Research on Fault Location Method of Track Circuit Compensation Capacitor Based on Probabilistic Neural Network

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Abstract: Compensation capacitor is an important component for extending the signal transmission of track circuit, and its safe operation is very important to the transportation business of rail transit. According to the difficulty of diagnosing the fault of compensation capacitor, a fault location model of compensation capacitor based on probabilistic neural network is established. Firstly, the influence of compensation capacitors on the current curve is analyzed from the two aspects of the failure reasons of compensation capacitors and the influence on signal transmission. Then, according to the parameters of the track circuit, the important characteristic parameters affecting the compensation capacitors are screened. According to 4 different failure modes, a fault diagnosis model based on probabilistic neural network is constructed, and the BP neural network model is selected as the comparison experiment. The results show that the compensation capacitor fault location model based on probabilistic neural network has higher relative prediction accuracy and the shortest time.
Keywords: compensation capacitor, probabilistic neural network, fault location, track circuit

1. Introduction

The inductance and capacitance of the track itself have a large inductive reactance to the frequency-shifted signal during the signal transmission process of the track circuit, which greatly reduces the transmission distance of the signal. For this reason, adding compensation capacitors can effectively reduce the influence of the track inductance on the signal. Once the compensation capacitor fails, it will reduce the transmission distance of the track circuit signal, making the system more prone to red light band faults and affecting the normal operation of the train. The fault detection of compensation capacitors has always been one of the common concerns of researchers in the field of railway signaling. Many scholars have conducted in-depth research on the detection of compensation capacitors: In reference [1], aiming at the problems of low precision and long time of fault detection results of track circuit at present, simulated annealing algorithm was used to obtain the optimal value of compensation capacitor, and the parallel current amplitude envelope curve was drawn.. Reference [2] proposes a fault feature analysis method based on wavelet packets according to the amplitude fluctuation law of the normalized shunt current curve when the compensation capacitors are all normal, disconnection faults and capacitance drop faults. Reference [3] et al. proposed a method for predicting the number of compensation capacitor faults in track circuits based on long short-term memory (LSTM) based on the compensation capacitor fault records at the railway site, so as to mine the variation law of the compensation capacitor fault quantity with time, and realize the compensation Prediction of the number of capacitor failures over a period of time in the future. Reference [4] analyzes the influence of compensation capacitors on the signal amplitude of track circuits, proposes a calculation method for the importance of compensation capacitors, and further determines the maintenance priority of compensation capacitors.

Under the background of big data, various intelligent algorithms have been widely used, and many of them have been used in the fault diagnosis of track circuits. In this paper, starting from the compensation capacitor failure and the influence of compensation capacitor on signal transmission, the main features that have a strong influence on compensation capacitor are identified for the current variation of compensation capacitor in normal and fault states, and subsequently a probabilistic neural network fault diagnosis model of compensation capacitor is constructed based on the single and multiple compensation capacitor failures in the track. The specific chapters are arranged as follows: the second part analyzes the influence of the fault of the compensation capacitor; the third part analyzes the setting of the characteristic parameters of the track circuit; the fourth part analyzes the application of the probabilistic neural network in the fault diagnosis of the compensation capacitor.

2. Influence analysis of compensation capacitor failure

2.1 Cause analysis of compensation capacitor failure

Since the compensation capacitor follows the track line, the surrounding environment is harsh, causing the equipment to fail easily. The fault of the compensation capacitor makes the transmission distance of the frequency-shifted signal in the rail drop sharply, shortens the transmission distance of the signal, and reduces the receiving voltage of the receiving end, which leads to the occurrence of the red light band. The position of the compensation capacitor is shown in Figure 1. The more the compensation capacitor fails, the more serious the track signal drops, and the more likely the red light band is to occur, which affects the normal driving safety [5].

Figure 1. Compensation capacitors in track circuits

The fault of the compensation capacitor will have a direct impact on the short-circuit current fault curve. The main reasons for the failure are [6-7]: (1) The capacitance value of the compensation capacitor decreases. The interference of the external environment causes the compensation capacitor to be easily aged. Thunderstorm weather, equipment surge voltage, etc. will cause the compensation capacitor to fail quickly [8]. (2) The compensation capacitor is disconnected. The connection line between the compensation capacitor and the track is broken, so that the compensation capacitor cannot play its due role, resulting in a decrease in the signal transmission distance. (3) Poor contact of compensation capacitor leads. The poor contact of the lead leads to a drastic change in the contact resistance between the lead and the rail, resulting in an excessive load on the compensation capacitor, resulting in the fluctuation of the rail voltage [9].

