Sensitivity and Permissible Deviation in Electric Track Circuits

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Abstract: New expressions have been obtained for assessing the sensitivity and permissible deviations of the electric track circuit elements parameters, allowing to evaluate their influence on the implementation of the shunt and control modes of operation of the track circuits.

1 INTRODUCTION

Track circuits in railway automation devices are used as the main sensor for monitoring the state of the rail line. There are three main states of the rail line. The rail line (RL) is free of rolling stock, the RL is occupied by rolling stock, the RL has a break in one of the rails. These states have the corresponding names: normal, shunt and control modes of operation of the track circuit. The determining modes of operation in terms of meeting the requirements for the safety of train traffic are shunt and control modes. Failure to comply with these modes leads to catastrophic failures in the transportation of passengers and goods by rail (Lisenkov, 1999; Lee, 2013; Moine, 2019; Spunei, 2018; Efanov, 2019).

It is known that the task of synthesizing track circuits is to determine the maximum length of the rail line and the input resistance at the ends of the rail line, in which the shunt and control modes are performed. Energy ratios, which are associated with the optimization of the transmission of electrical energy from one (transmitter) end of the rail line to the other (relay) end, are secondary.

The choice of the input resistance value at the ends of the electric rail line is due to the simultaneous fulfillment of the criteria of the shunt mode $К_s = f(Z_{\text{in}})$ and the control $К_c = f(Z_{\text{in}})$ for the maximum allowable length of the rail line. Figure 1 shows the dependences of the criteria for the shunt and control modes of operation of the track circuit on the input resistances at the ends. (Arkatov, 1990)

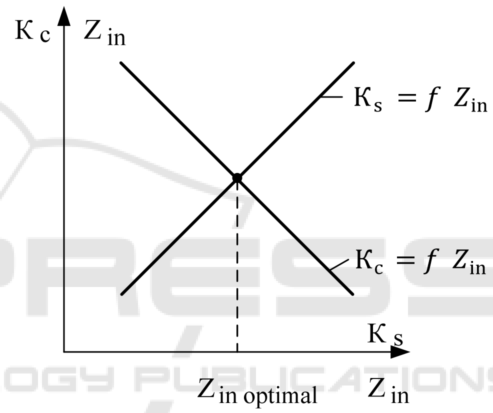

Figure 1: The dependences of the criteria for the shunt and control modes of operation of the track circuit.

As can be seen from Figure 1, the dependences under consideration represent mutually inverse functions, so the intersection point determines the optimal value of Z_{in} at which the shunt and control modes are performed. It also follows from the graph that the deviation from the optimal value leads to an improvement in one of the modes and a deterioration in the other.

To exclude catastrophic failures due to violation of the operating modes of track circuits, it is necessary to stabilize the input resistances at the ends of the rail line. However, in the operation of track circuits, situations occur that the input resistances at the ends of the track line are subject to change. At the same time, it is important that the changes are within the specified tolerances, so that with the accepted tolerances, taking into account the accepted safety factors, the specified modes are ensured.

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At the second stage of the synthesis of track circuits, the configuration of the input resistances of the track circuit is selected based on the given impedance of the input resistance. When choosing elements to create a given impedance, energy relationships are taken into account, but issues related to the analysis of tolerances that determine the effect of deviation of any parameter of the input resistance impedance from its nominal value are not taken into account.

2 MATERIALS AND METHODS

At the second stage of the synthesis of track circuits, the problem of tolerances is associated with the choice of such equivalent circuits that have minimal tolerances. In the case of structural synthesis, the achievement of minimum tolerances can be considered as an independent task. This problem can be partially solved by using the methods of analysis and synthesis, however, significantly new results can be obtained if the knowledge of tolerances is used in the optimization process in the structural synthesis of input resistances at the ends of the rail line.

Changing the input impedance values of the track circuit elements is undesirable from the point of view of tolerance theory. However, this disadvantage can be used as a positive factor in optimization. The connection between the parameter space of input resistance impedance elements and tolerance optimization is carried out using the sensitivity of the circuit function (Lanne, 1969), which can be defined as a partial derivative:

$$S_i = {}^{d\,y}/_{d\,x_i} = {}^{\partial\, Z_{in}}/_{\partial\, Z_i} \tag{1}$$

Sensitivity plays an important role in determining the parameters of the circuit elements of the input resistance Z_{in} depending on the configuration of the electrical circuit and the values of its elements Z_i. Thus, the sensitivity of the characteristic of the input impedance of the end of the track circuit is a function of the parameter Z_i.

