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The Mathematical Model of the Sensor for Monitoring the State of the Track Section with Current Receivers

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***Abstract:** Derivation of analytical expressions for research and development of sensors for monitoring the state of track sections with current track receivers. To achieve this goal, it is proposed to consider the sensors for monitoring the state of the track sections with power supply in the middle of the rail line, and to connect the receivers inductively to the rail line at the ends of the control sensors. The derivation of the basic equations was carried out using the theory of four-terminal and the theory of electrical circuits with the representation of control sensors in the form of equivalent circuits, by which the coefficients of the rail four-terminal of the main control sensor were determined at the initial stage. On the basis of which the equations of absolute shunt sensitivity and the criterion of sensitivity to the normative shunt were then derived. As a result of the work, analytical expressions were determined to determine the current flowing over the inductive coils, as well as the values of the absolute shunt sensitivity and the sensitivity criterion for the standard shunt for monitoring sensors with current track receivers. A method is proposed for deriving analytical expressions for research, development, and design of jointless control sensors with current receivers.The proposed method for monitoring the state of track sections using jointless control sensors with current receivers allows us to provide a clear boundary for fixing the entrance and exit of trains from the controlled section, regardless of fluctuations in the resistance of the ballast of the rail line and thereby increase the safety of train traffic.*

***Keywords:** tonal rail chains; track receiver; equivalent circuits, input resistances, quadrupole coefficients, receiver current, transmission resistance, shunt sensitivity.*

I. INTRODUCTION

In the world in the field of improving the safety of train traffic, the leading place is the creation of highly efficient interval control systems for train traffic using modern information technologies [9,14,15]. In this regard, special attention is paid to the development of sensors for monitoring the state of track sections in interval train control systems. In this direction, in developed countries, including the USA, England, France, Germany, Sweden, Japan and Russia, much attention is paid to technical means of ensuring the safety of high-speed trains and improving interval control systems.

In the Republic of Uzbekistan, measures are currently being taken to improve technical devices and complexes that ensure the safety of high-speed trains, including the expansion of electrified railway lines and the improvement of elements of railway automation systems.

One of the directions for the implementation of these tasks in train control systems is the improvement of sensors for monitoring the state of track sections and their implementation to ensure the safety of train movements [1, 17, 18]. One of the ways to improve control sensors is to use tonal rail circuits without insulating joints [1, 2].

On railways, sensors for monitoring the state of track sections of the tonal frequency without insulating joints are widely used [5,10]. In these chains, potential track receivers of Fig. 1 are traditionally used, which have a significant drawback, namely that the train shunt affects all modes of their operation not only when the train is on the block - section controlled by the control sensor, but also outside of it [10.], i.e. such control sensors have floating additional shunt zones for the approach and departure of the train from the controlled section.

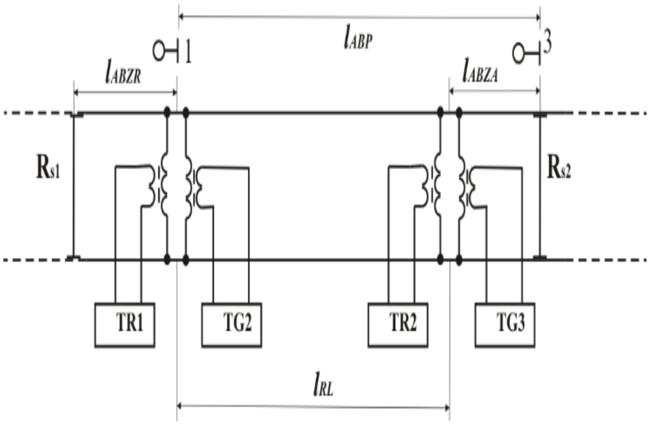

Fig. 1. Control sensor diagram with potential tracking receivers

To eliminate these drawbacks, it is proposed to use a current track receiver [1, 2] fig. 2, which connects to the rail threads inductively.

