

*When studying transients in pulsed current traction motors, it is important to take into consideration the eddy and hysteresis losses in engine steel. Magnetic losses are a function of the magnetization reversal frequency, which, in turn, is a function of the engine shaft rotation frequency. In other words, magnetic losses are a function of time. Existing calculation procedures do not make it possible to derive the instantaneous values of magnetic losses as they are based on determining average losses over a period.*

*This paper proposes an improved model of magnetic losses in the steel of a pulsed current traction motor as a function of time, based on the equations of specific losses.*

*The adequacy criteria of the procedure for determining magnetic losses in electrical steel have been substantiated: the possibility to derive instantaneous values of magnetic losses in the magnetic material as a function of time; the possibility of its application for any magnetic material; and the simplicity of implementation. The procedure for determining magnetic losses in the steel of a pulsed current traction motor has been adapted by taking into consideration the magnetic properties of steel and the geometry of the engine's magnetic circuit. In order to determine the coercive force, the coefficient of accounting for the losses due to eddy currents, as well as the coefficient that considers the losses on hysteresis, the specifications' characteristics of specific losses in steel have been approximated using the pulsed current traction motor as an example. The simulated model of magnetic losses by the pulsed current traction motor has demonstrated the procedure for determining average magnetic losses and time diagrams of magnetic losses.*

*The proposed model for determining magnetic losses could be used for any magnetic material and any engine geometry under the condition of known material properties and the characteristics of change in the magnetic flux density in geometry*

*Keywords: magnetic losses, eddy currents, hysteresis, traction motor, universal magnetic characteristic*

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## 1. Introduction

Most tractive electric rolling stock units are equipped with pulsed current motors that serve as traction engines. In particular, these are the alternating current electric locomotives, series VL-80<sup>T</sup> and VL-80<sup>K</sup>, equipped with NB-418-K6 engines. In addition, pulsed current motors are used in the electric locomotives ChS4, VL8, VL40, VL60, 2EL5K, as well as industrial traction units OPEL1A(M).

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# IMPROVEMENT OF THE MODEL OF POWER LOSSES IN THE PULSED CURRENT TRACTION MOTOR IN AN ELECTRIC LOCOMOTIVE

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the nonlinearity of the universal magnetic characteristic of the traction motor. Second, with the implementation of the model of losses in the motor's active power.

The issue related to power losses by traction rolling stock was considered in several studies. Paper [1] scientifically grounded directions for reducing the power losses of traction engines by improving the process of directing the wheelsets with a rail track. Work [2] examines the cases of power loss in traction motors under extreme driving parameters, in particular when wheelsets derail.

The losses of active power could be divided into the following:

- magnetic losses in steel caused by hysteresis and eddy currents;
- electrical losses in the motor's windings and brush-collector contact;
- additional losses, whose magnitude depends on the load current;
- mechanical losses.

In terms of determining them, the most difficult are the losses caused by hysteresis and eddy currents.

Existing models of induction motors have a separate magnetization circuit. With this chain, magnetic processes in the induction motor could be investigated separately, in particular, magnetic losses, as reported in [3, 4]. Unlike the induction motor, there is no separate magnetization circuit in the existing models of pulsed current motors, making it difficult to investigate magnetic processes.

Mathematical modeling of magnetic losses in the steel of the pulsed current traction motor is associated with the need to take into consideration a series of dependences accompanying electromechanical processes. First, the dependence of magnetic flux on the load current of a traction motor is a nonlinear function, which should be approximated when building the model; it was performed in [4–7]. Second, it is necessary to take into consideration the parameters of a hysteresis loop inherent in the magnetic characteristic of electrical steel [8, 9]. Third, the dependence of specific magnetic losses in electrical steel on the magnetization reversal frequency, which, in turn, is a function of the rotation frequency of the traction motor shaft [10, 11]. Fourth, the motor shaft rotation frequency depends on the load, which, for the traction motor, is the wheelset of an electric locomotive. The load is affected by external factors, which are the condition and profile of a railroad track [12, 13]. Fifth, when moving from specific magnetic losses in motor steel, the geometric motor dimensions should be taken into consideration, in particular the intersection area and the volume of the armature yoke and teeth [14].

In addition, when designing traction motors, calculating these losses involves formulae most of which are empirical. It is very difficult to implement such a model using software packages. For the dynamic modes of operation, for example, when starting, braking, in the transition from one position of the driver controller to another, the performance of such a model would be incorrect. Consequently, the results of simulating dynamic processes in the traction drive of an electric locomotive, produced by such a model, would not be adequate.

Determining magnetic losses in the steel of a traction motor, which change over time, could make it possible to define with higher accuracy the spectral components in the traction current of an AC electric locomotive. This would make it possible to adjust the operation of the reactive power compensator control system to the operating modes of the

electric locomotive. This renders relevance to the subject of our research aimed at determining the instantaneous values of magnetic losses in motor steel.

