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ABOUT TRACK CIRCUIT CALCULATION METHOD DEPENDENT ON FERROMAGNET PROPERTIES IN CONDITIONS OF TRACTION CURRENT NOISE INFLUENCE

Purpose. The work is intended to investigate the electromagnetic processes in impedance bond in order to improve noise immunity of track circuits (TC) for safe railway operation. **Methodology**. To achieve this purpose the methods of scientific analysis, mathematical modelling, experimental study, a large-scale simulation were used. **Findings**. The work examined the interference affecting the normal performance of track circuits. To a large extent, part of track circuit damages account for failures in track circuit equipment. Track circuit equipment is connected directly to the track line susceptible to traction current interference, which causes changes in its electrical characteristics and electromagnetic properties. Normal operability, performance of the main operating modes of the track circuit is determined by previous calculation of its performance and compilation of regulatory tables. The classical method for determination of track circuit parameters was analysed. The classical calculation method assumes representation of individual sections of the electrical track circuit using the quadripole network with known coefficients, usually in the A-form. Determining the coefficients of linear element circuit creates no metrological or mathematical difficulties. However, in circuits containing nonlinear ferromagnets (FM), obtaining the coefficients on the entire induction change range in the cores is quite a difficult task because the classical methods of idling (I) and short circuit (SC) are not acceptable. This leads to complicated methods for determining both the module and the arguments of quadripole network coefficients. Instead of the classical method, the work proposed the method for calculating the track circuit dependent on nonlinear properties of ferromagnets. **Originality**. The article examines a new approach to the calculation of TC taking into account the losses in ferromagnets (FM), without determination of equivalent circuit quadripole network coefficients. When building the FM reversal model in parallel magnetic fields, the most accurate methods are the approximation ones that take into account not only the changes in values and over time, but also their derivatives. The development of computer hardware and software makes real the mathematical methods for calculating TC with significant change in ferromagnetic inductance, including the saturation areas. Herewith, it is important to search for approximating analytical expression that describes the dynamic limit hysteresis loop (HL). **Practical value**. The changes in the electrical parameters of the same TC were analysed using the classical and the new calculation methods, the difference made less than 10%. The work introduced some measures to increase operational noise immunity of TC.

*Keywords***:** track circuit; impedance bond; quadripole network; ferromagnet; hysteresis; spectrum; vortical currents; magnetic viscosity; magnetizing curve; simulation

Introduction

Experience has shown that certain conditions and operating modes of the power network create a powerful influence of the traction current noise on the work of electric track circuits (TC). Such exposure results in magnetization of nonlinear ferromagnets (transformers, impedance bonds and components containing ferromagnetic core) in track circuits and, consequently, in failure of TC and signalling systems. Adverse conditions [11, 12, 13] for TC operation are created in the following cases:

1) At a certain switching circuit of DC traction network of splicing stations the level of permanent traction current potentials «rail-to-earth» in the rail network increases. It results in increased **leakage currents** into the open-line track of AC electric traction lines, causing magnetization of impedance bonds and track transformers, and disruption of short (less than 500 m) track circuits;

2) In the areas of AC electrified railroads the ice on the contact network collectors creates an electric arc, accompanied by electrical transients in the power circuit of an electric locomotive. Con-

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stant component of this current at the rail line asymmetry also causes saturation of ferromagnets;

3) Switching on the locomotive main switch in a certain voltage phase of the circuit power line also leads to transition process with the consequences given above;

4) When a laden electric locomotive enters the neutral section on the current collectors there are several electric arcs repeated aperiodically; this leads, as mentioned above, to the occurrence of transients and failures of TC. From the above it follows that improvement of track circuit noise immunity in the signalling systems in conditions of permanent reverse traction current influence is an actual scientific and technical problem.

Purpose

The purpose of this work is to examine the causes of traction current harmful influence on TC operation, to create the calculation method for TC with nonlinear ferromagnets (FM) and to propose technical solutions to improve the reliability of TC and railway automation systems.

Methodology

Disruption of TC operation. Let’s consider one of the causes of TC operation disruption – longitudinal asymmetry of track lines. Measurements show that the asymmetry coefficient is higher in winter than in summer due to increased insulation resistance. It is established that the best way to approximate the conductive joint resistance distribution is asymmetric Weibull law, resistance variation reaches 1.8 … 15 m.e.r. (meters of entire rail); longitudinal asymmetry coefficient ranges from 10% to 12% – in summer, up to 18% – in winter [1, 6].