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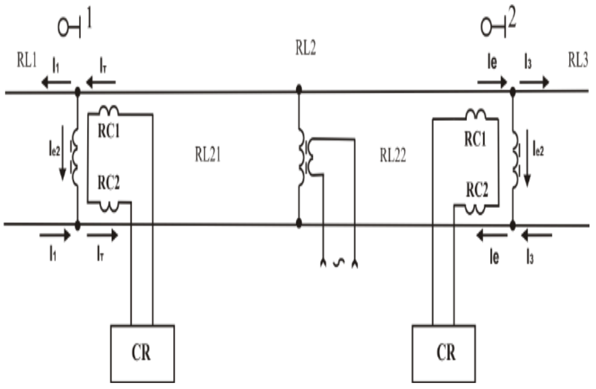

Fig. 2. Control sensor circuit with current track receivers

With this connection of current track receivers, the input and output boundary of the monitoring sensor is fixed and located at the installation location of the receiving track coils.

II. MATHEMATICAL MODEL OF CONTROL SENSOR WITH CURRENT TRACK RECEIVER

To analyze and synthesize such sensors, it is necessary to develop a mathematical model and derive analytical expressions for determining the current of the track receiver [8, 11, 19] flowing over the receiving coils.

The current flowing over the receiving track coils can be determined by the known formula:

$$I_{\text{Т}} = \frac{U_{min}}{Z_{ct}},(1)$$

Where

U_{min}- the minimum voltage value of the power source;

$I_{\text{Т}}$ -is the current flowing over the track coils of the receiver;

Z_{ct} - the resistance of the transmission of the monitoring sensor on the current receiver.

Transmission resistance is a function of the coefficients of the rail four-terminal monitoring sensor without insulating joints.

To derive these coefficients, we present the circuit of Fig. 2 in the form of an equivalent circuit of Fig. 3.

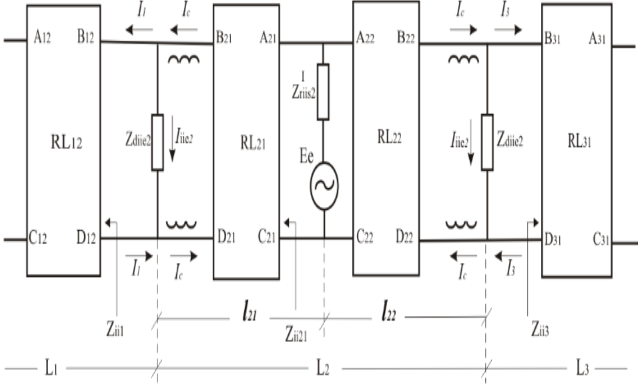

Fig. 3.General circuit of the monitoring sensor with current track receiver

Where

L_1, L_2, L_3 - according to the length of the control sensors;

L_2- length of test sensor;

Z^I_{ris2} - reverse input resistance of the supply end of the control sensor;

Z_{die2} - direct input resistance of the receiving end of the control sensor;

RL1, RL2 and RL3, - four-pole rail lines of control sensors;

A, B, C, D - coefficients of rail four-terminal.

We replace the adjacent control sensors to the left and to the right of the desired control sensor with their input resistances Z_{i1} and Z_{i3}, then the circuit will be presented as follows Fig. 3

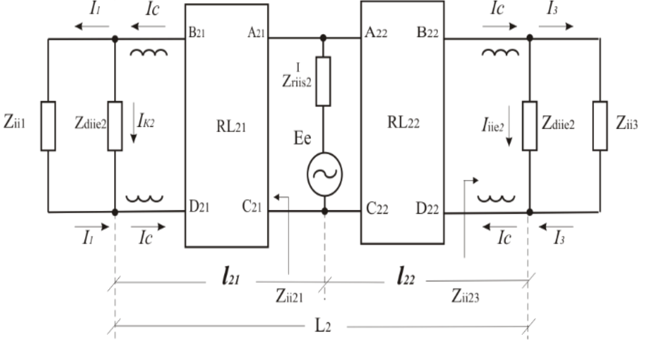

Fig. 3. Converted equivalent circuit

Where

$$Z_{i21} = \frac{ch\gamma_{21}l_{21} * \left(\frac{Z_{i1} * Z_{die2}}{Z_{i1} + Z_{die2}}\right) + Z_{i21} * sh\gamma_{21}l_{21}}{\frac{1}{Z_{i21}} sh\gamma_{21}l_{21} * \left(\frac{Z_{i1} * Z_{die2}}{Z_{i1} + Z_{die2}}\right) + ch\gamma_{21}l_{21}},$$

$$Z_{i1} = \frac{ch\gamma_{12}l_{12} * Z^I_{ris1} + Z_{i12} * sh\gamma_{12}l_{12}}{\frac{1}{Z_{i12}} sh\gamma_{12}l_{12} * Z^I_{ris1} + ch\gamma_{12}l_{12}},$$

$$Z_{i23} = \left(\frac{Z_{i3} * Z_{die2}}{Z_{i3} + Z_{die2}}\right),$$

$$Z_{i3} = \frac{ch\gamma_{31}l_{31} * Z^I_{ris3} + Z_{i31} * sh\gamma_{31}l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31}l_{31} * Z^I_{ris3} + ch\gamma_{31}l_{31}}.$$