The deviation of the characteristic of the input resistance Z_i from the optimal values is defined as

$$\Delta Z_{in} = \sum_{i=1}^{N} S_i \Delta Z_i \tag{2}$$

The relative sensitivity, in turn, can be defined as:

$$S_i^r = \frac{\partial \ln Z_{in}}{\partial\, ln\, Z_i} = \frac{Z_i}{Z_{in}} S_i = S_i^r (Z_{in}, Z_i) \tag{3}$$

The relative deviation of the input resistance Z_i is equal to

$$\frac{\Delta Z_{\text{in}}}{Z_{\text{in}}} = \sum_{i=1}^{N} S_i^r \frac{\Delta Z_i}{Z_i} \tag{4}$$

When calculating the electrical circuit of the input resistance, it is assumed to use, first of all, relative units (Ablin, 1970; Holt, 1969).

Consider the issue of using relative units on the example of the circuit shown in Figure 2.

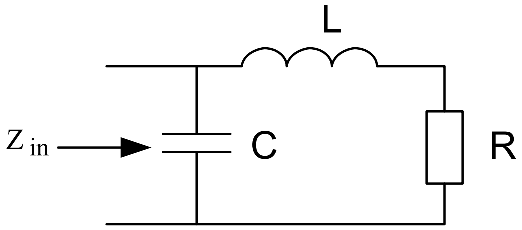

Figure 2: Circuit input impedance.

For the presented circuit in Figure 2, arbitrary circuits can be obtained by choosing the normalized values *R, L, C,* ω in relative units. With an increase in λ times the units of measurement, and the simultaneous invariance of the unit of measurement of the frequency ω, the impedance of the input resistance Z_i will increase by λ times. For the convenience of mathematical analysis, we separate the values of resistance, inductance and capacitance in the impedance Z_i.

We introduce the reciprocal values of the capacitance and denote them by *D*. Then we obtain the expression for the impedance

$Z_{\text{in}} = Z(R_1 \dots R_{\text{NR}}, L_1 \dots L_{\text{NL}}, D_1 \dots . \text{D}_{\text{NC}}, \omega)$, where $N_R + N_L + N_C = N$.

For the impedance, the following relationship holds.

$$\begin{aligned} Z_{\text{in}} &= Z(\lambda R_1 \dots \lambda R_{\text{NR}}, \lambda L_1 \dots \lambda L_{\text{NL}}, \lambda D_1 \dots . \lambda D_{\text{NC}}, \omega) \\ &= \lambda Z(R_1 \dots R_{\text{NR}}, L_1 \dots L_{\text{NL}}, D_1 \dots . \text{D}_{\text{NC}}, \omega) \end{aligned} \tag{5}$$

$$\begin{aligned} Z_{\text{in}} &= Z(\lambda R_1 \dots \lambda R_{\text{NR}}, \lambda L_1 \dots \lambda L_{\text{NL}}, \lambda D_1 \dots . \lambda D_{\text{NC}}, \omega) \\ &= \lambda Z(R_1 \dots R_{\text{NR}}, L_1 \dots L_{\text{NL}}, D_1 \dots . \text{D}_{\text{NC}}, \omega) \end{aligned}$$

Z – linear homogeneous function of variables *R*, *L*, *D*.

Differentiating Eq. (5) with respect to λ, we obtain:

$$\sum_{i=1}^{NR} \frac{\partial Z_{in}}{\partial \lambda R_i} \cdot \frac{\partial \lambda R_i}{\partial \lambda} + \sum_{i=1}^{NL} \frac{\partial Z_{in}}{\partial \lambda L_i} \cdot \frac{\partial \lambda L_i}{\partial \lambda} + \sum_{i=1}^{NC} \frac{\partial Z_{in}}{\partial \lambda D_i} \cdot \frac{\partial \lambda D_i}{\partial \lambda D_i} = Z_{in} \tag{6}$$

From expression (6), expression (7) follows

$$\sum_{i=1}^{NR}\frac{R_i}{Z_{in}}\cdot\frac{\partial Z_{in}}{\partial\lambda R_i}+\sum_{i=1}^{NL}\frac{L_i}{Z_{in}}\cdot\frac{\partial Z_{in}}{\partial\lambda L_i}+\sum_{i=1}^{NC}\frac{D_i}{Z_{in}}\cdot\frac{\partial Z_{in}}{\partial\lambda D_i}=1 \qquad (7)$$

