SIMULATION ANALYSIS OF TRANSMISSION CHARACTERISTICS AND AUTOMATIC COMPILATION OF ADJUSTMENT TABLE FOR TRACK CIRCUIT BASED ON TRANSMISSION LINE THEORY

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Summary: *Atheoretical research on transmission performance of track circuit signal transmitted on rail line is made in this paper. A simulation platform of track circuit is built through developinga program with Microsoft Visual C++(VC++) and the influence of the track environment and capacitor faultson transmission performanceof track circuit are analyzed. The simulation results show that when the leakage of the ballastbed increases thedecreasing amplitude of the rail surface voltages enlargesas well, and thatprobablycauses the "red-light-strap" failures. If the capacitor has broken the amplitude curve of the rail surface voltages would change whose waveform is wavy when there are no capacitor failures and the voltages in receiving end would slightly decrease. In addition, to satisfy the once adjusting requirement of track circuit, the adjustment table is compiled based on the simulation platform using field test parameters. It provides a theoretical basis for field commissioning and maintenance.*

Keyword: *Track circuit, transmission characteristics, VC++, transmission line theory, adjustment table.*

I. INTRODUCTION

Track circuit is one of the most important equipment in China Train Control System (CTCS). It implements train positioning and integrity check through sending track signal to the rail. Moreover, the track signal provides train control information for the on-board devices by electromagnetic induction. The working performance of track circuit largely dependents on the transmission quality of the track signal and it directly affects the transportation safety and efficiency. In addition, due to the complex and changeable working environment of the track

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circuit the failures occurconstantly. According to statistics, a total of 4744 faults of track circuit occurred during 2006-2010 in China [1]. Except the turnouts the track circuits are the equipmentwhich failures occur most frequently. Therefore, it's necessary to conduct research on the transmission characteristics for track circuit.

Thead just menttable isanindispensable technical documentation during the installation and commissioning of track circuitequipment. The construction organization can adjust the alterable electrical parameters of track circuit only once according to the adjustment table and thenit can meet the requirements of the track circuit working states such as normal, shunt, cab signal and broken rail state [2]. The automatic establishment of track circuit adjustment tableis of great significance to ensuringonce adjustment and enhancing efficiency of construction.

II. BASIC PRINCIPLEOF TRANSMISSIONLINETHEORY

The overhead communication lines, cablecommunication lines and track circuits which use rail instead of wire to transfer control signal are called transmission lines [3]. The characteristic of transmission line can be represented by per unit lengthresistance R (Ω/km), inductance L (H/km), capacitance C (F/km) and conductance G (S/km). To facilitate the analysis, the transmission line is divided into many small pieces and the length of each segment Δx is small enough. Then each segment can be describedwith anequivalent four-terminal network (EFTN) which is shown in fig. 1.

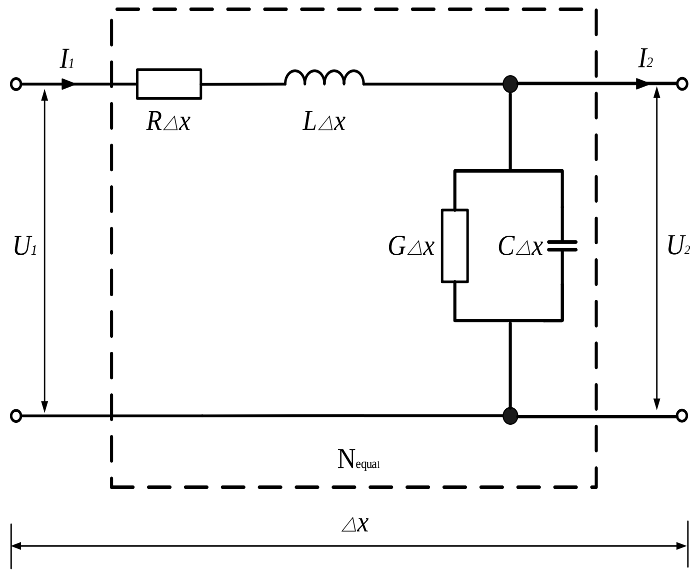

Fig 1. *Schematic diagram of transmission line equivalent four-port network*

U_1, I_1 are the input voltage, current of EFTN and U_2, I_2 are the output voltage, current. Assumed that U_1, I_1 are independent variables and then U_2, I_2 can be calculated usingequation (1) [4].