2.2 Effect of compensation capacitor failure on signal transmission

The simulation experiment of the track circuit is carried out according to the following parameters: The length of the main track line is 1km, the signal carrier frequency is 1700Hz, the ballast resistance is $R = 1.5\Omega \cdot km$, the shunt resistance is $R_f = 1.5\Omega$, the 10 compensation capacitors are all 55uf. On the basis of the simulation of the rail circuit, for the fault problem of compensation capacitor, the scheduled compensation capacitor disconnection is used as the research object, mainly analyzing four fault problems such as compensation capacitor C5 disconnection, compensation capacitor C7 disconnection, compensation capacitor C4 and C6 disconnection, compensation capacitor C5 and C7 disconnection, while adding the normal state most comparative test, the experimental model to obtain the voltage situation of each part is shown in Table 1.

Table 1. Track circuit signal transmission process

Sessage	Normal	C5 disconnection	C7 disconnection	C4 C6 disconnection	C5 C7 disconnection
Transmit voltage (V)	153.00	153.00	153.00	153.00	153.00
Transmitter cable side voltage (V)	101.89	103.19	103.08	100.02	104.47
Transmitter rail voltage (V)	2.21	2.76	2.57	1.84	2.61
Receiver rail voltage (V)	0.63	0.48	0.47	0.30	0.32
Main rail into voltage (V)	1.03	0.82	0.79	0.52	0.55
Main rail out voltage (V)	0.42	0.34	0.32	0.21	0.23
Voltage at main rail C1 (V)	2.93	2.61	2.72	3.69	2.34
Voltage at main rail C2 (V)	2.57	3.39	3.09	1.55	3.54
Voltage at main rail C3 (V)	2.26	1.86	1.99	3.35	1.48
Voltage at main rail C4 (V)	1.89	3.06	2.58	1.02	3.24
Voltage at main rail C5 (V)	1.75	1.38	1.40	1.64	0.96
Voltage at main rail C6 (V)	1.53	1.20	2.32	0.75	1.58
Voltage at main rail C7 (V)	1.36	1.07	1.03	0.66	0.69
Voltage at main rail C8 (V)	1.16	0.91	0.88	0.57	0.62
Voltage at main rail C9 (V)	1.05	0.82	0.79	0.49	0.54
Voltage at main rail C10 (V)	0.90	0.72	0.70	0.42	0.46

In Table 1, there are 16 items of detection data, including the sending voltage, the cable side voltage of the sending end, the rail surface voltage of the sending end, the main rail input voltage, the main rail output voltage, and the voltage at the main rail C1 to C10. Compared with the simulation data of the track circuit under normal conditions, when the compensation capacitor fails, the monitoring data are changed to varying degrees: (1) the failure of a single compensation capacitor has a slight impact on the system, but a greater impact on the subsequent voltage of the compensation capacitor in the main track; (2) When multiple compensation capacitors fail in the section, the monitored voltage value of the main track and the receiving end decreases, while comparing the single compensation capacitor failure, it is found that the voltage value decreases more rapidly when multiple capacitors fail, which is closer to the lower limit of 240mV of the voltage out of the main track, and the "red light band" failure occurs in the system, and the system appears to have no car occupancy, which has an adverse effect on the traffic information.

2.3 Effect of compensation capacitor failure on short-circuit current

The transmission of the short-circuit current in the track section is limited by the characteristics of the compensation capacitor, showing a wave-like attenuation, and the short-circuit current between the two compensation capacitors first increases and then decreases. The fault of the compensation capacitor produces faster attenuation on the downstream part of the short-circuit current, delaying the arrival of the next trough and peak; when multiple compensation capacitors fail, the current attenuation downstream of the fault is more obvious, and it continues to attenuate and attenuate after the subsequent fault location. The trend is greater than the failure of a single compensation capacitor.

