A Rail line model with distributed parameters of track circuit

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Abstract. Models of continuous jointless track circuits with an adaptive receiver are presented, where the power supply is connected to the beginning or middle of the rail circuit, and also to the locomotive receiver. The aim of the work is to develop models of rail lines, which take into account the actual current distribution along the track line and which may be used to research adaptive jointless track circuits. The electric schemes of the jointless track circuits are given, equations, connecting currents and voltages at the ends of the rail line, coefficient of four-pole rail lines, algorithms for calculating track circuits. In conclusion, that the track circuit can operate at an insulation resistance four times lower than the permissible value, where the permissible insulation resistance is $R_i = 1\text{m}^*\text{km}$. New approaches and tools for analyzing and synthesizing solutions are considered, with considering account real operating conditions and disturbing factors.

1. Introduction
The analysis of the operation of tonal jointless track circuits is devoted to [1–6, 10–12] and others. The issues of automation of the process of their design and reliability are considered in [7–9, 16–20]. On the problems of expertise and safety testing of railway automation and telemechanics systems are considered [18–20]. At the same time, there are practically no publications on the intellectualization of the solution of problems of the analysis and optimization of the parameters of track circuits in various operating modes. In connection with this actual seems to development of a hybrid expert system for analyzing the operation of a jointless tonal track circuit.

2. Methods
After a series of transformations shows a generalized substitution scheme of a rail line for normal and shunt modes with a locomotive receiver for an unlimited jointless track circuit [15], where shown: rail line RL, equivalent generator EG with internal resistance $Z_G$, equivalent receiver with internal resistance $Z_{er}$, the first shunt with resistance $R_{sh1}$ and the second shunt with resistance $R_{sh2}$, input resistances $Z_{bi}$ and $Z_{ei}$ of adjacent rail lines, input equivalent impedance $Z_{ei}^*$, the directions of currents $I$, voltage $U$ and lengths of sections $l$ are shown.
Voltage $U_1$ and current $I_1$ are related to voltage $U_{sh2}$ and current $I_{sh2}$ by equations:

$$U_1 = A_{shl}U_{sh2} + B_{shl}I_{sh2};$$

$$I_1 = C_{shl}U_{sh2} + D_{shl}I_{sh2},$$

where

$$A_{shl} = c_1 \left( chyl_1 + \left( \frac{Z_w}{R_{shl}} \right) shyl_1 \right) + c_2 \left( chyl_1 + shyl_1 \right);$$

$$B_{shl} = Z_w( shyl_2 chyl_1 + c_3( chyl_1 + shyl_1) );$$

$$C_{shl} = \left( \frac{1}{Z_w} \right) chyl_2 ( c_4 \left( \frac{Z_w}{R_{shl}} \right) + c_5 shyl_2 ) + c_2 c_4;$$

$$D_{shl} = c_3(chyl_3 + shyl_3)c_4 + c_5shyl_2.$$  

Here

$$c_1 = \frac{1}{thyl_2 + \left( \frac{Z_w}{Z_{el}} \right) shyl_2};$$

$$c_2 = \frac{1}{cthyl_2 + \left( \frac{Z_w}{Z_{el}} \right) chyl_2};$$

$$c_3 = \frac{1}{thyl_2 + \left( \frac{Z_w}{R_{shl}} \right) shyl_2};$$

$$c_4 = \frac{1}{thyl_1 + \left( \frac{Z_w}{Z_{bi}} \right) shyl_1};$$

$$c_5 = \frac{1}{cthyl_1 + \left( \frac{Z_w}{Z_{bi}} \right) chyl_1};$$

$$Z_{el}^I = \frac{Z_w Z_{er} Z_{el} chyl_3 R_i R_{sh1} + Z_w R_i R_{sh 2} (Z_{er} + Z_{el}) shyl_3}{Z_w Z_{er} Z_{el} shyl_3 R_i R_{sh1} + Z_w R_i R_{sh 2} (Z_{er} + Z_{el}) chyl_3}.$$
Figure 2. Generalized substitution scheme of unlimited track circuit with adaptive track receiver for normal and shunt modes.

Figure 1 is converted to the figure 2 in order to represent the track circuit with the locomotive receiver in the form of the track circuit with the track receiver.