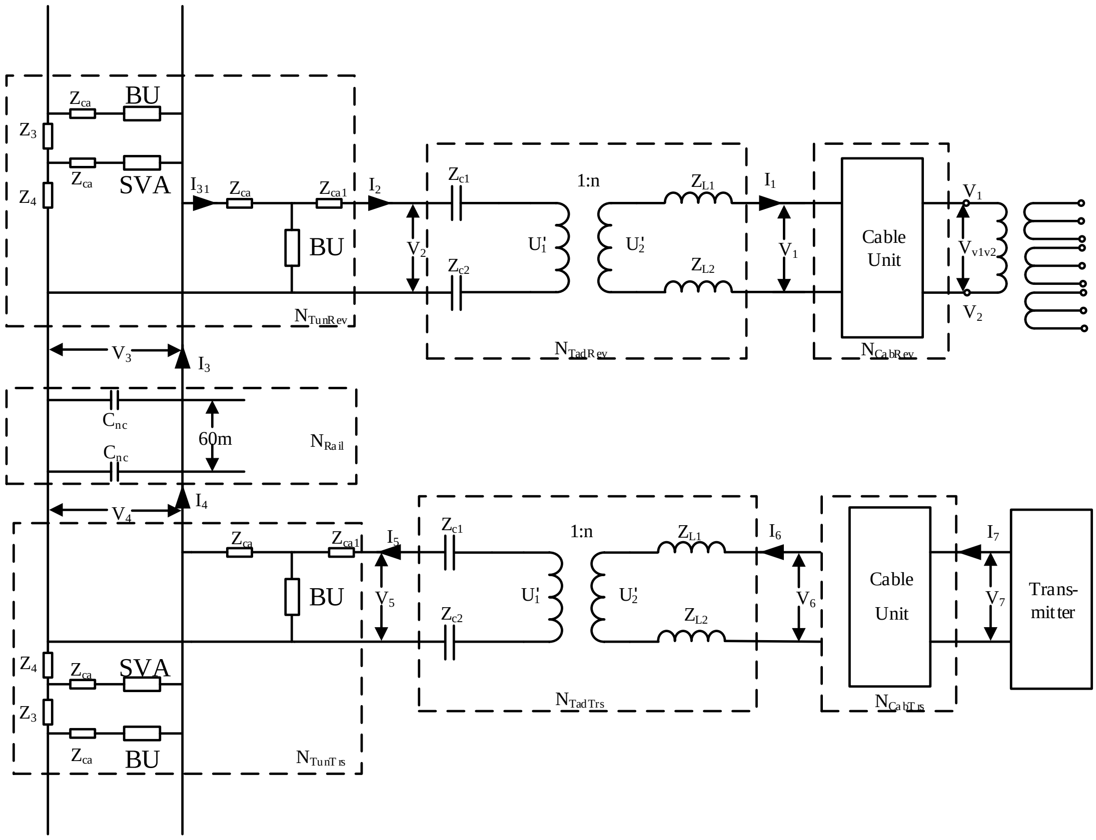

Fig 2. *Schematicdiagram of the jointless track circuit*

$$\begin{cases} \dot{U}_2 = N_{eq22}\dot{U}_1 - N_{eq12}\dot{I}_1 \\ \dot{I}_2 = -N_{eq21}\dot{U}_1 + N_{eq11}\dot{I}_1 \end{cases} \tag{1}$$

N_{eq} is the transmission parameter matrix of the transmission line EFTN which can beexpressed as

$$N_{eq} = \begin{bmatrix} N_{eq11} & N_{eq12} \\ N_{eq21} & N_{eq22} \end{bmatrix} = \begin{bmatrix} ch(\dot{\gamma}l) & \dot{Z}_c \cdot sh(\dot{\gamma}l) \\ sh(\dot{\gamma}l)/\dot{Z}_c & ch(\dot{\gamma}l) \end{bmatrix} \tag{2}$$