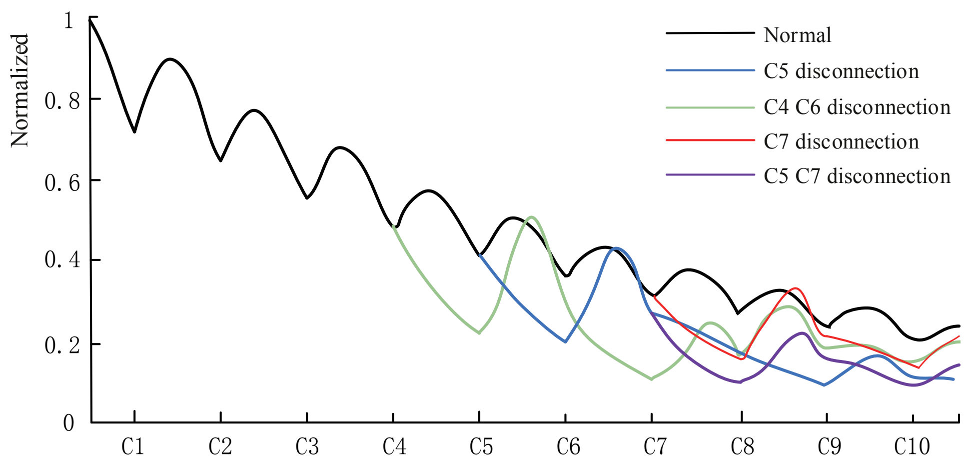

Figure 2. Variation of short-circuit current curve

3. Tuning of characteristic parameters of track circuit

3.1 Characteristic parameters of track circuit adjustment state

The selection of the characteristic parameters of the track circuit can better characterize the fault characteristics. In order to better select the characteristic parameters, firstly, the characteristic parameters need to be easy to monitor and collect; secondly, there is a weak correlation between the characteristic parameters. According to the theory and simulation model of the track circuit, some parameters of the sender, the main track and the receiver are collected as characteristic parameters. Among them, at the sending end, it includes the sending voltage, the sending current and the voltage on the cable side of the sending end. Since the sending voltage is set by the system, it has less sensitivity to the change of the compensation capacitance of the track part. Therefore, the sending current is selected as the sending end. Characteristic parameters; the parameters of the main track part include the rail surface voltage of the sending end, the voltage at the compensation capacitor of the track part, and the rail surface voltage of the receiving end. The change of the compensation capacitor has a great influence on the values of these parameters, but the voltage measurement and acquisition of the compensation capacitor part It is very difficult, so the rail surface voltage of the transmitter and the receiver is selected as the characteristic parameter; at the receiver, it includes the cable side voltage of the receiver, the main rail in and the main rail out voltage, but because the main rail in and the main rail out voltage are related Therefore, the cable side voltage at the receiving end and the main rail input voltage are selected as characteristic parameters. The above five types of parameters are selected as the characteristic parameters greatly affected by the compensation capacitance, and the data of the five types of system states are normalized, as shown in Table 2.

Table 2. Characteristic parameter value and each fault type of compensation capacitor

Numble	Send current	Transmitter rail voltage	Receiver rail voltage	Receiver cable side voltage	Main rail input voltage	Fault type
1	0.0082	0.3386	0.0715	1.0000	0.1390	Normal
2	0.0056	0.4316	0.0490	0.7786	0.1021	C5 disconnection
3	0.0068	0.2917	0.0466	0.7576	0.0986	C7 disconnection
4	0.0125	0.2716	0.0174	0.4687	0.0512	C4 C6 disconnection
5	0.0045	0.4096	0.0219	0.5095	0.0570	C5 C7 disconnection

3.2 Characteristic parameters of the shunt state of the track circuit

The short-circuit current curve is the main research tool for the shunt state of the track circuit. By analyzing the characteristics of the short-circuit current curve, the characteristic parameters of the shunt state of the track circuit can be extracted. For the track circuit section with 10 compensation capacitors, according to the method of evenly arranging the compensation capacitors, it can be divided into 11 sections according to the position of the compensation capacitance, and the area formed by the envelope of the shunt current and the section length, denoted as the characteristic parameter of short-circuit current.

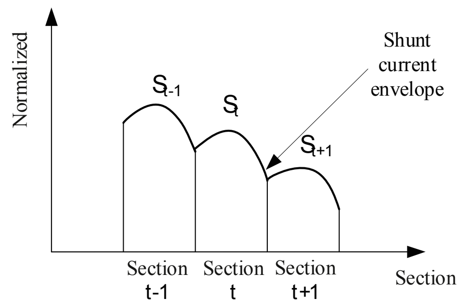

Figure 3. Short circuit current extraction features

According to Figure 2 and Figure 3, the area enclosed by the short-circuit current curve $S(t)$ is related to the shape of the short-circuit current envelope curve. The shunt current envelope curve formed by the fault compensation capacitor is relatively low compared to the normal state, and the characteristic area parameter formed $S(t)$ is small. Normalized, $S(t)$ as shown in Table 3 under different fault conditions.

