tc} (1,1) + T_{tc} (1,2)/Z_z|}
$$

At this point, $| \cdot |$ represents the modular value of the matrix, and the transmission equation from the sending end to the partition point is as shown in equation (14):

$$
T_{xxrf} = T_{sBA1} \times T_{ca} \times TR
$$

The shunting current at this time shows:

$$
I_{rf} = \frac{U_{se}}{|T_{xxrf} (1,1) \times R_f + T_{xxrf} (1,2)|}
$$

4. Simulation Analysis of Tuned Area Fault
In the fault diagnosis study of track circuits, the data of the track voltage at the receiving and the shunting current end are often used to determine whether the track circuit has a fault. The list of parameters is as follows:
Table 1. List of component parameters.

| Number | Component                   | figure  |
|--------|-----------------------------|---------|
| 1      | Receiver impedance          | 400Ω    |
| 2      | L1 (BA1)                    | 37.145mΩ|
| 3      | C1 (BA1)                    | 130.44µF|
| 4      | L2 (BA2)                    | 93.472mΩ|
| 5      | C2 (BA2)                    | 90.9µF  |
| 6      | C3 (BA2)                    | 276.61µF|
| 7      | Lsva                        | 33.5mΩ  |
| 8      | Zca                         | 8.3+j31.4mΩ|
| 9      | Capacitors compensated      | 13      |
| 10     | Compensation capacitance    | 55µF    |
| 11     | Main track length           | 1200meters|

Since the tuning area is mainly used to isolate the signal interference of adjacent sections, the fault of the tuning area will cause interference of adjacent sections. The tuning area failure is generally divided into the tuning area failure and the receiver tuning area failure, and the fault types of the three components BA1, SVA, and BA2 in the tuning area are divided into open circuit failure and short circuit failure. There are six cases of failure in each tuning area.

4.1. Sending Tuning area Fault

The shunting current if based on the previously proposed shunting track model. The most unfavorable conditions determined by the simulation analysis of the shunting current are: the lowest voltage at the transmitting end, the minimum impedance of the wheel pair, and the highest impedance of the rail.

An open circuit fault occurs in the sending end element, and a fault value is added during simulation calculation. The fault value is greater than 0. The short-circuit fault of the transmitter element causes the component value in equation (5) to be reduced to 0. During simulation calculation and is considered as a wire; It is worth noting that poor exposure can also be classified as open circuit failure.

![Track circuit shunting current](image)

**Figure 4.** Track circuit circuit current curve

The simulation results show that the BA1 fault will destroy the parallel resonance of the section, reduce the impedance and increase the voltage of the transmitting rail surface. Since BA1 acts as a zero
impedance of adjacent sections, it acts as a means of isolating signals from adjacent sections. The BA1 open circuit failure will cause the problem of interference in the adjacent section. Since the receiving end is at the end of the section, the signal sent by the adjacent section to the receiving end of the section will lose weight and have a small impact on the rail voltage of the receiving end. However, the influence on the shunting current is large, and the adjacent section interference will occur. At this point, the TCR induction voltage will exceed the threshold.

The BA1 short-circuit fault at the transmitting end will cause the transmitter to short-circuit, and the track voltage of the entire track circuit will be greatly reduced, resulting in a “red band” phenomenon. The short circuit fault of each component in the tuning area of the transmitting terminal will not cause the interference of the signal crossing area in the adjacent section.

4.2. Receiver tuning area failure

Since the receiving end of this section is far away from the sending end, this section emulates the voltage $U_{re}$ of the receiving end track surface according to the previously proposed track separation track model. The most unfavorable conditions of the distribution state are: the highest voltage at the transmitting end, the largest impedance of the wheel pair, the smallest impedance of the rail, and the largest leakage resistance of the channel bed.

![Figure 5. Voltage of the receiving end of the track circuit](image)

The short-circuit fault of the receiver zero-impedance tuning unit BA2 will cause the impedance of the tuning area of the receiving end to decrease, and the track voltage of the entire track circuit will increase slightly. The short circuit at the receiving end of SVA will also cause the impedance of the tuning area in this section to be reduced, resulting in an increase in the track voltage. The phenomenon is similar to that of the BA2 short circuit fault, but the magnitude is smaller. The zero-impedance tuning unit BA1 short-circuit fault at the receiving end will cause the receiver voltage in this section to be significantly reduced, resulting in a "red band" phenomenon. However, due to the reduced impedance of the tuning area at the receiving end, the track voltage of the receiving end will be slightly increased.
The short circuit fault of each component in the tuning area of the receiving end will not cause the interference of the adjacent section signal crossing area.

5. Analysis of fault protection capability in tuning area

Fault protection ability refers to the ability of the system to ensure train efficiency and detect faults without affecting safety if safety problems occur. According to the changes in transmission characteristics of the above track circuit in case of failure without affecting safety, it can be concluded that: 1. The circuit current can detect the open circuit faults of the tuning BA1, SVA, and BA2 at the transmitting end and the SVA short circuit faults at the transmitting end through the change of the current, and various types of faults can be separated by the large area of the current change. The fault of BA1 short circuit at the transmitting end will reduce the scoring current directly to 0, and the short circuit fault of BA2 at the transmitting end will have little effect on the transmission characteristics of this section. However, it is possible to determine whether there is a short circuit through the small rail inspection of the receiver. 2. The open circuit faults of the receiving end BA1, SVA and BA2 and the short circuit faults of the receiving end can be detected by the change of the track voltage at the receiving end. Various kinds of faults are separated by the variation of the track voltage at the receiving end. The BA1 short-circuit fault at the receiving end will directly reduce the rail voltage at the receiving end to 0. The short-circuit fault at the receiving end BA2 will have little effect on the transmission characteristics of this section, but it can be judged by the small rail inspection of the receiver at the rear section.

6. Conclusion

In summary, the failure of various components at the transmitting and receiving ends will affect the transmission characteristics of the ZPW-2000 track circuit. Based on the analysis of the fault protection capability, it is concluded that the track circuit has the ability to detect and resolve all kinds of faults in the tuning area without affecting the safety and efficiency of driving. Therefore, it is concluded that the ZPW-2000 track circuit has the ability to protect the tuning area from failure.

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