Where, l is the length of transmission line and Z_c, $\gamma$are the characteristic impedance and propagation constantwhich can be calculated usingequation (3) [5].

$$\dot{Z}_c = \sqrt{(R + jwL)/(G + jwC)} \tag{3-a}$$

$$\dot{\gamma} = \sqrt{(R + jwL)\cdot(G + jwC)} \tag{3-b}$$

Where, w is angular frequency of the signal and R, L, G, C are the resistance, inductance, conductance, andcapacitance per unit length (PUL).

Theoretically, from the point of the structural characteristics of the rail and ballast bedthe track circuit can be considered as auniform transmission line. Therefore, its transmission characteristics can be described with thefour-terminal network as well [6].

III. SIMULATION MODEL OF TRACK CIRCUIT

A. WorkingPrinciple of Track Circuit

The jointless track circuit is mainly composed of transmitter, cables (includinganalog cables and digital cables), matching transformer, tune unit, steel rails and compensation capacitors installed between the rails with the equalspace. The schematic diagram of the jointlesstrack circuit is shown as fig. 2. When the track circuit is idle, thetrack signal coded with train target speed and generatedby the transmitter flows into the receiver through thetransmission cable, tuning unit and the rails. But when a train enters the track section the track circuit is short-circuited, then most of the track signal flows back through the axle and wheels. Meanwhile, the antennas in the track circuit reader (TCR) generate the corresponding induction voltages. Afterwards, the target speed can be extracted to the CTCS computer by analog to digitalsampling, signal demodulation, and decoding.

B. Equivalent Four-Terminal Network Model of Track Circuit

According to the overall structurethe track circuit is divided into seven units and each unit isdescribed with an EFTN. The whole simulation model is composed of the seven unitswhich are cascaded with each other.

1. EFTN of the Cable Unit

In order to make the total length (10km) of the cablesin different track circuits equal the cable unit is composed of the SPT category cable and the analog cable. In this paper the SPT cable is considered as a uniform transmission line on the basis of its structure. Therefore, the EFTN of the SPT cable$N_{realcable}$ can be calculated using equation (2). The analog cableshas four specifications such as 4Km, 2Km, 1Km, 0.5km. The basic structureof the 2Kmanalog cable is shown as fig. 3 and the others are similar.

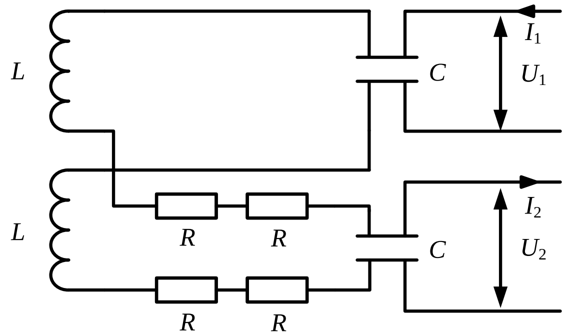

Fig 3. *Structure diagram of 2 Km simulation cable*

According tothe characteristic of analog cable with lumped parameters its EFTN can be written as

$$N_{simcab} = N_c \cdot N_l \cdot N_r \cdot N_c \quad (4)$$

Where, $$N_c = \begin{bmatrix} 1 & 0 \\ j\omega C & 1 \end{bmatrix}, N_r = \begin{bmatrix} 1 & 2R \\ 0 & 1 \end{bmatrix}, N_l = \begin{bmatrix} 1 & 2j\omega L \\ 0 & 1 \end{bmatrix} \quad (5)$$

The analog cableand the SPT category cableconnect with each other in the form of cascadeso the EFTN of the cable unit can be expressed as

$$N_{Cab} = N_{simcab} \cdot N_{realcab} \quad (6)$$

2. EFTN of the Matching Transformer

The impedance matching between the cables and the rail is achieved through the matching transformer so the loss of the transmit power of the track signal has decreased. The schematic diagram of the matching transformer is shown in fig. 2. The role of the series capacitor Ct is to preventmagnetic saturation caused by the DC signal along the rail and the inductanceLtplays a role in current-limiting. The EFTN of the matching transformer can be calculated using equation (7).