Using expressions (1), (2) and (3) together with expression (7), we obtain (8).

$$\sum_{i=1}^{NR}S_i^r(Z_{in},R_i)+\sum_{i=1}^{NL}S_i^r(Z_{in},L_i)+\sum_{i=1}^{NC}S_i^r(Z_{in},D_i)=1 \qquad (8)$$

In another way, using the common sign of the sum, we get:

$$\sum_{i=1}^{N}S_i^r(Z_{in},Z_i)=1 \qquad (9)$$

Using expression (9), the sum of the relative sensitivities of the impedance Z_i, considering it with respect to *R, L*, and also *D*=1/*C*, is equal to 1. Using the sensitivity invariant, a number of useful results can be obtained when solving the problem of optimizing the input resistances at the ends of the rail line, in particular when calculating the input impedance having a minimum sensitivity (Fjallbzant, T. 1969; Tomovich, 1972; Nekrasov, 2001; Nekrasov, 2002).

When analyzing tolerances for deviations of input resistances at the ends of a rail line, various assumptions can be made regarding the law of addition of partial deviations $\Delta Z_{\text{in i}} = S_i\Delta Z_i$. But at the same time, the issue of calculating the worst case deviation of the input resistance can be considered

$$\Delta Z_{in\,i}\le\varepsilon=\sum_{i=1}^{N}|S_i||\Delta Z_i|=\sum_{i=1}^{N}|S_i|d_i \qquad (10)$$

ε defines the maximum allowable deviation, and d_i is the maximum change in the value of the circuit element. This method can be used in the synthesis of track circuits in the case of deterministic deviations of the input resistance elements, when the number of elements included in the electrical circuit is not large.

From expression (10) d_i is determined according to the following algorithm. We accept that the maximum permissible deviation ε and sensitivity S_i are known. We also accept that for all elements of the circuit the absolute values of partial deviations $|S_i|d_i$ will be the same. Thus, there is a chain with a uniform distribution of partial deviations. Then it is possible to determine partial deviations, knowing the ratio of the maximum permissible deviation ε to the number of circuit elements *N*:

$$\varepsilon/_N=|S_i|d_i \qquad (11)$$

From here we can calculate the absolute tolerance of the electrical circuit element

$$d_i=\varepsilon/_{N|S_i|} \qquad (12)$$

3 CONCLUSIONS

Summing up the above reasoning, we can conclude that if the corresponding sensitivity is small, then the circuit element will have a large tolerance and vice versa. Each element of the circuit makes the same contribution to the deviation of the characteristic of the circuit. When the number of circuit elements is large (more than 5 in practice), relation (12) gives very small tolerances for the electrical circuit elements. (Nekrasov, 2016; Lisenkov, 2014).

In the case of statistical calculation of deviation tolerances and input resistances, partial deviations can be considered as random variables, and a certain probability of failures (rejection) is allowed. The input resistance circuit is rejected if

$$|\Delta Z_{in\,i}|=\left|\sum_{i=1}^{N}S_i\Delta Z_i\right|>\varepsilon \qquad (13)$$

To determine the probability $P(|\Delta Z_{\text{ini}}|>\varepsilon)$ of rejection, we introduce a random variable μ and determine the basic properties and addition laws of this variable. Assume the existence of a probability density function μ and denote this function by *P(x)*. Then the probability of an event μ <*x* is defined as

$$P(\mu<x)=\int_{-\infty}^{x}P(x)dx \qquad (14)$$

and the mathematical expectation will look like

$$\mathrm{M}(\mu)=\int_{-\infty}^{\infty}xP(x)dx \qquad (15)$$

In turn, the variance will be defined as

$$D^2(\mu)=M\{\mu-M[\mu]\}^2=\int_{-\infty}^{\infty}(\mu-M[\mu])^2P(x)dx \qquad (16)$$

When calculating deviation tolerances statistically, it is necessary to know the actual distribution of the parameters of the elements included in the electrical circuit of the input impedance of the end of the rail line. (Nekrasov, 2001)

However, with the real distribution of element parameters, one can always associate the Gaussian distribution with the same mathematical expectation and variance. Then statistical calculations can be easily carried out for the obtained tolerances of deviations of input resistances at the ends of the rail line.

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