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## 2. Literature review and problem statement

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Work [15] stated that modeling magnetic losses in electrical steel should consider a series of assumptions. The concept of loss division, based on the statistical loss theory, ensures a complete and accurate description of the frequency dependence of energy losses under the assumption of the uniform reverse magnetization through the cross-section of a sheet. However, this assumption is incorrect for nonlinear materials, at high induction values, and hysteresis contours [15].

The solution to this task, when predicting the losses in magnetic materials, is proposed in works [16, 17], based on a new model of dynamic energy hysteresis, which combines the statistical theory of losses and a static model of energy hysteresis. However, the cited works considered only a case where the magnetic field was shifted by DC, but the change in induction, as a function of the magnetization reversal frequency, has a sinusoidal shape. However, in a pulsed current motor, the magnetic field offset would be driven by a pulsed current. In addition, when one changes the motor shaft rotation frequency, the magnetization reversal frequency would also change. All these factors confirm that the shape of change in induction could be non-sinusoidal.

A solution to this task in the modeling of magnetic losses in electrical steel is reported in work [18], which considered magnetic losses in electrical steel at the triangular symmetrical and asymmetrical shapes of changes in induction. In the cited work, the shortcomings of the popular approach to calculating losses in inductive components, based on the empirical Steinmetz equation, are overcome by the generalized application of the statistical theory of losses and the associated concept of magnetic loss division. The work shows that this concept applies to both ferrites and metal alloys and hysteresis losses (quasi-static) and classical loss components. The authors related magnetic energy losses at the symmetrical triangular induction and sinusoidal induction. The behavior of losses at the asymmetric triangular induction was derived from the symmetrical one by averaging energy losses belonging to two different half-periods. However, the cited work considered only the case for a triangular shape of induction change.

Study [19] considered a generalized case for the non-sinusoidal induction change shape; the analytical expressions were built on the basis of the improved generalized Steinmetz equation to calculate magnetic losses in electrical steel at the above shapes of change in induction. Despite the correct statement of the problem, the cited study does not show the connection between magnetic losses in the steel of the motor with the geometry of the motor magnetic circuit, the connection between the universal magnetic characteristic and the load on a traction motor.

The above allows us to argue about the expediency of modeling magnetic losses in a traction motor steel. In addition, our analysis revealed that investigating the impact exerted by different modes of traction motors' operation on magnetic losses requires a new approach to the mathematical modeling of the electromagnetic processes in a pulsed current traction motor. That implies choosing a procedure for determining magnetic losses as a function of time, as well as adapting this procedure to the geometry and load of the traction motor.

### 3. The aim and objectives of the study

The aim of this study is to improve the procedure for determining power losses in a pulsed current traction motor based on the refined model of eddy and hysteresis losses in the steel elements of magnetic circuits.

To accomplish the aim, the following tasks have been set:

- to improve the procedure for calculating losses due to hysteresis and eddy currents in the armature of a traction motor;
- to design a simulation model of the magnetic losses in a pulsed current motor using the traction motor NB-418-K6 as an example.

### 4. The study materials and methods

#### 4.1. The study object and subject

The object of this study is the magnetization reversal processes in the steel elements of magnetic circuits in a pulsed current traction motor.

The subject of the study is the pulsed current traction motor in an electric locomotive. The prototype chosen for our research was the NB-418-K6 engine with the following technical parameters for the long-term operation mode:

- power, 740 kW;
- the rated armature rotation frequency, 915 rpm;
- power supply voltage, 950 V;
- efficiency, 94.8 %;
- the number of poles, 6.

For the rated mode of this motor, the following parameters were calculated based on the procedure given in [20]:

- the intersection area of the armature yoke and the armature teeth;
- the volume of the armature yoke and the armature teeth;
- the rated armature current.

The calculation results are given in Table 1.

Table 1

Results of calculating the NB-418-K6 motor parameters

Parameter	Parameter value
Armature yoke intersection area – $S_y$ , cm <sup>2</sup>	810
Armature teeth intersection area – $S_z$ , cm <sup>2</sup>	415
Armature yoke volume – $V_y$ , cm <sup>3</sup>	1,751.3
Armature teeth volume – $V_z$ , cm <sup>3</sup>	12,150
Armature rated current – $I_a$ , A	820
Pole pairs' number – $p$	3
Pair quantity of armature winding parallel branches – $a$	3
Quantity of armature winding active conductors – $N$	696

The yoke and armature teeth are made from electrotechnical steel, grade 1312, whose relative magnetic permeability ( $\mu_{r1}$ ) at a frequency of 50 Hz and induction of 1.8 Tl is equal to 2,400 [20].

#### 4.2. The study hypothesis

Underlying our study are the following hypotheses about the dependence of eddy and hysteresis power losses in the steel magnetic circuits in a pulsed current motor on the shape of the curve of change in the magnetic flux parameters over the period of magnetization reversal.

#### 4.3. Methods and models involved in the calculation of specific magnetic losses

Most models of losses due to eddy currents and hysteresis are based on the Preisach theory, whereby the losses in electrical steel are represented by a frequency function [10, 11]. However, in these studies, the equation of the model describing magnetic losses in an electrotechnical steel sheet is described as averages over the period of current fluctuations.