$$N_{Tad} = N_{ct} \cdot N_t \cdot N_{lt} \quad (7)$$

where, $$N_{ct} = \begin{bmatrix} 1 & 2/j\omega C_t \\ 0 & 1 \end{bmatrix}, N_{rt} = \begin{bmatrix} 1/n & 0 \\ 0 & n \end{bmatrix}, N_{lt} = \begin{bmatrix} 1 & 2j\omega L_t \\ 0 & 1 \end{bmatrix} \quad (8)$$

Here, n is the ratio of the matching transformer.

3. EFTN of the Electrical Insulated Joint

The electrical insulated joint is composed of two tuning units (BU) and an air core coil (SVA). Each of them is connected to the rail through the ladle copper lead wirewhose equivalent impedance is Zca.To the track signal of the adjacent section the impedance valueof electrical insulated joint is low enough which can be considered as “zero”, so that the electrical isolation is achieved.But to this section the impedance value can be considered as“infinite” so that the stable propagation of the track signal is achieved. The EFTN of the electrical insulated joint can be given by.

$$N_{Tun} = N_{BU1} \cdot N_{tu} \cdot N_{SVA} \cdot N_{tu} \cdot N_{BU2} \quad (9)$$

Where, $$N_{BU1} = \begin{bmatrix} 1 & 0 \\ 1/(Z_{ca} + Z_{Z0}) & 1 \end{bmatrix} \quad (10\text{-a})$$

$$N_{SVA} = \begin{bmatrix} 1 & 0 \\ 1/(Z_{ca} + Z_{SVA}) & 1 \end{bmatrix} \quad (10\text{-b})$$

$$N_{BU2} = \begin{bmatrix} 1 + \frac{Z_{ca}}{Z_{P0}} & Z_{ca} + Z_{ca1} + \frac{Z_{ca} \cdot Z_{ca1}}{Z_{P0}} \\ \frac{1}{Z_{P0}} & 1 + \frac{Z_{ca1}}{Z_{P0}} \end{bmatrix} \quad (10\text{-c})$$

Here, N_{tu} is the EFTN of the rail which is half the length of the electrical insulated joint and it can be calculated using equation (2).

4. EFTN of the Rail Line

In order to counteract the high inductive impedance of the railandim prove thet ransmission performance of the track circuit the compensation capacitors are installed between the railswith equal distance. For applying the transmission line theory to studying the transmission characteristic the rail isdivided into some compensation units which are cascaded with each other [7]. A single compensation unitcan be expressed as

$$\mathrm{N_{cp}} = \mathrm{N_g} \cdot \mathrm{N_{cz}} \cdot \mathrm{N_g} \tag{11}$$

Where,

$$\mathbf{N}_{cz} = \begin{bmatrix} 1 & 0 \\ j\omega C_z & 1 \end{bmatrix} \tag{12}$$

N_g is the EFTN of the rail which is half the length of the compensation unit and it can be calculated using equation (2). The whole EFTN model of the rail line can be given by

$$\mathbf{N}_{Rail} = \mathbf{N}_g \cdot (\mathbf{N}_{cp})^n \cdot \mathbf{N}_g \tag{13}$$

Here, n is the number of the compensation capacitors.