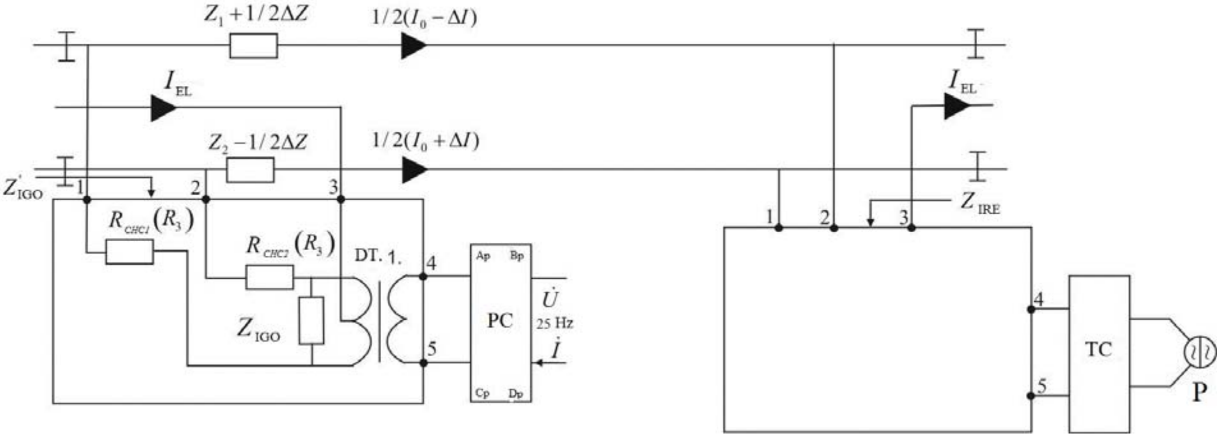

Fig. 1. Equivalent circuit of track lines

The EMF equation for equivalent circuit contour of the track (Figure 1) consisting of two rails, equipment impedance $Z^{`}_{igo}$, Z_{ire} and choke cables, for the difference in currents can result in the following expression:

$$\Delta I=\frac{\Delta Z'+2\left(R_{CHC1}-R_{CHC2}\right)}{\left[\begin{array}{l}Z+Z'_{IGO}+Z_{IRE}+\\+2\left(R_{CHC1}+R_{CHC2}\right)+Z_{MWR}\end{array}\right]}I_{EL}, \quad (1)$$

where I_{EL} – electric locomotive current; $\Delta Z=Z_1-Z_2$ - difference in rail resistance, Ohm; Z − rail loop resistance, Ohm/km; Z_{MWR} − main winding resistance DT.1, Ohm; $R_{CHC1(2)}$ − choke cable resistance, Ohm.

It follows from (1) that $Z^{`}_{igo}$, Z_{ire} perform the symmetric action, but their impedance for the signal current under the track integrity monitoring conditions is small and can be neglected.

For DC the equation (1) can be written as:

$$\Delta I=\frac{\Delta R_{CC}+2\left(R_{ДП1}-R_{ДП2}\right)}{R_P+2\left(R_{ДП1}+R_{ДП2}\right)+R_{ДР}}I_{ЭЛ},$$

or

$$\Delta I=K_a\cdot I_{ЭЛ}, \quad (2)$$

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Thus, the longitudinal asymmetry coefficient of track line is:

$$K_a = \frac{\Delta R_{RC} + 2\left(R_{CHC1} - R_{CHC2}\right)}{R_P + 2\left(R_{CHC1} + R_{CHC2}\right) + \Delta R_{MWR}}, \quad (3)$$

where ΔR_{RC} – difference in track resistance due to resistance of connectors.

In short TC (less than 500 m) longitudinal asymmetry is one of the main causes of traction current asymmetry $K_a = \frac{I_1 - I_2}{I_1 - I_2}$, where $I_{1,2}$ – traction currents in the rails 1 and 2.

Measurements show that the resistance of the steel DC rail connector is distributed among its components, so [4, 3]:

$$R_{RC} = R_{SC} + \left(R_N + R_{WS}\right) = \frac{2}{5}R_{RC} + \frac{3}{5}R_{RC},$$

where R_M – resistance of nipple – rope junction; R_{SC} – resistance of steel cable; R_{WS} – resistance of weld seam.

For steel connector with 100 mm^2 cross-section, which is widely used in practice, it appears that averages R_{SC} = 295 mcOhm; $R_N + R_{WS}$ = 437 mcOhm; R_{RC} = 232 mcOhm; for the connector with 90 mm^2 cross-section – R_{RC} = 770 mcOhm [8].

Rules for protection of metallic structures from stray-current corrosion allow increasing rail resistance through the joints by max 20%, while the DC asymmetry coefficient is $K_a = \frac{\Delta R}{R_P}$ =0,12…0,13. Approximate calculation of asymmetry for alternate traction current is performed with the following assumptions [3, 8]:

− Resistance of rails differ among themselves by the amount of resistance of connectors;

− Connector losses do not depend on the frequency;

− Resistance in points of welding and junctions cable – nipple – plug – rail depends on the frequency as much as the internal resistance of the rails.

− Herewith, the minimum coefficient of longitudinal asymmetry:

$$\left|K_Z\right| = K_a \left|\frac{R_{SC}}{R_C \cdot Z} + \frac{\left(R_N + R_{WS}\right)Z_i}{R_C \cdot Z}\right| \le$$

$$\le 0{,}008\%, \text{ or } 8.0\%, \quad (4)$$

where Z_i – internal resistance of rails, 0.35e^{j35} Ohm/km; rail loop resistance R_p = 0.1 Ohm; Z = 0.8e^{j65} Ohm/km – rail resistance to 50 Hz current. For higher frequency the coefficient $\left|K_Z\right|$ is reduced to 1.608% for 420 Hz frequency and 1.376% for 780 Hz.