Since two rail lines RL_{21} and RL_{22} are connected to the power supply of the monitoring sensor in parallel, for further consideration the rail line RL_{21} and the equipment connected to it can be represented as input impedance Z_{i21}, and input impedances Z_{die2} and Z_{i3} with resistance Z_{i23} Fig. 4.

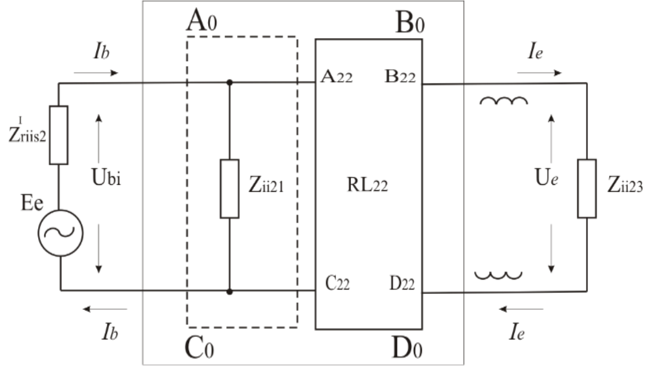

Fig. 4. Basic equivalent circuit of a monitoring sensor with current receivers.

Where

$$A_0 = ch\gamma_{22}l_{22}\ , B_0 = Z_{\text{В}22}sh\gamma_{22}l_{22},$$

$$C_0 = \frac{ch\gamma_{22}l_{22}}{Z_{ii1}} + \frac{1}{Z_{\text{В}22}}sh\gamma_{22}l_{22}\ ,$$

$$D_0 = \frac{Z_{\text{в}22} sh\gamma_{22} l_{22}}{Z_{ii1}} + ch\gamma_{22} l_{22}.$$

In monitoring sensors with a current track receiver, the track receiver is triggered by the electromotive force E_{EMF}, which is induced in the travel coils by a current of I_T in the rails flowing over the travel coils.

The magnitude of this E.M.F when turning on the windings of the travel coils:

$$E_{emf} = I_{\text{т}} * Z_{tcr} (2)$$

Where Z_{MPK} is the equivalent resistance of mutual induction of two track coils and a rail

$$I_{\text{т}} = I_{\text{к}2} + I_3;(3)$$

$$I_{\text{к}2} = \frac{U_{\text{т}}}{Z_{die2}};(4)$$

$$I_3 = \frac{U_{\text{т}}}{Z_{i3}};(5)$$

$$I_{\text{т}} = \frac{U_{\text{т}}}{Z_{die2}} + \frac{U_{\text{т}}}{Z_{i3}};(6)$$

$$I_{\text{т}} = U_{\text{т}} * \left(\frac{Z_{die2}+Z_{i3}}{Z_{die2}*Z_{i3}}\right),(7)$$

$$U_{\text{т}} = I_{\text{т}} * \left(\frac{Z_{die2}*Z_{ii3}}{Z_{die2}+Z_{ii3}}\right).(8)$$

From the general theory of rail chains it is known that

$$U_1 = A_0 U_{\text{т}} + B_0 I_{\text{т},}$$

$$I_1 = C_0 U_{\text{т}} + D_0 I_{\text{т},} (9)$$

Where A0, B0, C0, D0 are the coefficients of the rail four-terminal network.