In figure 2 shows the rail line of the beginning $R_{Lb}$, the middle $R_{Lm}$ and the end $R_{Le}$ with shunts $R_{SB}$, $R_{Sm}$, $R_{Se}$, respectively. The impact on the rail line $R_{Sm}$ of adjacent track circuits is taken into account by means of the resistances of the beginning $Z_{LB}$ and the end $Z_{LE}$. (instead of $Z_{ib}$ and $Z_{ie}$ in figure 1).

Instead of the second shunt, the resistance of which in figure 1 is designated $R_{Sh2}$, on figure 2 includes an equivalent ER receiver with a resistance $Z_e$. Through means of resistances $Z_{LB1}$ and $Z_{LE1}$ (instead of $Z_{eq}$ in figure 1) the influence of rail lines is taken into account located behind the $R_{Lb}$ and $R_{Le}$ shunts, respectively. On each of the rail lines $RL_b$, $RL_m$ and $RL_e$, different insulation resistance and rail can be set, therefore, instead of the propagation constant $γ$, the designations $γ_N$, $γ_M$ and $γ_E$ are provided, and instead of the wave impedance $Z_w$ - designations $Z_{wb}$, $Z_{wm}$ and $Z_{we}$. The dependences between the voltages and currents of the equivalent generator $eG$ and the equivalent receiver ER are shown by equation (7). These equations are obtained from equation (1) with the replacement of the notation in figure 1 to the designations in figure 2:

$$U_1 = A_m U_2 + B_m I_2;$$
$$I_1 = C_m U_2 + D_m I_2;$$

where

$$A_m = c_1 \left( sh_y m x_{m2} + ch_y m x_{m2} + \left( \frac{Z_w}{R_{sm}} \right) sh_y m x_{m2} \right) + c_2 (sh_y m x_{m2} + ch_y m x_{m2});$$

$$B_m = Z_{WM} (x_{m1} ch y m x_{m2} + c_3 sh y m x_{m2}) + R_{se} Z_{LE1} (ch y m x_e);$$

$$C_m = \left( \frac{1}{Z_{WM}} \right) c_1 ch y m x_B \left( c_4 \left( \frac{Z_{WM}}{R_{sm}} \right) + c_5 Z_{B} \right) + c_2 c_4 R_{se} x_e;$$

$$D_m = c_3 c_4 t h y m x_e + c_5 c t h y m x_e;$$

$$c_1 = 1/t h y m x_{m1} + \left( \frac{Z_{wm}}{Z_{lb}} \right) sh y m x_{m1};$$
\[c_2 = \frac{1}{cth \gamma_m x_{m1}} + \left(\frac{Z_{wm}}{Z_{LE}}\right) ch \gamma_m x_{m1};\]
\[c_3 = \frac{1}{th \gamma_m x_{m1}} + \left(\frac{Z_{wm}}{R_{SM}}\right) sh \gamma_m x_{m1};\]
\[c_4 = \frac{1}{th \gamma_m x_{m2}} + \left(\frac{Z_{wm}}{Z_{LE}}\right) sh \gamma_m x_{m2};\]

\[c_5 = \frac{1}{cth \gamma_m x_{m2}} + \left(\frac{Z_{wm}}{Z_{LE}}\right) ch \gamma_m x_{m2};\] (12)

\[Z_{LE} = Z_{WE} \frac{R_{SE}Z_{LE1}(sh \gamma_e + ch \gamma_e)x_e + Z_{WE}(R_{SE} + Z_{LE1})sh \gamma_ex_e}{R_{SE}Z_{LE1}(sh \gamma_e - ch \gamma_e)x_e + Z_{WE}(R_{SE} + Z_{LE1})ch \gamma_ex_e} + Z_{WE}(R_{SE} + Z_{LE1})ch \gamma_ex_e;\] (13)

\[Z_{LN} = Z_{WB} \frac{R_{SB}Z_{LB1}ch \gamma_b x_b + Z_{WB}(R_{SB} + Z_{LB1})sh \gamma_b x_b}{R_{SB}Z_{LB1}sh \gamma_b x_b + Z_{WB}(R_{SB} + Z_{LB1})ch \gamma_b x_b};\] (14)

On figure 3 shows the algorithm of the program for calculating a rail line with distributed parameters with an adaptive receiver powered from the end. Block-schemes of the algorithm have the following purpose:
Taking into account the proposed algorithm, programs were developed, which are an integral part of the track circuit model.