Let's assess the numerator of the fraction (3) for TC that most often fail with length of 0.25 … 0.5 km. We assume that $R_{RC} = 770 \cdot 10^{-6}$ Ohm, $R_{CHC1} = 8000 \cdot 10^{-6}$ Ohm ($\ell_{CHC} = 3.25$ m), $R_{CHC2} = 3076 \cdot 10^{-6}$ Ohm ($\ell_{CHC} = 1.25$ m), rail link 25m, rail resistance 0.1Ohm/km, $n_C = \frac{\ell_{TC}}{0{,}025} - 2$. It turned out that ΔR = 0.026…0.056 Ω, and the value K_a is in the range of 30.2% … 38.6%. We should note here that the resistance of 300 m long line to 50 Hz current does not exceed 0.1 Ohm/km and is compared to the total impedance of contact connectors «cable – plug – nipple -wing IB» (normative 60 … 80).

Let us consider the proposed TC calculation method for nonlinear FM modes of TC circuits, based on the mathematical model of ferromagnet reversal magnetization [2, 4].

Originality and practical value

*Mathematical description of model***.** We assume that ferromagnetic saturation leads to changes in induction (intensity) of the magnetic field of DT.1.150 core according to the complex law

$$b = b_0 + \sum_{k=1}^{m} \begin{bmatrix} b_{k\sin} \sin\left(k\omega t\right) + \\ + b_{k\cos} \cos\left(k\omega t\right) \end{bmatrix}, \quad (5)$$

where k = 1, 2, …, m , nd measuring of quadripole network using the known methods of idling and short circuit is too complicated [2].

It is known that when there is cyclical change in the external magnetic field the ferromagnetic induction retards in phase from the tension and enables the cycle of dynamic hysteresis loop (HL)

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(Fig. 2 (a)). HL area defined the power losses caused by reversal magnetization, vortical currents and magnetic viscosity [3].

The mathematical model that accurately describes the research HL is as follows:

$$h = \left(Ae^{-\gamma^2 bm^2}\right)\alpha_1 \sinh\left(\beta_1 b\right) + \alpha_2 \frac{db}{dt}\cosh\left(\beta_2 b\right),$$

$$b = b_0 + b_m \sin\left(\omega t\right) \ \left(b = b_m \sin\left(\omega t\right)\right), \qquad (6)$$

($Ae^{-\gamma^2 bm^2}$ – makes sense when building the specific loop exits and depends on constructive features of the subject) and allows taking into account the influence of harmonic spectrum for ferromagnet reversal input current. The values A, γ, α_1, β_1, α_2, β_2 – approximation coefficients of the function (6), are determined using numerical methods by HL experimental end value and magnetization curve, taken at the maximum values of induction and signal frequency. The first term (6) describes the basic magnetization curve (BMC), the second one describes dissipative processes both for hysteresis and vortical currents, and depends on the magnetic viscosity.

Coefficients α_1 and β_1 of anhysteretic component (6) are determined by the selected points on the BMC curve, the values A and γ are determined by expressions [1]

$$\ln(A) = \gamma^2 b_m^2 \max;$$

$$\gamma^2 = \frac{\ln\left(h_0 / \alpha_1 \cdot \sinh\left(\beta_1 b_0\right)\right)}{b_m^2 \max - b_0^2},$$

Herewith, we take the points b_0, h_0 close to the maximum induction b_m, and induction b_m max corresponds to the maximum operating value. The coefficients α_2 и β_2 are calculated by the formulas:

$$\alpha_2 = \frac{h_c}{\Omega \cdot b_m}, \quad \beta_2 = \frac{1}{b_m},$$

where h_c – coercive force, A/m.

Let us consider the ferromagnetic reversal process affected by induction core created $b = b_0 + b_m \sin\left(\Omega t\right)$ by direct current field and signal current field of 25 Hz (Fig. 2 (b)). We substitute this expression as an argument in the formula (6) and turn it omitting the exponential factor $Ae^{-\gamma^2 bm^2}$, which does not affect the quantitative result of the first term. As the argument b changes according to the periodic law, then the functions $\sinh\left(\beta_1 b\right)$ and $\cosh\left(\beta_2 b\right)$ are also periodic and can be represented by Fourier series [10], in which the coefficients in the trigonometric functions are Bessel functions of different orders of imaginary argument jx_m. The result is:

$$\begin{aligned} h = {} & \alpha_1 \sinh\left(\beta_1 b_0\right)\cdot\cosh\left(\beta_1 b_m \sin\left(\omega t\right)\right) + \\ & + \alpha_1 \cosh\left(\beta_1 b_0\right)\cdot\sinh\left(\beta_1 b_m \sin\left(\omega t\right)\right) + \\ & + \alpha_2 \cdot \omega b_m \cos\left(\omega t\right) \times \\ & \times \left[\begin{aligned} & \cosh\left(\beta_2 b_0\right)\cdot\cosh\left(\beta_2 b_m \sin\left(\omega t\right)\right) + \\ & + \sinh\left(\beta_2 b_0\right)\cdot\sinh\left(\beta_2 b_m \sin\left(\omega t\right)\right) \end{aligned}\right]. \end{aligned} \qquad (7)$$