Since $\mathrm{U}_{\text{т}} = \mathrm{I}_{\text{т}} * \left(\frac{\mathrm{Z}_{\mathrm{die}2}*\mathrm{Z}_{\mathrm{ii}3}}{\mathrm{Z}_{\mathrm{die}2}+\mathrm{Z}_{\mathrm{ii}3}}\right)$, substituting this expression in equation 2.66, we get:

$$U_s = I_{\text{т}}\left(A_0 \left(\frac{Z_{die2}*Z_{i3}}{Z_{die2}+Z_{i3}}\right) + B_0\right),(10)$$

$$I_s = I_{\text{т}}\left(C_0 \left(\frac{Z_{die2}*Z_{i3}}{Z_{die2}+Z_{i3}}\right) + D_{0)}\right.(11)$$

It is known [20] that the voltage of a power source is determined by the formula:

$$U = U_s + I_s * Z_{ris2}^I.(12)$$

Substituting the values of U_1 and I_1 from equations (10, 11) into equation (12), we obtain:

$$U = I_{\text{т}}\left(A_0 \left(\frac{Z_{die2} * Z_{i3}}{Z_{die2} + Z_{i3}}\right) + B_0\right) + \rightarrow$$

$$\rightarrow + I_{\text{т}}\left(C_0 \left(\frac{Z_{die2}*Z_{i3}}{Z_{die2}+Z_{i3}}\right) + D_{0)} * Z_{ris2}^I\right. (13)$$

Transmission resistance of monitoring sensors with current track receiver:

$$Z_{ct} = \frac{U}{I_{\text{т}}} (14)$$

Substituting the value of U from equation (13) into equation (14) and making reductions, we obtain the transmission resistance in normal mode:

$$Z_{ct} = A_0 \left(\frac{Z_{die2} * Z_{i3}}{Z_{die2} + Z_{i3}}\right) + B_0 + \rightarrow$$

$$\rightarrow + \left(C_0 \left(\frac{Z_{die2}*Z_{i3}}{Z_{die2}+Z_{i3}}\right) + D_0\right) * Z_{ris2}^I (15)$$

$$Z_{ct} = A_0 \left(\frac{Z_{die2} * \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}}{Z_{die2} + \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}} \right) + B_0 \rightarrow$$

$$\rightarrow + \left(C_0 \left(\frac{Z_{die2} * \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}}{Z_{die2} + \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}} \right) + D_0\right) * Z_{ris2}^I$$

For the control mode, the transmission resistance is obtained by the corresponding substitution in Eqs. (15) instead of the coefficients $A_{0,}$ B_0, C_0, D_0, the values of $A_{\text{к}}$, $B_{\text{к}}$, $C_{\text{к}}$, $D_{\text{к}}$when one of the threads of the rail line breaks.

$$Z_{ct} = A_{\text{к}} \left(\frac{Z_{die2} * \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}}{Z_{die2} + \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}} \right) + B_{\text{к}} \rightarrow$$

$$\rightarrow + \left(C_{\text{к}} \left(\frac{Z_{die2} * \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}}{Z_{die2} + \dfrac{ch\gamma_{31} l_{31} * Z_{ris3}^I + Z_{i31} * sh\gamma_{31} l_{31}}{\frac{1}{Z_{i31}} sh\gamma_{31} l_{31} * Z_{ris3}^I + ch\gamma_{31} l_{31}}} \right) + D_{\text{к}}\right) * Z_{ris2}^I \qquad (16)$$

These equations of transmission resistance of the monitoring sensor of the state of the track sections without insulating joints during normal operation of the monitoring sensors and the breakage of one of the rail threads can be further used in the analysis and synthesis of control sensors and determine the optimal parameters.

III. RESULT

A method is proposed for deriving analytical expressions for research and design of jointless tonal control sensors with current receivers. Analytical expressions are determined to determine the current flowing over inductive coils, as well as the values of the absolute shunt sensitivity and the sensitivity criterion for the standard shunt for tonal control sensors with current track receivers. The proposed method for monitoring the state of track sections using continuous-tone tonal control sensors allows a clear boundary to be recorded for the entry and exit of trains from a controlled section regardless of fluctuations in the resistance of the ballast of the rail line and thereby increase the safety of train traffic.

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IV. CONCLUSION

One of the directions for the further improvement of tonal rail circuits is the use of current track receivers and the supply of power to the rail line in the middle of the rail circuit.

When deriving the equations, the influence of adjacent rail circuits and the longitudinal asymmetry of the insulation resistance of the rail line were taken into account.

The proposed analytical expressions will allow research and development of sensors for monitoring the state of the track sections. Their use in interval control systems for train traffic, including at level crossings, will significantly improve the safety of train traffic in rail transport.

V. CONFLICT OF INTEREST

The authors confirm that the data presented do not contain a conflict of interest.

VI. THANKS

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