IV. AUTOMATIC ESTABLISHMENT OF TRACK CIRCUIT ADJUSTMENT TABLE

A. Working State Analysis of Track Circuit

The working state of the track circuit includes: normal, shunt, cab signal and broken rail state. During the establishment of the adjustment table it must be calculated repeatedlytill the working state of track circuit fully meet the conditions. Namely,in the case of maximum ballast bed leakage (0.6Ω·Km) the receiving-end voltage should be higher than the excitation thresholdof the track relay when the track circuit works in normal state. In addition, the shunt current should be high enough that the TCR is able to generate induction voltagesand the receiving-end voltage should be lower than the release threshold when the train short out the track circuit at any point of the rail line. The jointless track circuit adopts FSK signal as its track signal. The expression of the track signal is written as

$$\mathrm{U_{Trs}(t) = A_{Trs}\cos(2\pi f_c t + 2\pi\Delta f_p \int s_m(t)dt + \phi_{Trs})} \tag{14}$$

Here, A_{Trs} is the amplitude of the track signal, f_c, Δf_p,φ_{Trs} are the carrier frequency, frequency offset and initial phaserespectively. $s_m(t)$ is the square wave signal whose duty cycle is 50%.

For an example ofcalculation of cab signal state. According to the analysis in section 3.2 the EFTN of the track circuit which is shorted out by the train can be expressed as.

$$\mathrm{N_{Track}(x) = N_{Cab\_Trs} \cdot N_{Tad\_Trs} \cdot N_{Tun\_Trs} \cdot N_{Rail}(x)} \tag{15}$$

Here, xis the distance from the shunt point to sending end. Then the amplitude and initial phase of the shunt current can be calculated using equation (16) [8].

$$\mathrm{A_{sc}(x) = A_{Trs} \Big/ \left(\left|N_{Track11}(x)R_f + N_{Track12}(x)\right|\right)} \tag{16-a}$$

$$\mathrm{\phi_{sc}(x) = \phi_{Trs} - \arg\left(\left|N_{Track11}(x)R_f + N_{Track12}(x)\right|\right)} \tag{16-b}$$

B. Establishment logic ofadjustment table

The establishment of adjustment table has to meet the requirements of the working conditions of track circuit and its establishment logic is shown as fig 4. Where, R_d is the ballast resistance, N_2 is the secondary coil turns of the receiving-end transformer, R_{dstep} is the incremental step of ballast resistance.