We present the hyperbolic functions in (7) by rows:

$$\begin{aligned} sh\left(x_m \sin\left(\omega t\right)\right) = {} & 2\left[-jJ_1\left(jx_m\right)\right]\cdot\sin\left(\omega t\right) - \\ & -2\left[jJ_3\left(jx_m\right)\right]\cdot\sin\left(3\omega t\right) - \ldots, \end{aligned}$$

$$\begin{aligned} ch\left(x_m \sin\left(\omega t\right)\right) = {} & \left[J_0\left(jx_m\right)\right] + \\ & +2\left[J_2\left(jx_m\right)\right]\cdot\cos\left(2\omega t\right) + \ldots \end{aligned}$$

and keeping harmonics no higher than the second one, after transformations we obtain:

$$\begin{aligned} h = {} & h_0 + m_1 \sin\left(\omega t\right) + n_2 \sin\left(2\omega t\right) + \\ & + m_2 \cos\left(\omega t\right) + n_1 \cos\left(2\omega t\right), \end{aligned} \qquad (8)$$

where

$$h_0 = \alpha_1 \cdot \sinh\left(\beta_1 b_0\right)\cdot\left[J_0\left(j\beta_1 b_m\right)\right];$$

$$m_1 = \alpha_1 \cdot \cosh\left(\beta_1 b_0\right)\cdot 2\left[-J_1\left(j\beta_1 b_m\right)\right];$$

$$n_1 = \alpha_1 \cdot \sinh\left(\beta_1 b_0\right)\cdot 2\left[J_2\left(j\beta_1 b_m\right)\right];$$

$$\begin{aligned} m_2 = {} & \alpha_2 \omega b_m \cdot \cosh\left(\beta_2 b_0\right)\cdot J_0\left(j\beta_2 b_m\right) + \\ & + \alpha_2 \omega b_m \cdot \sinh\left(\beta_2 b_0\right)\cdot\left[-J_0\left(j\beta_2 b_m\right)\right]; \end{aligned}$$

$$n_2 = \alpha_2 \omega b_m \cdot \sinh\left(\beta_2 b_0\right)\cdot\left[-J_1\left(j\beta_2 b_m\right)\right];$$

We examine the term h_0 in the formula (8), since this is the component of the magnetic field strength that leads to the choke core saturation and, ultimately, to failure of TC receiver.

When applying the numerical estimate for field intensity dependence on induction in the formulas (6) and (8), the following parameters are used: $\alpha_1 = 2.1\frac{A}{m}$, $\beta_1 = 4.5\frac{1}{T}$, $\alpha_2 = 0.26\frac{A}{m}$, $\beta_2 = 0.77\frac{1}{T}$, $\gamma = 0.92\frac{1}{T}$, $A = 5.92$ (steel grade 2412), cross-sectional area of the DT.1.150 choke core is $29.2.10^{-4}$ m^2, average length of the magnetic power line $\ell = 0.58$ m, number of operating winding turns $W_0 = 16$. Maximum values of induction b_m for different lengths of TC are calculated by the formula $b_m = \frac{U_{\text{Ch max}}}{4.44 fWS}$, where $U_{\text{Ch max}}$ – voltage on the choke primary winding, taken according to the reference data and the regulatory tables of phase-sensitive TC as 25 Hz [10]. For TC of 250 … 500 m long $U_{\text{Ch max}} = 1.45 \ldots 2.5$ V $b_m = 0.28 \ldots 0.42$ T; marginal field voltage h_{fv} is in the range of 240 … 280 A/m, bias current $I_0 = h_{fv} \cdot 0.036 = 8.5 \ldots 9.5$ A, and asymmetry current 17 … 19 A.

TC bench tests showed that the limiting current for choke magnetizing, in which the receiver transits to zero state, reaches 8.4 … 9.25 A.

Figure 2 (b) shows the BMC curve, approximated by the expression (6), and the hysteresis loop at constant field induction (displacement) $b_0 = 1.1$ T; it also represents reversible permeability curve, $\mu_r(h_0)$, calculated by the formula $\mu_r \le \tan(\alpha) = \frac{\Delta b_0}{\Delta h_0} \cdot \frac{m_h}{m_b}$, where Δb_0, Δh_0 – incremental induction and field intensity in i-th point of the curve $b_0(h_0)$; m_b, m_h – axis scales.