Work [21] analyzes the instantaneous values of magnetic losses in armature steel as a function of time over the period of fluctuations. The equations of specific losses take into consideration the accumulation of magnetic energy in steel. The reported equations could be used for any magnetic material and any geometry for which the properties of the material and magnetic flux density are known. Specific power losses in electrical steel on eddy currents and hysteresis, taking into consideration the accumulation of magnetic energy at the reduced magnetic permeability  $\mu_r=1$  as a function of time, according to [21], could be recorded in the form of the following equation

$$p_{loss}(t) = (H_c + K_{hyst} \cdot |B_p \cdot \sin(\omega t)|) \times |B_p \cdot \omega \cdot \cos(\omega t)| + K_{addy} \cdot B_p^2 \cdot \omega^2 \cdot \cos^2(\omega t), \quad (1)$$

where  $H_c$  is the coercive force, A/m;  $B_p$  is the induction amplitude, Tl;  $\omega$  is the magnetization reversal frequency, rad/s;  $t$  is the time, s;  $K_{hyst}$  is the coefficient taking into consideration specific losses due to hysteresis, A/(kg·s·Tl<sup>2</sup>);  $K_{addy}$  is the coefficient that takes into consideration specific losses due to eddy currents, W/(kg·s<sup>2</sup>·Tl<sup>2</sup>);  $p_{loss}$  is the specific power loss, W/m<sup>3</sup>.

Average losses in steel per unit of volume [21] are

$$\langle p_{loss}(t) \rangle = \left( \frac{2 \cdot H_c \cdot B_p}{\pi} + \frac{K_{hyst}}{\pi} \cdot B_p^2 \right) \cdot \omega + \frac{K_{addy}}{2} \cdot B_p^2 \cdot \omega^2. \quad (2)$$

The magnetization reversal frequency is determined from the expression given in [20]

$$\omega = p \cdot n_{eng}, \quad (3)$$

where  $p$  is the number of pairs of poles;  $n_{eng}$  is the electric motor shaft rotation frequency, rad/s.

The coefficients  $H_c$ ,  $K_{hyst}$ , and  $K_{addy}$  could be found in the specifications provided by manufacturers of electrical steel subject to approximation.

### 5. The study results

#### 5.1. Determining the coercive force and coefficients that take into consideration losses due to hysteresis and eddy currents

The specific specification-based losses in electrical steel 1312 are given in Table 2 [22].

In Table 2:  $f$  is the frequency, Hz;  $p_{p50}$ ,  $p_{M50}$ ,  $p_{p60}$ ,  $p_{M60}$  are, respectively, the specific losses in the electrical steel 1312 depending on frequency (50 and 60 Hz) – specification-based ( $p_{p50}$  and  $p_{p60}$ ) and data from the approximation ( $p_{M50}$  and  $p_{M60}$ ).

For ease of approximation, expression (2) is represented in the following form

$$p_{p50} = 4 \cdot H_c \cdot f \cdot B_p + (2 \cdot K_{hyst} \cdot f + 2 \cdot \pi^2 \cdot K_{addy} \cdot f^2) \cdot B_p^2. \quad (4)$$

Table 2

Specifications and data resulting from the approximation of specific losses in the electrical steel 1312

$B, \text{Tl}$		0	0.5	0.6	0.7	0.8	0.9	1.0	1.1
$f=50 \text{ Hz}$	$p_{p50}, \text{ W}$	0	0.755	1.085	1.472	1.782	2.17	2.558	3.115
	$p_{M50}, \text{ W}$	0	0.713	1.011	1.361	1.764	2.218	2.724	3.282
$f=60 \text{ Hz}$	$p_{p60}, \text{ W}$	0	0.953	1.335	1.811	2.192	2.669	3.146	3.832
	$p_{M60}, \text{ W}$	0	0.877	1.244	1.675	2.169	2.728	3.351	4.037
$B, \text{Tl}$		1,2	1.3	1.4	1.5	1.6	1.8	1.9	1.3
$f=50 \text{ Hz}$	$p_{p50}, \text{ W}$	3.798	4.573	5.348	6.123	6.975	7.673	8.525	9.688
	$p_{M50}, \text{ W}$	3.892	4.554	5.268	6.034	6.852	7.722	8.644	9.617
$f=60 \text{ Hz}$	$p_{p60}, \text{ W}$	4.671	5.624	6.577	7.531	8.579	9.437	10.486	11.916
	$p_{M60}, \text{ W}$	4.788	5.602	6.48	7.422	8.428	9.498	10.632	11.829

Expression (4) is a function of induction and the square of induction. It is approximated using a least-square method [23]. Since, according to Table 2, at a zero input value ( $B_p=0$ ), the value of the function  $p_{p50}=0$  in the equation based on a least-square method would lack a free term. Thus, expression (4) is represented in the following form

$$p_{M50} = a \cdot B_p + b \cdot B_p^2, \tag{5}$$

where  $a$  and  $b$  are the coefficients of approximation for a least-square method.