Figure 3. Algorithm work of the program for calculating the track circuits with adaptive receiver for rail line with distributed parameters.
3. Result and discussion

The model of a rail line with distributed parameters makes it possible to carry out studies of the ATC (adaptive track circuit) taking into account the real current distribution along the rail line. The disadvantage of the presented model is that it cannot be used for jointless track circuits powered from the middle. For the research of jointless track circuits with two receivers at the ends of the rail line, a universal model is proposed.

3.1. Universal model rail line of the jointless track circuit with adaptive receiver

A typical running jointless track circuit has one track generator and one or two track receivers. On the figure 4 shows the replacement scheme of the track circuit, which allows you to calculate and research a track circuit with an adaptive receiver, both with power from the end and from the middle. On the scheme shows: RLB start rail line, two rail lines middle RLM* and RLM, rail line of end RLE, eG equivalent generator, equivalent receiver of the beginning of ERe with resistances Ze and an equivalent receiver of the end of ERe with resistances Ze, train shunts RsB, RsM, RsS and RsE, input resistances Zlb1, Zle1, Zlb, Zle, Zle* and Zle. The rail lines of the RLM and RLE of both schemes completely coincide, and the rail lines RLM* and RLB on Fig.4 are a mirror image of the right side, i.e. rail lines RLM and RLE. By changing the values of insulation resistances, rails, shunts and their coordinates, as well as the parameters of equivalent receivers and a generator can be imitated any train situations and jointless track circuit parameters.

Figure 4. Universal replacement scheme of the track circuit with an adaptive receiver for normal and shunt modes

The dependences between the voltages and currents of the equivalent generator of the eG and the equivalent receiver of the ERe for the circuit in figure 4 can be written by analogy with equations (7-11) for the circuit in figure 2 (in the notation of the diagram in figure 4):

\[ U_1 = A_m U_2 + B_m I_2; \]
\[ I_1 = C_m U_2 + D_m I_2, \]  \hspace{1cm} (15)

where

\[ A_m = c_1 \left( c h \gamma m X_{m2} + \left( \frac{Z_{wm}}{R_{sm}} \right) s h \gamma m X_{m2} \right) + c_2 s h \gamma m X_{m2}; \]  \hspace{1cm} (16)
\[ B_m = Z_{wm} (s h \gamma m X_{m1} c h \gamma m X_{m2} + c_3 s h \gamma m X_{m2}); \]  \hspace{1cm} (17)
\[ C_m = c_1 \left( 1 \left( \frac{Z_{wm}}{R_{sm}} \right) + c_5 \right) + c_2 c_4; \]  \hspace{1cm} (18)
\[ D_m = c_3 e_4 + c_5 s h y_m X_{m1} \]  
\[ c_1 = th y_m X_{m1} + \left( \frac{Z_{WM}}{Z_{LE}} \right) c th y_m X_{m1} + R_i (Z_{LE} c h y_e x_e + R_{SE} s h y_e x_e) \]  
\[ c_2 = c th y_m X_{m1} + \left( \frac{Z_{WM}}{Z_{LE}} \right) c th y_m X_{m1} + R_i (Z_{LE} c h y_e x_e + R_{SE} s h y_e x_e) \]  
\[ c_3 = th y_m X_{m1} + \left( \frac{Z_{WM}}{Z_{RE}} \right) c th y_m X_{m1} + R_i (Z_{LE} c h y_e x_e + R_{SE} s h y_e x_e) \]  
\[ c_4 = th y_m X_{m2} + \left( \frac{Z_{WM}}{Z_{LB}} \right) c th y_m X_{m2} + R_{SM} c h y_b x_b + Z_{LB} s h y_b x_b \]  
\[ c_5 = c th y_m X_{m2} + \left( \frac{Z_{WM}}{Z_{LB}} \right) c th y_m X_{m2} + R_{SM} c h y_b x_b + Z_{LB} s h y_b x_b \]  
\[ Z_{LE} = Z_{WE} \frac{R_{SE} Z_{LE} c h y_e x_e + Z_{WE} (R_{SE} + Z_{LE}) s h y_e x_e}{R_{SE} Z_{LE} s h y_e x_e + Z_{WE} (R_{SE} + Z_{LE}) c h y_e x_e} \]  
\[ Z_{LB} = (Z_{LB} A_m + B_m) / (Z_{LB} C_m + D_m) \]