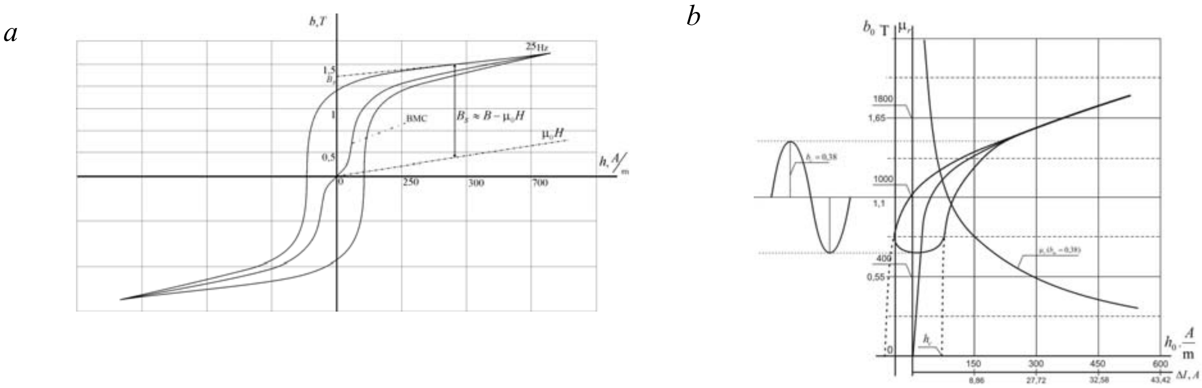

Fig. 2. Dependence of field intensity on induction at 25 Hz frequency:
a − harmonic signal; *b* − harmonic signal with bias

Coercive force h_c of HL is determined taking into account the fact that anhysteretic component (6) is zero, then 62.2 A/m, and maximum loop induction corresponds to $b_m = b_0 + b_c = 1.4$ T. The given value μ_r allows easy determination of inductance L_0 and impedance Z_0 of the main winding, and BMC – magnetization current.

The impedance argument Z_0 can be determined by the value of power losses for vortical currents and hysteresis [5]:

$$P_{B.T.} = Vf_c \int_0^{2\pi} HdB\,, \tag{9}$$

where V − core volume. Phase shift between first EMF harmonics and winding current is determined at the intensity $u = U_m \sin \Omega t$, if induction and intensity are the given functions:

$$B(t) = \sum_{n=1}^{\infty} B_{m_n} \sin(n\Omega t - \gamma_n)\,,$$

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$$i(t)=\sum_{n=1}^{\infty} I_{m_n}\sin(n\Omega t+\psi_n). \qquad (10)$$

From (10) and the equation of magnetized winding circuit of the choke DT.1 with the resistance r :

$$ri+W_0S\frac{dB}{dt}=u \qquad (11)$$

we obtain EMF and phase for the first harmonic: $E_1=\Omega W_0\Phi$; $\psi_1=\gamma_1+\frac{\pi}{2}$. Substituting intensity $H_0=\frac{iW}{l}$ and core volume $V=S\cdot l$ into (9) we determine that

$$P_{B.T.}=\Omega W_0 S\left[I_1B_1\sin(\gamma_1-\psi_1)\right]. \qquad (12)$$

If induction

$$b_1=b_0+b_{1m}\sin(\Omega t-\gamma_1)=$$

$$=1.1+0.38\cdot\sqrt{2}\sin(157t-\gamma_1),$$

current i_Ω= 2.6 A adopted by BMC for b_0= 1.1 T, b_{1m}= 0.521 T, r = 0.003 Ohm, then from (11) we find that E_{1m}= 2.174 V; voltage losses for circuit resistance 7.8·10^{-3} V, voltage u=2.7178 B, V, and full power $S=2.7178\cdot 2.6=$ 7.066 VA, where we get that $P_{B.T.}$ = 7.0563 W.

The impedance argument Z_0 is $\varphi=\arcsin\frac{P_{B.T.}}{S}=86^0 57^{`}$. The argument Z_0 can be found in another way. Magnetic flow (11), passing through the core sheet bands,

$$\dot{\Phi}=\frac{2\mu b h_0}{(1+j)\beta d}\tanh\left(\beta(1+j)\frac{d}{2}\right), \qquad (13)$$

where $h_0=\frac{iW}{l}$, $\beta=\sqrt{\pi f\mu_0\mu_r\gamma}$, γ – steel conductivity ($7\cdot 10^3\ {}^{1}\!\big/_{Ohm\cdot mm}$), μ_r – magnetic permeability of steel is taken 500, d = 0.055m, b= 0.18m –thickness and width of the package of core plates [6].

Calculation of complex impedance growth of DT.1.150 core winding due to vertical current effect is possible thanks to (13):

$$0,2\leftarrow\Delta Z=\begin{matrix}\dfrac{2j\cdot\mu_r S_{\Pi}\Omega W^2}{(1+j)\beta\cdot l\cdot d}\times\\ \times\tanh\left(\beta(1+j)\dfrac{d}{2}\right)\end{matrix}, \qquad (14)$$

where $S_{\Pi}=a\cdot b$ – flowed cross-section area of the package; a = 0.175m m – steel package height.