For the convenience of approximating using a least-square method, expression (5) is represented in the form

$$p'_{M50} = \frac{p_{M50}}{B_p} = a + b \cdot B_p, \tag{6}$$

The approximation yielded a value for the coefficients  $a=0.127 \text{ W}/(\text{kg}\cdot\text{Tl})$ ;  $b=2.597 \text{ W}/(\text{kg}\cdot\text{Tl}^2)$ .

Values of the specific losses at a magnetization reversal frequency of 50 Hz, obtained by using the approximating function, are given in Table 2. A deviation in the approximation data from the specifications was determined as follows

$$\delta_{50} = \frac{p_{p50} - p_{M50}}{p_{p50}} \cdot 100 \%. \tag{7}$$

To determine the unknown coefficients  $H_c, K_{hyst}, K_{addy}$  in equations (4), (5), we derived an additional equation by approximating specific losses in steel at a magnetization reversal frequency of 60 Hz. Our calculations were based on the following considerations. GOST 33212-2014 [22] gives specific losses at a magnetization reversal frequency of 50 Hz and an amplitude of induction of 1.0 Tl, as well as at a magnetization reversal frequency of 60 Hz and an amplitude of induction of 1.5 Tl. We calculated a transition factor to determine specific losses at a magnetization reversal frequency of 60 Hz, which was defined from the following expression

$$k_p = \frac{p_{1.5/60}}{p_{1.5/50}} = \frac{7.53}{6.123} = 1.23, \tag{8}$$

where  $p_{1.5/50}=6.123 \text{ W}/\text{kg}$  are the specific losses at a magnetization reversal frequency of 50 Hz and an amplitude of induction of 1.5 Tl (Table 2).

Considering the above, the specific losses at a magnetization reversal frequency of 60 Hz could be determined from the following ratio

$$p_{p60} = k_p \cdot p_{p50}. \tag{9}$$

The results are given in Table 2, according to which at a zero input value ( $B_p=0$ ) the value of the function  $p_{p60}=0$  in the equation using a least-square method would lack a free term. Thus, expression (4) is represented in the following form

$$p_{M60} = a_1 \cdot B_p + b_1 \cdot B_p^2, \tag{10}$$

For the convenience of approximation using a least-square method, expression (10) is represented in the following form

$$p'_{M60} = \frac{p_{M60}}{B_p} = a_1 + b_1 \cdot B_p, \tag{11}$$

where  $a_1$  and  $b_1$  are the coefficients of the approximating function by a least-square method for a frequency of 60 Hz.

The approximation using a least-square method yielded the values for the coefficients  $a_1=0.16 \text{ W}/(\text{kg}\cdot\text{Tl})$ ;  $b_1=3.29 \text{ W}/(\text{kg}\cdot\text{Tl}^2)$ .

Values of the specific losses at a magnetization reversal frequency of 60 Hz, derived by using the approximating function, are given in Table 2.

Based on the results given in Table 2, we constructed the charts of the dependence of specification-based specific losses in the electrical steel 1312 at frequencies 50 Hz and 60 Hz ( $p_{p50}$  and  $p_{p60}$ , respectively) and their approximation ( $p_{M50}$  and  $p_{M60}$ , respectively) (Fig. 1).

A root-mean square error of approximation was determined, calculated from the following expression:

$$\sigma_\delta = \sqrt{D_\delta} = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^N (\delta_{Mi} - \delta M_{mean})^2}, \tag{12}$$

where  $N$  is the number of approximation points;  $\delta_{Mi}$  is the error of approximation at the  $i$ -th point;  $\delta M_{mean}$  is the mean error value.

The rms error of approximation was 1.14 %, which indicates a high degree of reliability of our results.

Equations (4), (5) were used to derive an expression for the coercive force at 50 and 60 Hz:

$$H_c = \frac{a}{4 \cdot f} = 0.000634 \frac{\text{A}}{\text{kg} \cdot \text{m}}; \quad H_{c1} = \frac{a_1}{4 \cdot f} = 0.00065. \tag{13}$$

To determine the coefficients  $K_{hyst}$  and  $K_{addy}$ , we considered the system of equations (4), (5), and (4), (11).