Table 3. Normalized data

Numble	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	Fault type
1	0.496	1.000	0.841	0.734	0.618	0.534	0.448	0.380	0.324	0.270	0.085	Normal
2	0.496	1.000	0.841	0.734	0.618	0.304	0.372	0.233	0.247	0.168	0.049	C5 disconnection
3	0.496	1.000	0.841	0.734	0.618	0.534	0.448	0.212	0.264	0.156	0.046	C7 disconnection
4	0.496	1.000	0.841	0.734	0.361	0.438	0.159	0.183	0.107	0.107	0.008	C4 C6 disconnection
5	0.496	1.000	0.841	0.734	0.618	0.305	0.376	0.129	0.151	0.152	0.006	C5 C7 disconnection

Compared with the failure of a single compensation capacitor, when multiple compensation capacitors fail at the same time, the impact on the following track circuit will be superimposed. For the above four types of faults, the selected characteristic parameters can effectively reflect the influence of the compensation capacitors, which can be found in used in actual troubleshooting.

4. Application of probabilistic neural network in compensation capacitor fault diagnosis

4.1 Probabilistic neural network fault diagnosis method

Fault classification is achieved by using a probabilistic neural network (PNN) architecture specifically designed for classification problems. When there is an input, the first layer mainly calculates the distance from the input vector to the training input vector.This produces a vector with elements representing how close the input is to the training input. The second layer sums the weights of each class of input and gives its net output as a probability vector. Finally, the maximum of these probabilities and the full transfer function on the second layer output are taken and yield positive recognition for that class and negative recognition for non-target classes. The PNN model [10] has extremely high speed and accuracy and is suitable for real-time fault diagnosis and signal classification problems. The PNN structure for fault classification consists of two hidden layers.

The output of the PNN is the class of that particular fault, a numeric integer between 1 and 5. The features of 11 fault voltage signals for each fault type are used for training. Since the training dataset contains 1100 elements, the PNN network is tested with 80 data signals by changing the training samples 12 times. The fault diagnosis model of track circuit short-circuit current based on probabilistic neural network, its process is shown in Figure 4.

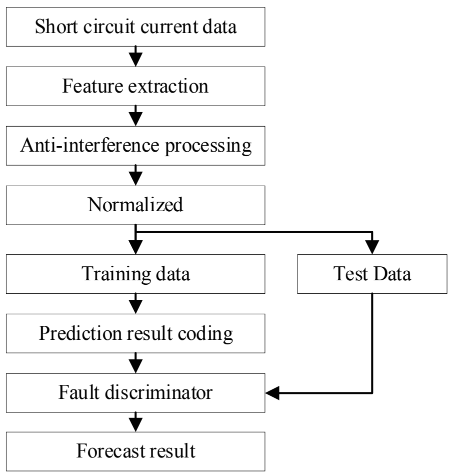

Figure 4. Track circuit fault diagnosis process

(1) Track circuit adjustment state analysis and short-circuit current characteristic data collection. Combined with the track circuit simulation model, the short-circuit current characteristic area parameters are extracted, and the fault types are shown in Table 2.

(2) Normalization of feature data. The data of different types and magnitudes are scaled to between [0, 1] according to the numerical distribution, which is convenient for the algorithm to process the data. The normalization is calculated as:

$$T = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

(3) Coding of prediction results. According to the fault types in Table 3, use (0, 1) coding mode, 0 means no fault, 1 means fault, and the position of 1 means one of the above four faults. Type, that is, the matrix [0,0,0,0,0] is the normal state, and [0,0,1,0,0] is the third type, and the compensation capacitor C7 is faulty.

(4) Probabilistic neural network model. One of the most important key parameter variables in the model analysis is the PNN smooth coefficient. When the smooth coefficient tends to be around 0, the generalization or approximation processing ability of the model data is poor; when the absolute value of the smooth coefficient is also larger, the model Theoretically, the approximation of a larger range of sample data will appear to be closer to smoothness, but the actual estimated error is relatively large, so it is appropriate to select a smooth coefficient with a suitable value range, which can be further greatly improved. The true performance of the PNN approximation algorithm in the model.

(5) Prediction result generation and inspection. It is used for reliability analysis, evaluation and analysis of the prediction results in the adjustment state and the branch state, respectively, and to evaluate the practical performance of the prediction model design.

4.2 Experimental results and analysis

A total of 1500 sets of simulation data can be finally obtained through the simulation test, and the package contains 5 types of simulation faults. The simulation data of the simulation test set is randomly divided into two parts, and a total of 1250 sets of simulation data are randomly selected as the data used for simulation training, and the remaining 250 sets of simulation data will be used as the test data for simulation testing. After testing, the network mean square error generated in the probabilistic neural network system should gradually increase with the increase of the optimal smooth coefficient of the system, and show a significant decrease at first and then a gradual increase. When it is about 1.6, the mean square error of the network model is close to the minimum, so the optimal smooth coefficient size of the system is generally slightly larger than 1.6. The classification effect of the PNN network is shown in Figure 5.