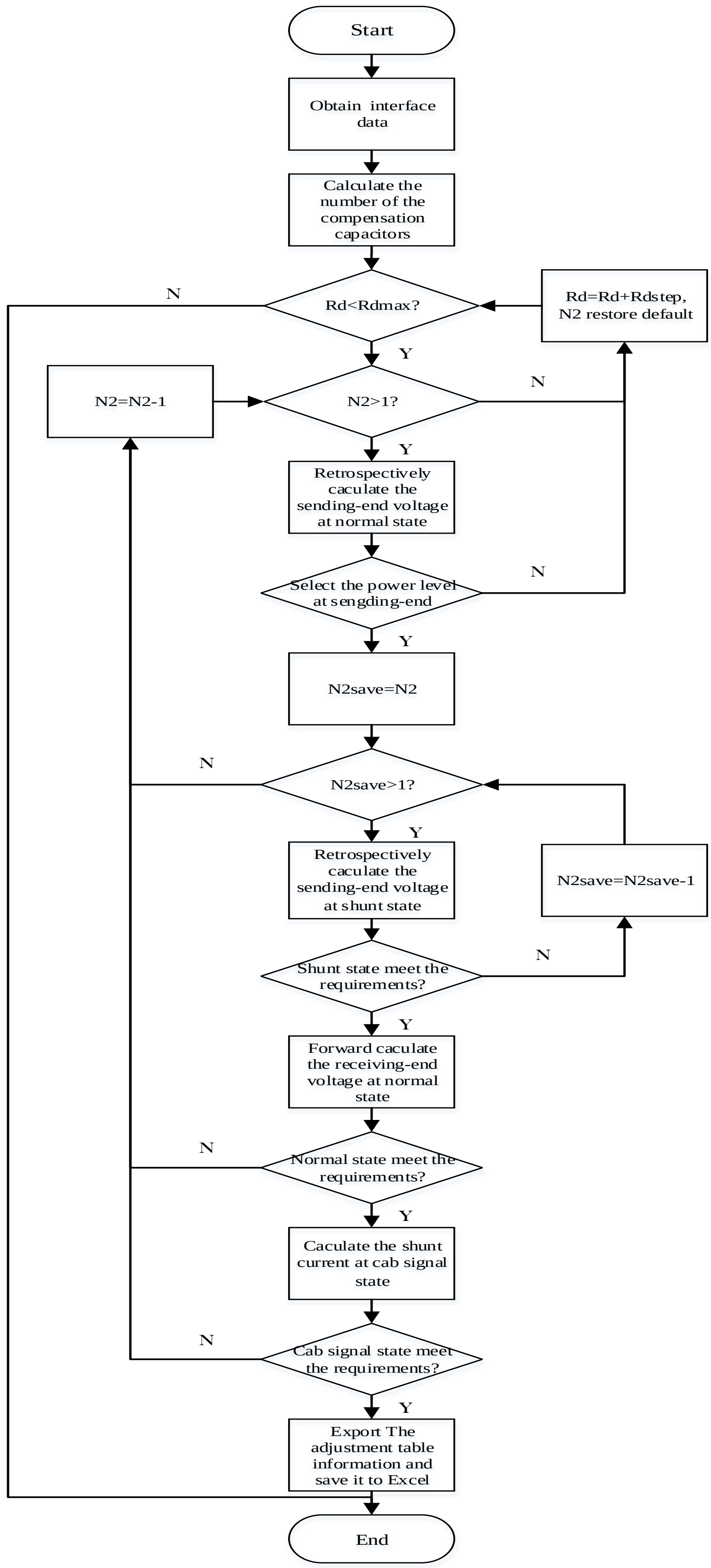

Fig 4. *Establishment logic of the track circuit adjustment table*

From the minimum (0.1Ω·Km) to the maximum (10Ω·Km). First, calculate the sending-end voltagebackward at normal state with theexcitation threshold of receiving end, minimum ballast resistance, maximum receiver transformer ratioas the initial state. If the calculated sending-end voltage is outside the allowable range adjust the receiver transformer ratio. If it is still outside the allowable rangeit means thatthe ballast bed leakage is excessive. So increase the ballast resistance gradually and let the calculation continue until the calculated sending-end voltage is within the permissible range. Next, calculate the receiving-end voltage at shunt state repeatedlyby certain step length with currentsending-end level, currentreceiver transformer ratio and infiniteballast resistance as the initial state. And adjust the receiver transformer ratio until the receiving-end voltage is lower than the release threshold. Then, calculate the shunt current and ensure that it is high enough no matter where the train short out the track circuit. If not, increase the sending-end level and start over the calculation.Finally, export the adjustment table information to excel file.

V. SIMULATION RESULT ANDANALYSIS

A. Validationusingfield data

In order to verifythe accuracy of the simulation model the track circuit at normal state has been simulated according to the basic electrical parameters of track circuit [9] in this paper. And a set of field datatested in Beijing railway bureau in November 2014 is chosen as a comparison object. The relevant parameters of the track circuit is shown in table I. The comparison of the field test data and the simulation results is shown in table I. It can be seen that the maximum relative error of the field test data and the simulation results is 6.1%. It indicates that the track circuit simulation model built in this paper has achieved high accuracy.

Table I. *Parameters oftestedtrack circuit*

Carrier frequency	Length	Compensation capacitor			Ballast resistance	Sim-cable Length(km)	Real-cable Length(km)	Sending-end level	Matching transformer ratio	Receiver transformer ratio
		Number	Value	Spacing						
2300	1132m	14	22uF	80m	3Ω·km	4.5&5.5	5.01&4.07	2	1:11	12

Table II. *Comparisonoffield testeddata and simulated results*

Output voltage	Sending-end	Sending-end cable	Matching transformer	Sending-end rail surface	Receiving-end rail surface	Matching transformer	Receiving-end cable	Receiving-end
Measurements	115.3	62.78	4.68	3.87	2.13	2.02	24.78	3.48
Calculation	115.3	65.63	4.84	4.04	2.26	2.11	25.86	3.62
Absolute error	0.0	-2.85	-0.16	-0.17	-0.13	-0.09	-1.08	-0.14
Relative error	0%	-4.5%	-3.4%	-4.4%	-6.1%	-4.5%	-4.4%	-4.0%