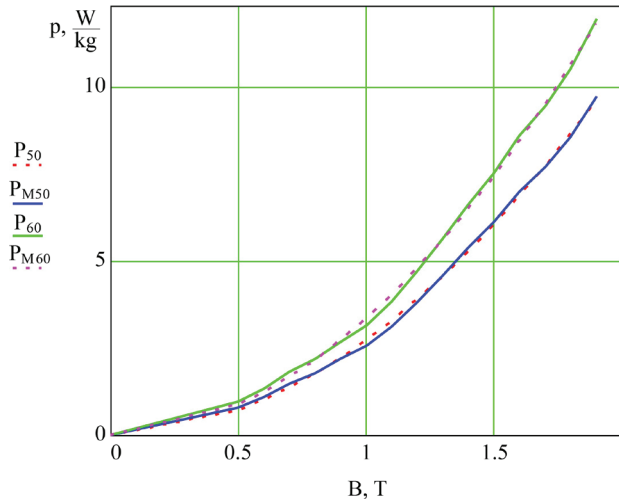


Fig. 1. Specific specification-based losses in electrical steel and approximation results for the magnetization reversal frequencies 50 and 60 Hz

It takes the following form:

$$\begin{cases} 2 \cdot K_{hyst} \cdot f + 2 \cdot \pi^2 \cdot K_{addy} \cdot f^2 = b, \\ 2 \cdot K_{hyst} \cdot f_1 + 2 \cdot \pi^2 \cdot K_{addy} \cdot f_1^2 = b_1, \end{cases} \quad (14)$$

where  $f=50$  Hz,  $f_1=60$ Hz.

The following values of the coefficients  $K_{hyst}$  and  $K_{addy}$  were obtained:  $K_{hyst}=0.018$  W/(kg·s·Tl<sup>2</sup>);  $K_{addy}=1.449 \cdot 10^{-5}$  W/(kg·s<sup>2</sup>·Tl<sup>2</sup>).

### 5.2. Calculation of induction in the structural elements made from electrical steel

To implement the model of magnetic losses in electrical steel (1), (2), it is necessary to find the amplitudes of inductions in nodes made from electrical steel – the armature yoke and teeth [20].

Magnetic induction in the armature yoke is determined from the following expression

$$B_a = \frac{2 \cdot \Phi_a}{S_a}, \quad (15)$$

where  $S_a$  is the intersection area of the armature yoke (Table 1);  $\Phi_a$  is the magnetic flux of the armature.

Magnetic induction in the armature teeth is determined from the following expression

$$B_z = \frac{\Phi_a}{S_z}, \quad (16)$$

where  $S_z$  is the intersection area of the armature teeth (Table 1).

The armature’s magnetic flux is determined from the universal magnetic characteristic of the traction motor.

### 5.3. Approximation of the universal magnetic characteristic of a traction motor

The universal magnetic characteristic of the traction motor NB-418-K6 is given in work [24]. In practice, it is more convenient to use the dependence of the electro-motive force (EMF), reduced to the motor shaft rotation frequency, as a function of the traction motor excitation current. That is

$$\frac{E}{n} = f(I_{ex}), \quad (17)$$

where  $E$  is the motor EMF, V;  $n$  is the motor shaft rotation frequency, rps;  $I_{ex}$  is the excitation current, A.

A traction motor EMF is calculated from the formula given in [24]

$$E = C_E \cdot n \cdot \Phi, \quad (18)$$

where  $\Phi$  is the magnetic flux of motor excitation, Wb;  $C_E$  is the structural motor coefficient for EMF, 1/s, which is determined from the expression given in [24]

$$C_E = \frac{p \cdot N}{a} = \frac{3 \cdot 696}{3} = 696 \frac{1}{s}, \quad (19)$$

where  $p=3$  is the number of pairs of poles;  $a=3$  is the number of pairs of parallel branches of the armature windings;  $N=696$  is the number of active armature winding conductors (Table 1).

Expression (16) is used to determine the magnetic flux of motor excitation

$$\Phi = \frac{E}{C_E \cdot n}. \quad (20)$$

We have recalculated from the universal magnetic characteristic the numerical values for building a dependence of EMF reduced to the motor shaft rotation frequency as a function of the excitation current of the traction motor NB-418-K6. Recalculations were based on the following conditions. The traction motor NB-418 K6 is a sequential excitation engine with a rated excitation degree of 95.7 %. That is

$$I_{ex} = 0.957 \cdot I_a. \quad (21)$$

When an electric locomotive runs, the rim of a wheelset moves at linear speed ( $v$ , m/s). The linear speed of the roll surfaces is the same for both wheels in the wheelset

$$v = \frac{\pi \cdot D \cdot n \cdot k_p}{60 \cdot \mu}, \quad (22)$$

where  $n$  is the motor shaft rotation frequency, 1/s;  $D=1.25$  is the wheel diameter, m;  $\mu=88:21$  is the gear ratio;  $k_p=0.975$  is the gear efficiency [25].

Then the motor shaft rotation frequency is

$$n = \frac{60 \cdot \mu \cdot v}{\pi \cdot D \cdot k_p}. \quad (23)$$

Our calculations were carried out for an unloaded mode of operation of an electric locomotive, that is, without a train. When switching to the operation of an electric locomotive with a load, the following formula should be used

$$\Phi_{el} = \frac{E}{C_E \cdot n} \cdot \frac{n}{n_{el}}, \quad (24)$$

where  $n$  is the motor shaft rotation frequency for the predefined excitation current when an electric locomotive operates without loading, rps;  $n_{el}$  is the motor shaft rotation frequency for the predefined excitation current when an electric locomotive operates with a load, 1/s.