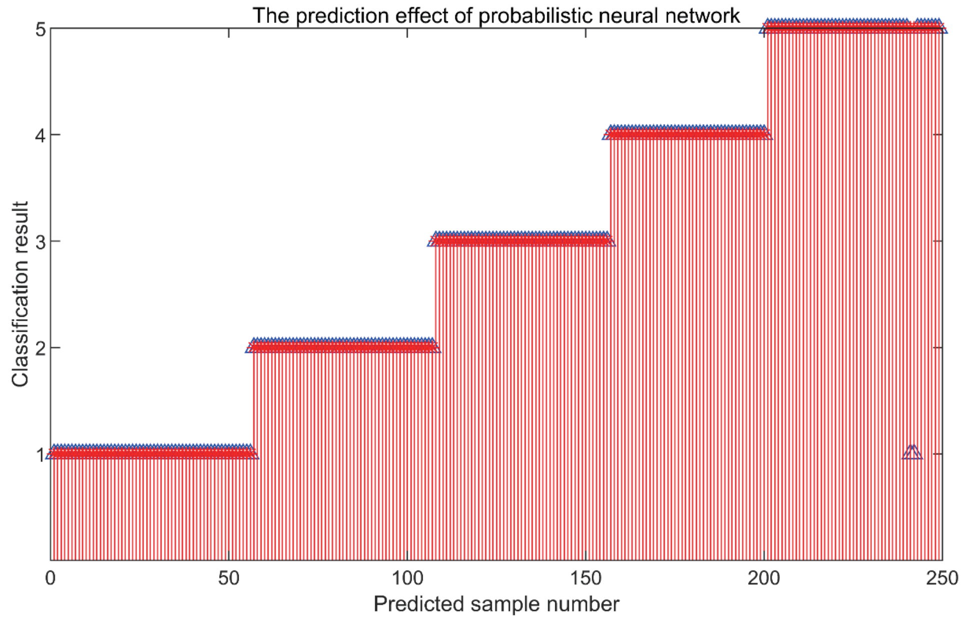

Figure 5. Classification effect of PNN network

At the same time, the BP neural network is selected as the control system for the experiment. The number of nodes in the input layer of the BP neural network is 5, the number of nodes in the output layer is 5, and the number of nodes in the implicit output layer is only 3~9 in the range of this value. The maximum number of iteration loops of the network is about 1000, and the learning rate is only about 0.1, and the training does not achieve the desired goal. When the number of hidden layer nodes is more than 5, the maximum diagnostic accuracy rate is 89.9%.

Table 4. Comparison of neural network diagnosis accuracy rate

Model	Test data prediction accuracy/%						Time/s
	Normal	C5 disconnection	C7 disconnection	C4 C6 disconnection	C5 C7 disconnection	Total data	
BP	91.4	90.6	89.9	88.3	89.3	89.9	12.76
PNN	99.4	98.3	97.9	97.2	96.3	97.8	2.45

According to Table 4, it can be seen that the prediction accuracy of the average prediction results of the 1200 sets of test data by the probabilistic neural network is about 97.3%, and the average prediction time complexity is 1.45s, while the accuracy of the prediction results of the BP neural network is about 88.5%. The time complexity is 12.76s, and the average correct rate of probabilistic neural network for each fault diagnosis and detection is higher than that of BP neural network.

From the diagnosis results, the PNN prediction model has the following significant advantages compared with the traditional BP network model: (1) In terms of the accuracy of the prediction results, the prediction accuracy of the PNN network prediction model is higher than that of the BP network model; (2) In terms of model structure, the PNN model has a simpler structure, fewer adjustment parameters, and shorter training time; (3) In terms of model convergence, the PNN model has high stability and no local optimal solution.

5. Conclusion

Firstly, the reasons for the failure of the compensation capacitor and its influence on the current curve are analyzed, the characteristic area parameters of the short-circuit current are extracted and analyzed, and 5 types of parameters are selected as the characteristic parameters. The BP neural network model is selected as the comparison experiment, the accuracy of the probabilistic neural network model is increased by 7.9%, and the model time is shortened by 10.31s. Therefore, the track circuit compensation capacitance diagnosis algorithm of the probabilistic neural network model is more suitable for the fault diagnosis of the uninsulated track circuit.

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