For low frequencies (below 900 Hz) $L_0=\frac{\mu_0\mu_r SW^2}{l}$, where L_0 – winding DC inductance; $S=29.2\cdot 10^{-4}$ m^2 – cross-sectional area of the magnetic core covered with windings; l= 0.58m – average length of the magnetic line for flows. Then (14) can be written as

$$\Delta Z=\begin{matrix}L_0\dfrac{2j\cdot\Omega}{(1+j)\beta\cdot d}\times\\ \times\tanh\left((1+j)\dfrac{d}{2}\right)\end{matrix}$$

and decomposed into real and imaginary parts. As a result we will get the formula for inductance evaluation $\Delta L=L_0\frac{1}{x}\cdot\frac{sh(x)+\sin(x)}{sh(x)+\cos(x)}$ and active resistance of winding $\Delta R=\omega L_0\frac{1}{x}\cdot\frac{sh(x)-\sin(x)}{sh(x)+\cos(x)}$. Complete winding inductance $L=L_0+\Delta L$, and impedance $R=R_0+\Delta R$, where $R_0=\rho\frac{\ell_n}{S_n}$, ℓ_n, S_n – wire length and cross section.

Let us consider the peculiarities of calculation of the track circuit with nonlinear ferromagnets.

Findings

Calculation of TC operation modes are conducted using the structural equivalent circuit (Fig. 3) of impedance bond, presented by the circuit of L-shaped quadripole network and ideal transformer.

Determination of quadripole network coefficients (usually in A-form) on the entire change range in the induction cores, which exceeds the saturation limit, is quite a difficult task because the classical methods of idling and short circuit are not acceptable. The proposed method of TC calculation facilitates the solution of the above problem.

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The calculations require the FM hysteresis loop (Fig. 2 (a)), taken at maximum induction, and the magnet permeability dependence $\mu_r(h_0)$ on the current (intensity) of magnetization. Then taking into account (8) we determine the intensity h_0, impedance Z_0 of magnetization needles at a given induction and A-matrix coefficients of the quadripole networks of DT.1.150 estimated equivalent circuit (Fig. 3):

$$A_T = n\left(1+\frac{r_1}{z_0}\right),\ B_T = nr_1,$$

$$C_T = \frac{1}{nz_0},\ D_T = \frac{1}{n} \qquad (15)$$

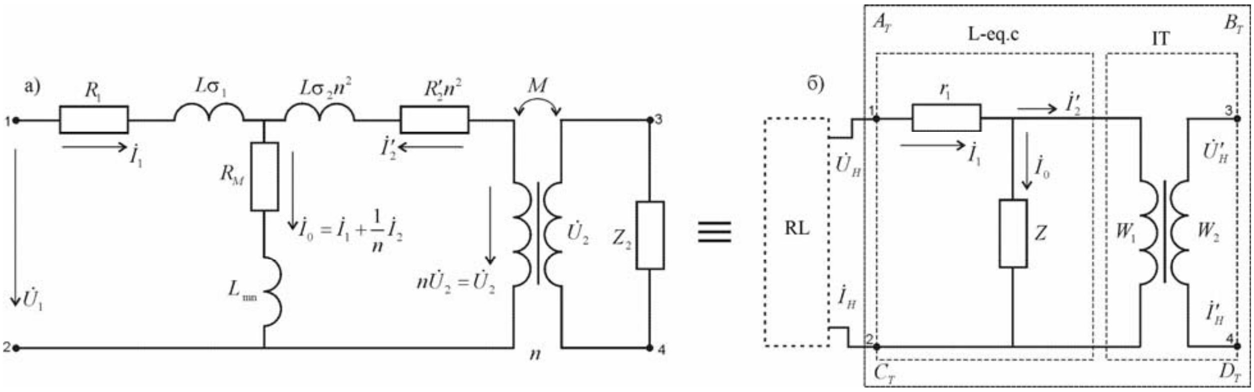

Fig. 3. Impedance bond equivalent circuit:
a – real; *b* –design

The design equivalent circuit of choke excludes the leak inductance of windings and the given additional winding resistance that affects the calculation accuracy to a small extent.

The calculation results for phase-sensitive twin TC at 25 Hz using the coefficients (15) with choke bias at the ends of TC showed coincidence with those obtained by conventional methods.

Table 1 shows comparative design parameters for the same TC, obtained by two calculation methods – classic and new, using a mathematical model of ferromagnet reversal magnetization.

Figure 4 shows the dependence of voltage at the receiver input resistance on the impedance module Z_0. It can be seen that the end value of resistance at saturation of both chokes reaches 0.44 Ohms, which is 1.6 times less than the nominal value. Switch of the receiver to zero state is possible at saturation of one choke up to resistance Z_0 = 0.2 Ohm (Fig. 4).