Study [26] noted that in the approximation of a magnetic characteristic a high enough accuracy was demonstrated by the approximating functions based on arctangent functions. In addition, when choosing an approximating function, in addition to the high accuracy of the approximation, it is necessary to take into consideration the simplicity of implementing an approximating function. These requirements are met by the mathematical model of the reduced EMF, which takes the following form

$$\frac{E}{n} = p_1 \cdot \text{arctg}(p_2 \cdot I_{ex}) + p_3 \cdot I_{ex}, \quad (25)$$

where  $p_1, p_2, p_3$  are the coefficients of approximation.

The dependences  $E/n(I_{ex})$  and  $n(I_{ex})$  are shown in Fig. 2, 3.

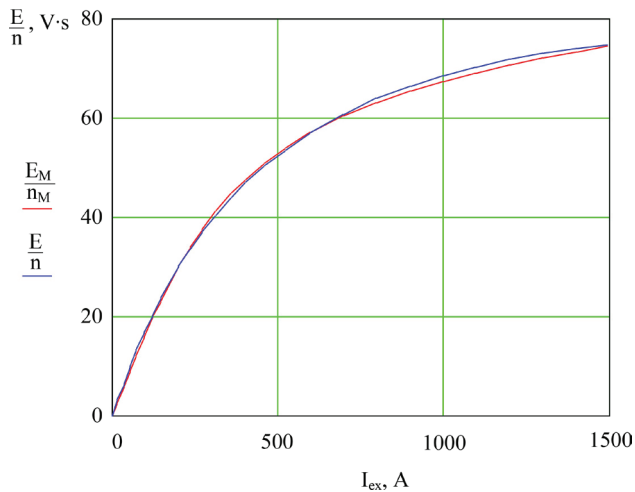


Fig. 2. Dependence of  $E/n$  of the traction motor NB-418-K6 on excitation current:  $E/n$  – specification data:  $E_M/n_M$  – the results of approximation

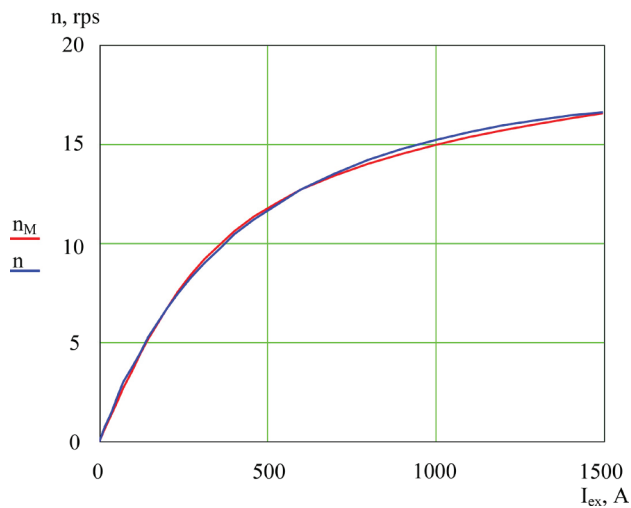


Fig. 3. Dependence of rotation frequency on excitation current at voltage  $U=950$  V:  $n$  – specifications:  $n_M/n$  – results of approximation

The approximation rms error was 0.98 %, which indicates a high degree of reliability of our results.

#### 5. 4. Calculation of total magnetic losses

Total magnetic losses are the sum of magnetic losses in an armature and the armature teeth. That is

$$P_{loss\Sigma}(t) = P_{lossY}(t) + P_{lossz}(t), \quad (26)$$

where  $P_{lossY}(t), P_{lossz}(t)$  are the magnetic losses in the core of the armature and the armature teeth, respectively. Similarly, the mean magnetic losses over a period are calculated

$$\langle P_{loss\Sigma}(t) \rangle = \langle P_{lossY}(t) \rangle + \langle P_{lossz}(t) \rangle, \quad (27)$$

where  $\langle P_{lossY}(t) \rangle, \langle P_{lossz}(t) \rangle$  are the mean magnetic losses in the core of the armature and the armature teeth, respectively.

The resulting magnetic permeability of the steel 1312 differs from 1 [20]. That is, to move from a generalized sheet of steel with the reduced magnetic permeability  $\mu_r=1$ , for which equations (1), (2) are recorded, to the sheet of the steel 1312 with permeability  $\mu_{r1}$ , equations (1), (2) are multiplied by  $\mu_{r1}$ .

The coefficients in equations  $H_c, K_{hyst},$  and  $K_{addy}$  (4) were determined for the specific power losses expressed in Wt/kg. To move to the losses expressed in W, equations (25) and (26) are multiplied by the weight of steel of the corresponding structural element of the motor. The weight of the steel of the structural element is determined from the following expression

$$m_i = \rho \cdot V_i, \quad (28)$$

where  $V_i$  is the volume of the structural element,  $m^3$ .