B. Impact analysis of ballast resistance on the transmission characteristics of track circuit

The structure of track circuit outdoor equipment is complicatedand the working environment of track circuit is veryharsh. When the precipitation is greater or the ballast bed is moister it often makes the track circuit generatea mass ofleakage current which most oftengive rise to“red-light-strap” failures [10]. Fig 5 shows the simulated results of receiving-end voltagewith different ballast resistance and four kinds of track signals of different frequencies are considered. It can be seen that the leakageincreaseswith the diminution of ballast resistance and it directly causes the decrescence of receiving-end voltage. When the ballast resistance is lower than 0.6Ω·Km the receiving-end voltage will below the excitation threshold of the track relay. So the track circuit is not able towork properly. Fig 6 shows the simulated results of rail surface voltagefrom sender to receiver with four kinds of ballast resistance and thefrequency of the track signal is 2300 Hz. It can be seen that the decreasing amplitude of the railsurface voltageincreaseswith the diminution of ballast resistance.

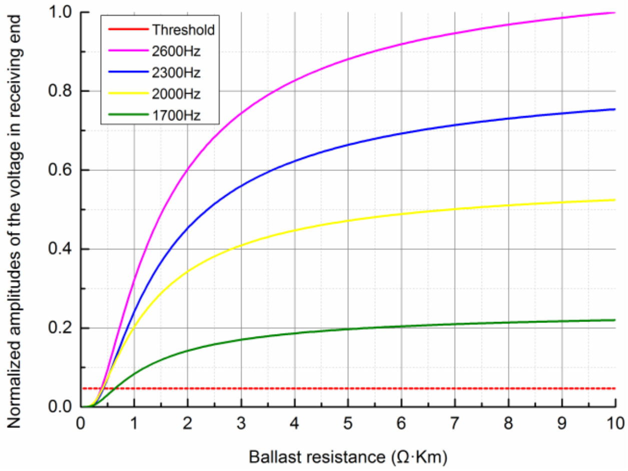

Fig 5. *Influence of ballast resistance on thereceiving-end voltage of track circuit*

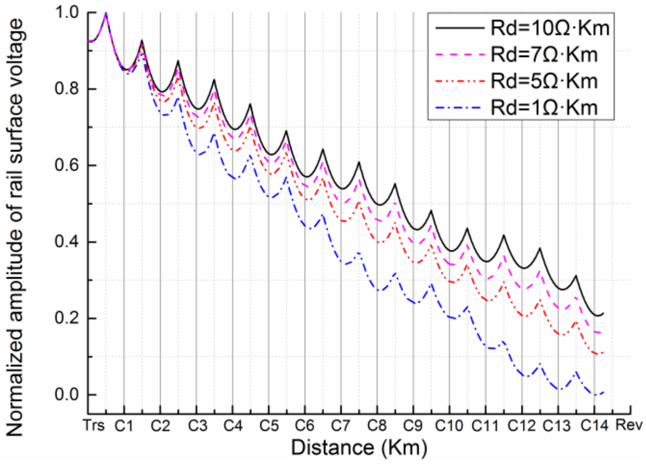

Fig 6. *Influence of ballast resistance onrail surface voltage of track circuit*

C. Impact analysis ofcompensation capacitor failure on the transmission characteristics of track circuit

The compensation capacitors have important effects on prolonging the transmission distance of track circuit. However, the compensation capacitorsmalfunction frequentlybecause of the lightning disaster, surge voltage, skin effect, etc [11]. In this paper the track circuit with single compensation capacitorfailure at different positions is simulated and the simulated results are shown in fig 7. It can be seen that when the track circuit is trouble-free the amplitude envelope of the rail surface voltage decays wavilydue to the existence of compensation capacitors. In addition, each trough corresponds to a position of a compensation capacitor. But when the compensation capacitor is broken the trough disappears and the voltage magnitudes of adjacentcompensation capacitors are affected.