Table 1

TC calculations results

Calculation methods	$\dot{U}_{IB}$	$\dot{I}_{IB}$	$\dot{U}_{SC}$	S	β_P	Notes
	B	A	B	BA	grad	
Classic	$3.75e^{j95.5^0}$	$0.82e^{j60^0}$	$5.1e^{j78.6^0}$	4.58	$6^0 32'$	The difference in results is caused mainly by accounting resistances of steel ChC. Values are given without correction for angle β_P
New	$4.1e^{j89^0}$	$0.77e^{j54^0}$	$5.5e^{j78^0}$	4.23	6^0	
Difference in calculations, %	9.3	9.3	7.8	7.64	-	

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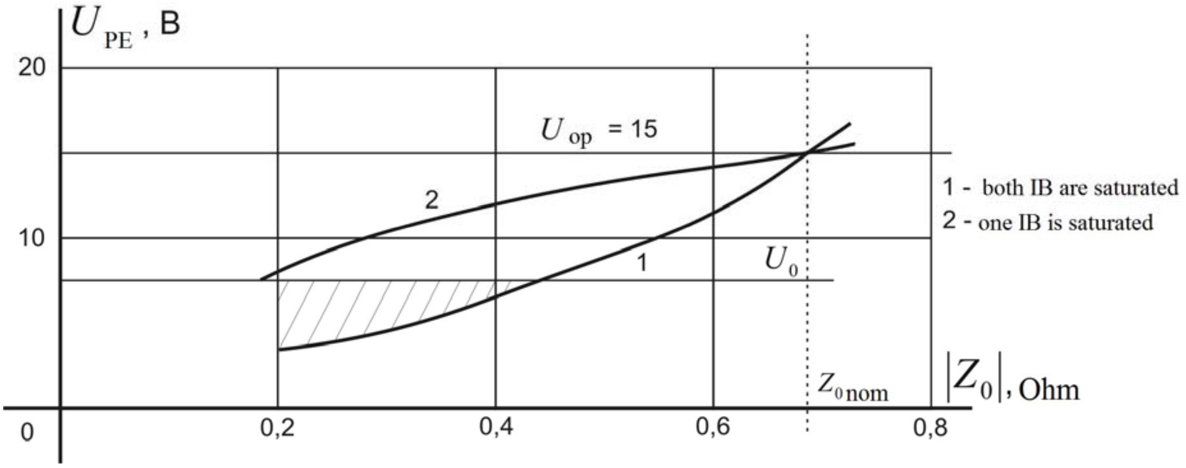

Fig. 4. Dependencies of receiver voltage on impedance module Z_0

Conclusions

To solve the problem of providing TC noise immunity under the influence of powerful noise of traction current, several solutions were proposed.

The first solution is to use DT.06.500S type, used for splicing stations, at the stations of impedance bonds with air gap [2, 3].

The second solution is to use switching units [9], which excludes spreading of traction DC out of the splicing station rail network towards the range of electric traction AC that, beside IB saturation, eliminates electric corrosion of supports and metal elements at a distance of 30 km from the source of noise. The device is tested in the laboratory of DNUZT and in the field of Pyatikhatky splicing station of Prydniprovs'ka railway.

The third solution is to install symmetric resistive (R_{CHC1} or R_{CHC2}) units [2, 8] in short TC at AC electric traction. The impedance values of unit resistors are designed to exceed substantially the sum of all resistances in the rail line bridge circuit (Fig. 1). The unit resistors (Fig. 1) are switched on in series with choke cables at one end of the rail line, which is much cheaper than in the case of choke replacement.

The conclusion should emphasize the following: it is found that the cause of TC failures is ferromagnetic core saturation under conditions of rail line asymmetry, herewith the asymmetry of direct current magnetizing FM is 4 … 5 times higher than the asymmetry of alternating current.

The new method of TC calculation using the mathematical model of ferromagnet reversal magnetization allowed obtaining the numerical evaluation of maximum allowable asymmetry currents and input impedances at the circuit ends, which cause failure of signalling system devices.

The work formulated the technical measures for improvement of noise immunity and TC protection under conditions of powerful traction current noise.

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ПРО МЕТОД РОЗРАХУНКУ РЕЙКОВИХ КІЛ ІЗ УРАХУВАННЯМ ВЛАСТИВОСТЕЙ ФЕРОМАГНЕТИКІВ В УМОВАХ ВПЛИВУ ЗАВАД ТЯГОВОГО СТРУМУ