The instantaneous values of losses in the armature yoke and teeth, taking into consideration equation (1), take the following form:

$$P_{lossY}(t) = p_{loss}(t) \cdot \rho \cdot V_Y^2 \cdot \mu_{r1}, \quad (29)$$

$$P_{lossz}(t) = p_{loss}(t) \cdot \rho \cdot V_z^2 \cdot \mu_{r1}, \quad (30)$$

where  $\rho=7,750$   $kg/m^3$  is the specific weight of the electrical steel 1312;  $V_Y, V_z$  are the volumes of steel in the armature yoke and teeth, respectively,  $m^3$  (Table 1).

Similarly, the mean magnetic losses were found

$$\langle P_{lossY}(t) \rangle = \langle p_{loss}(t) \rangle \cdot \rho \cdot V_Y^2 \cdot \mu_{r1}, \quad (31)$$

$$\langle P_{lossz}(t) \rangle = \langle p_{loss}(t) \rangle \cdot \rho \cdot V_z^2 \cdot \mu_{r1}, \quad (32)$$

where  $\langle p_{loss}(t) \rangle$  are the specific losses in steel, calculated from expression (2);  $\mu_{r1}=2,400$  is the relative magnetic permeability of the steel 1312 at a frequency of 50 Hz and induction  $B=1.82$  Tl [20].

#### 5. 5. Simulation model of magnetic losses in the steel of a pulsed current traction motor

The study of magnetic losses in the traction motor’s steel began by determining the magnetic flux of the traction motor armature, which is defined from expression (23). To this end, based on expression (24), we approximated the reduced EMF and the shaft rotation frequency and combined them into one block “Magnetic flux detection unit”.

The next step of our simulation involved the calculation of inductions in the armature yoke and teeth based on expressions (14), (15).

The elements in the calculation of inductions in the structural elements of a traction motor were combined into one block “Block of induction calculation”.

The estimation of time-dependent steel losses based on equations (28), (29) and the calculation of average losses in steel over a period from equation (30), (31), “Block of total loss calculation”.

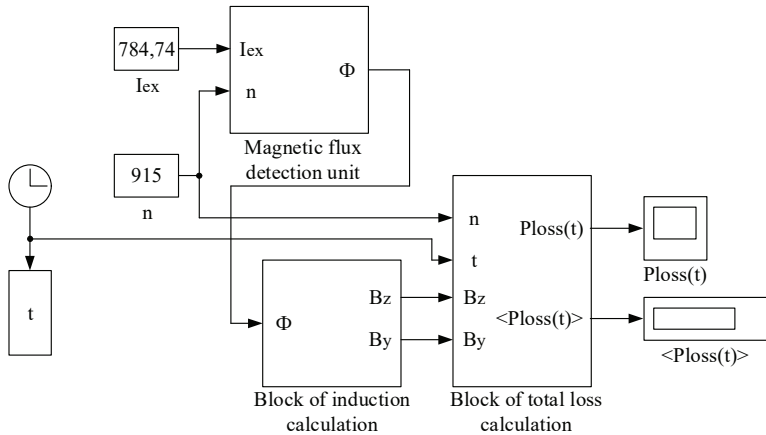


Fig. 4. Simulation model for calculating magnetic losses in a pulsed current traction motor

The general simulation model for calculating magnetic losses in a pulsed current traction motor is shown in Fig. 8.

The simulation model shown in Fig. 4 could be used to analyze magnetic losses in a traction motor’s steel. Using a constant  $I_{ex}$ , it sets the value of the excitation current in a traction motor. The time dependences of magnetic losses are displayed at an oscilloscope as  $P_{loss}(t)$ ; the mean losses over a period – in the measurement block  $\langle P_{loss}(t) \rangle$ .

For the rated values of the excitation current and the rated motor shaft rotation frequency, the model (Fig. 4) produced the average value of magnetic power losses (7,800 W). We also derived the dependences of instantaneous values of the magnetic power losses in steel on time. The dependences are shown in Fig. 5.

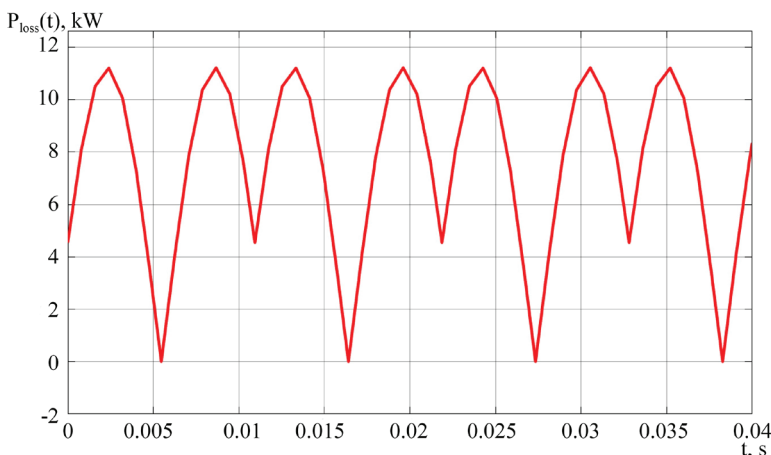


Fig. 5. Dependences of the instantaneous values of magnetic power losses in steel on time using the traction motor NB-418-K6 as an example

### 6. Discussion of results of modeling magnetic losses in a traction motor’s steel

The accuracy of the calculation of losses in an engine could be evaluated by comparing the estimated efficiency of the motor against its specification value. Work [20] analyzed the calculations of losses in the motor of series NB418K6

based on several known procedures. Table 3 gives the results of comparing the estimated data, obtained by different procedures, with the specifications. Table 3 also gives the value of the efficiency calculated according to the procedure proposed in this work.