The dependences between the voltages and currents of the equivalent generator of the \( eG \) and the equivalent receiver of the \( ERb \) for the scheme in figure 4 can be written by analogy with equations (15 and 21):

\[ U_1 = A_m, U_3 = B_m, I_3 \]  
\[ I_1 = C_m, U_3 = D_m, I_3 \]

where

\[ A_m = c_{1*}, \left( c h y_m, X_{m2} + \left( \frac{Z_{WM}}{Z_{RE}} \right) s h y_m, X_{m2} \right) + c_{2*} s h y_m, X_{m2} \]  
\[ B_m = Z_{WM} \left( s h y_m, X_{m2} c h y_m, X_{m1} + c_{3*} s h y_m, X_{m1} \right) \]  
\[ C_m = \left( \frac{1}{Z_{WM}} \right) (c_{1*} \left( c_{4*} \left( \frac{Z_{WM}}{Z_{RE}} \right) + c_{5*} \right) + c_{2*} c_{4*}) \]  
\[ D_m = c_{3*} c_{4*} + c_{5*} s h y_m, X_{m1} \]

\[ c_{1*} = c h y_m, X_{m1} + \left( \frac{Z_{WM}}{Z_{LE}} \right) s h y_m, X_{m1} \]
\[ c_{2*} = s h y_m, X_{m1} + \left( \frac{Z_{WM}}{Z_{LE}} \right) c h y_m, X_{m1} \]
\[ c_{3*} = c h y_m, X_{m1} + \left( \frac{Z_{WM}}{Z_{RE}} \right) s h y_m, X_{m1} \]
\[ c_{4*} = c h y_m, X_{m2} + \left( \frac{Z_{WM}}{Z_{LE}} \right) s h y_m, X_{m2} \]

\[ Z_{LB} = Z_{WN} \frac{R_{SE} Z_{LB} c h y_b x_b + Z_{WB} (R_{SE} + Z_{LB}) s h y_b x_b}{R_{SE} Z_{LB} s h y_b x_b + Z_{WB} (R_{SE} + Z_{LB}) c h y_b x_b} \]  
\[ Z_{LE} = (Z_{LE} A_m + B_m) / (Z_{LE} C_m + D_m) \]

In equation (20), which refer to the right side of the circuit in figure 4, you need to enter the value \( Z_{LE} \) from equation (22), which belongs to the left side of the scheme, and in equation (28) which refer to the left side of the scheme, you need to enter the value \( Z_{LE} \) from equation (22), which belongs to the right side of the scheme. This excludes the possibility of presenting in explicit as the values of the input resistances \( Z_{LB} \) and \( Z_{LE} \). The solution of the system of equations is possible only by a numerical method.
Figure 5. Algorithm of the universal track circuit calculation programs

In figure 5 shows the algorithm for the operation of the universal program for calculating the rail line. The model of a rail line with distributed parameters makes it possible to carry research adaptive track circuitries into account the real current distribution along the rail line in the presence of one or two track receivers.

Figure 6. Graphs of the influence of insulation resistance on the voltage of the track receiver
Where, on 1 graph shows the first track circuit, determines the voltage \( U \) at insulation resistance \( R_I = 1 \) om*km and \( R_{sh1} = 0.06 \) om, 2 graph at insulation resistance \( R_{sh1} = 0 \) om, 3 graph for the second track circuit, i.e. in our case, an adjacent jointless track circuit, with an insulation resistance \( R_I = 1 \) om*km and \( R_{sh2} = 0.06 \) om, 4 graph, respectively, \( R_{sh2} = 0 \) om consequently, adaptive join less track circuits define the voltage and fix free track section.

4. Conclusion
The proposed models of the rail lines make it possible to carry out studies of rail circuits with an adaptive receiver in conditions of significant longitudinal asymmetry of insulation resistance under the intense influence of atmospheric influences.

For the analysis of jointless track circuits with an adaptive receiver have to consider of condition (the presence of shunts, the value of the insulation resistance of each radar line, the dynamics and range of variation of this resistance, etc.) several jointless track circuits at the same time. Their mutual influence on each other.

In conditions, when monitoring condition of each jointless tone track circuit depends on the state of the rail lines of other sections, model needs to be investigated, which would represent a collection of rail lines. The research of such track circuits differs significantly from the study of track circuits with relay action receivers.

5. References
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