Мета. У роботі необхідно дослідити електромагнітні процеси в дросель-трансформаторі з метою підвищення завадостійкості рейкових кіл (РК) та, як наслідок, підвищення безпеки руху на залізниці. **Методика**. Для досягнення поставленої мети застосовано методи наукового аналізу, математичного моделювання, експериментального дослідження, масштабного моделювання. **Результати**. Розглянуто перешкоди, що впливають на нормальну працездатність рейкових кіл. Значною мірою частина пошкоджень у рейковому колі доводиться на відмову в його апаратурі. Апаратура рейкового кола підключена безпосередньо до рейкової лінії, схильної до впливу перешкод тягового струму, які викликають у них зміну електричних характеристик та електромагнітних властивостей. Нормальна працездатність при виконанні основних режимів роботи рейкового кола визначається попереднім розрахунком її характеристик та складанням регулювальних нормативних таблиць. Проаналізовано класичний метод визначення параметрів рейкового ланцюга. Класичний метод розрахунку передбачає подання окремих ділянок електричної схеми рейкових кіл чотириполюсниками з відомими коефіцієнтами, зазвичай в А-формі. Відшукування коефіцієнтів схем із лінійними елементами не представляє метрологічних та математичних труднощів. Разом із тим, у ланцюгах, що містять нелінійні феромагнетики (ФМ), отримання коефіцієнтів на всьому діапазоні зміни індукцій у сердечниках − досить важке завдання, оскільки класичні методи холостого ходу (ХХ) та короткого замикання (КЗ) стають неприйнятними. Це призводить до ускладнення методів визначення, як модуля, так і аргументів коефіцієнтів чотириполюсників. Замість класичного методу запропонований метод розрахунку рейкового кола з урахуванням нелінійної характеристики феромагнетиків. **Наукова новизна**. У статті розглянуто новий підхід до розрахунку рейкового кола з урахуванням втрат у феромагнетиках без пошуку коефіцієнтів чотириполюсників схеми заміщення. При побудові моделі перемагнічування ФМ у паралельних магнітних полях найбільш точними є апроксимаційні

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методи, що враховують не тільки зміни величин і у часі, а ще й їх похідні. З розвитком обчислювальної техніки та програмного забезпечення математичні методи розрахунку РК при значній зміні індуктивності феромагнетиків, включаючи ділянки насичення, стають реальними. При цьому важливим є пошук апроксимуючого аналітичного виразу, що описує динамічну граничну петлю гістерезису (ПГ). **Практична значимість**. Проведено аналіз зміни електричних параметрів одного й того ж РК при розрахунку класичним і новим методом: різниця склала не більше 10 %. Наведено деякі заходи з підвищення експлуатаційної завадостійкості РК.

Ключові слова: рейкове коло; дросель-трансформатор; чотириполюсник; феромагнетик; гістерезис; спектр; вихрові струми; магнітна в'язкість; крива намагнічення; моделювання

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О МЕТОДАХ РАСЧЕТА РЕЛЬСОВЫХ ЦЕПЕЙ С УЧЕТОМ СВОЙСТВ ФЕРРОМАГНЕТИКОВ В УСЛОВИЯХ ВЛИЯНИЯ ПОМЕХ ТЯГОВОГО ТОКА

Цель. В работе необходимо исследовать электромагнитные процессы в дроссель-трансформаторе с целью повышения помехоустойчивости рельсовых цепей (РЦ) и, как следствие, повышения безопасности движения на железной дороге. **Методика**. Для достижения поставленной цели применены методы научного анализа, математического моделирования, экспериментального исследования, масштабного моделирования. **Результаты**. Рассмотрены помехи, влияющие на нормальную работоспособность рельсовых цепей. В значительной мере часть повреждений в рельсовой цепи приходится на отказ в его аппаратуре. Аппаратура рельсовой цепи подключена непосредственно к рельсовой линии, подверженной влиянию помех тягового тока, что вызывает в них изменение электрических характеристик и электромагнитных свойств. Нормальная работоспособность при выполнении основных режимов работы рельсовой цепи определяется предварительным расчетом ее характеристик и составлением регулировочных нормативных таблиц. Проанализирован классический метод определения параметров рельсовой цепи. Классический метод расчета предполагает представление отдельных участков электрической схемы рельсовых цепей четырехполюсниками с известными коэффициентами, обычно в А-форме. Поиск коэффициентов схем с линейными элементами не представляет метрологических и математических затруднений. Вместе с тем, в цепях, содержащих нелинейные ферромагнетики (ФМ), получение коэффициентов на всем диапазоне изменения индукций в сердечниках − довольно трудная задача, поскольку классические методы холостого хода (ХХ) и короткого замыкания (КЗ) становятся неприемлемыми. Это приводит к усложнению методов определения, как модуля, так и аргументов коэффициентов четырехполюсников. Вместо классического метода предложен метод расчета рельсовой цепи с учетом нелинейной характеристики ферромагнетиков. **Научная новизна**. В статье рассмотрен новый подход к расчету РЦ с учетом потерь в ферромагнетиках, без поиска коэффициентов четырехполюсников схемы замещения. При построении модели перемагничивания ФМ в параллельных магнитных полях наиболее точными являются аппроксимационные методы, учитывающие не только изменения величин и во времени, но и их производные. С развитием вычислительной техники и программного обеспечения математические методы расчета РЦ при значительном изменении индуктивности ферромагнетиков, включая участки насыщения, становятся реальными. При этом важным является поиск аппроксимирующего аналитического выражения, описывающего динамическую предельную петлю гистерезиса (ПГ). **Практическая значимость**. Проведен анализ изменения электрических параметров одной и той же РЦ при расчете классическим и новым методом: разница составила не более 10 %. Приведены некоторые мероприя-тия по повышению эксплуатационной помехоустойчивости РЦ.

Ключевые слова: рельсовая цепь; дроссель-трансформатор; четырехполюсник; ферромагнетик; гистерезис; спектр; вихревые токи; магнитная вязкость; кривая намагничивания; моделирование

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