Table 3

The efficiency of the traction motor, series NB418K6, calculated by known procedures

Estimated efficiency of traction motor, $\eta$ %	Error in determining the efficiency $\delta_{\eta}$ %	Source
94.00		Specifications
93.78	-0.23	[27]
94.05	0.05	[28]
94.14	1.5	[29]
94.02	0.02	[30]
94.09	0.09	[31]
93.64	-0.38	[32]
94.00	0.00	Procedure by this paper’s authors

The analysis of the results given in Table 3 shows that our proposed procedure is more accurate compared to known ones. The high accuracy was achieved by taking into consideration a series of factors that were disregarded by available techniques.

Thus, when calculating magnetic losses in the steel of a traction motor, other procedures accounted for the loss on the accumulation of magnetic energy by the introduction of correcting coefficients. The expression for determining the average magnetic losses (2), namely its component  $(2 \cdot H_c \cdot B_p \cdot \omega) / \pi$ , makes it possible to accurately calculate these losses. In expression (2), the coercive force ( $H_c$ ), the loss factor on eddy currents ( $K_{addy}$ ), and the loss factor for hysteresis ( $K_{hyst}$ ) make it possible to establish a link between the specific losses of electrical material and magnetic losses.

That is, one could consider the simulation model of magnetic power losses in the steel of a traction motor adequate with a high degree of reliability.

The proposed improved procedure for calculating losses due to the hysteresis and eddy currents in a pulsed current traction motor is based on the representation of magnetic transformations in the steel elements of the motor in the form of a stationary deterministic process. According to these ideas, the total losses on hysteresis, eddy currents, and the accumulation of magnetic energy are considered as the functions of time (1). In the process of research, we have found a confirmation of the hypothesis about the dependence of the eddy and hysteresis losses of motor power on the shape of the magnetic flux change curve (15), (16), as well as inductiveness (1), (2), during the period of magnetization reversal.

The procedure for building a model of magnetic losses makes it possible to investigate magnetic processes under any modes of operation of engines (24). The advantage of the proposed technique is the possibility to analyze the current

(instantaneous) values of a series of time-dependent parameters of the motor magnetic system (1).

The adaptation of the model by taking into consideration the magnetic properties of the material and the geometry of the magnetic circuit of a traction motor ((29) to (32)) contributed to improving the accuracy of the model.

The simulation model built on the basis of the proposed methodology makes it possible to investigate magnetic losses for any magnetic system with known materials properties and law of change in the density of magnetic flux. In addition, the model takes into consideration the geometry of magnetic circuit chains and makes it possible to determine both average, over a period (2), and instantaneous values of magnetic losses (1).

The model is built using the traction motor NB-418-K6 as an example. The adequacy of modeling was assessed by the accuracy in determining the magnetic losses relative to the specifications (Table 3). Our calculations have confirmed the high accuracy of the proposed model.

However, as noted, the proposed procedure assumes the stationarity of the magnetization reversal process in the steel of a motor, which imposes a certain limitation for its use. For cases of the non-stationary, non-deterministic nature of a voltage change, additional research is needed. At the same time, we realize the difficulties associated with acquiring experimental data in the operation of an electric locomotive. This study could be advanced in the following ways:

- to study traction drive operation in an AC electric locomotive equipped with DC traction motors;
- to investigate the impact of the modes of operation of electric locomotives (starting and decelerating a train, transition from one position of the driver controller to another, towing, slip) on the energy indicators of a traction drive equipped with pulsed current traction motors.

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## 7. Conclusions

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1. We have improved a procedure for calculating losses due to the hysteresis and eddy currents in the armature of a traction motor. Underlying the improvement is a new approach to representing magnetic transformations in the steel elements of the motor. This approach implies the possibility to analyze the current (instantaneous) transformations of magnetic loss parameters during the period of magnetization reversal. This distinguishes our methodology from those known that estimate magnetic losses based on the average values over a magnetization reversal period.

2. The designed simulation model of magnetic losses in the traction motor NB-418-K6 has demonstrated the advantages of the proposed procedure compared to known ones in terms of the accuracy of approximation of the estimated characteristics of losses to those given in specifications. In particular, as regards the motor's overall efficiency coefficient, the result that we obtained fully coincides with its specification-based characteristics.

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