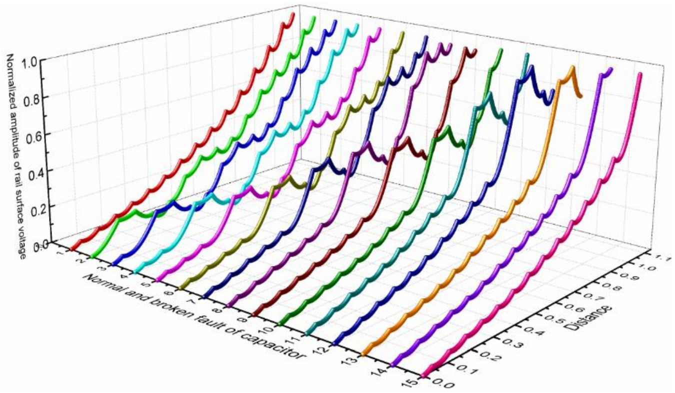

Fig 7. *Influence of compensation capacitor failureon transmission characteristicsof track circuit*

D. Establishment of adjustment table of track circuit

Thesimulation platform of transmission performance for track circuit is built usingMicrosoft Visual C++ based on transmission line theory in this paper and the automaticestablishment function of adjustment table is achieved. It provides theoretical data of the transmission limit length, transmission power level, number of outdoor capacitance and receiver transformer ratio of track circuit for construction organizations. Using the above-mentioned track circuit parameters the adjustment table is generated by the simulation platform which is shown in fig 8. It can be seen that the adjustment table includes both the basic information such as the electric parameters, signal carrier frequency and the calculated theoretical data such as the rail surface voltages, constitute of simulation cable, etc. In addition, the jumper lists of the transmitter board, analog network, receiver board are generated as well. This adjustment table can be directly applied to construction on site.

XX	Line
Section name	XXG

XX	Station
Carrier freg	2300Hz

Wiring of the transmitter board		
Carrier freg	2300Hz	
Wiring	A14-C14	
Transmit Lv	2	
Wiring	A22-C28;A20-C20	
Permanent	A4-C4;A10-C10;A12-C12	

Insulation joint type		
Electrical	——	Electrical

Section LEN:	1132.7	m
SVAC	——	SVAC

TU LEN:	29	m

Min of Rd:	1	Ω.Km
Min of signal:	0.5	A
Shunt resistance	0.15	Ω

Compensation capacitor		Compensation unit LEN	
Value(uF)	Num	Theoretical(m)	Practical(m)
22	14	80	79.54

Direction	Cable LEN	Cable LEN	
		Real cable LEN	Simcable LEN
Trs	9.51	5.01	4km+0.5km
Rec	9.57	4.07	4km+1km+0.5km

Wiring of the simulative cable		
Transmit	LEN	4km+0.5km
	Wiring	C26-C24;C22-C12; C10-C8;A26-A24; A22-A12;A10-A6;
Reception	LEN	4km+1km+0.5km
	Wiring	A8-A10;A12-A18;; A20-A22;A24-A26; C8-C10;C12-C18; C20-C22;C24-C28;

Wiring of the receiver board	
Reception lv	12
Wiring	16A-22A;14C-18C;12A-6A;20C-8C

Transmit Lv	Sending voltage(V)		RSV in sending end(V)		RSV in receiving end(V)		Reception lv	Receiving voltage(V)	
	Min	Max	Min	Max	Min	Max		Min	Max
2	114.00	126.00	3.07	4.13	0.61	2.46	12	0.23	0.94

Fig 8. *Schematic diagram of adjustment table of track circuit*

VI. CONCLUSION

A simulation platform of transmission performance for track circuit is built through writing a program based on transmission line theory. The analysis ofthe transmission characteristics for track circuit is achieved and the accuracy is verified through the comparison of the field test data and the simulated results generated by the simulation platform. The effect of ballast resistance and compensation capacitor failures on the transmission characteristics of track circuit is analyzed in this paper. It provides a theoretical basis for on-site maintenance. The automatic establishment of track circuit adjustment table is achieved using the simulation platform and it makes a contribution to improving the efficiency of equipment commissioning.

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