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Article

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DETERMINATION OF INDUCTANCES FOR PULSATING CURRENT TRACTION MOTOR

The object of research is a pulsating current traction motor. To improve the accuracy of its mathematical model, it is necessary to use the values of the parameters that are determined in experimental studies of the electric motor. In particular, it is important to use in the model of the electric motor inductance obtained experimentally. A method is proposed for calculating the inductance of the armature winding, main poles, additional poles and compensation winding and the total inductance of the traction motor armature circuit. The calculations are based on the results of the indirect inductance measurement method, in which the electrical values of various modes of power supply of the electric motor windings are directly measured, and the inductances are determined by auxiliary calculations. The inductances of the traction motor armature circuit have a non-linear dependence on the current flowing through them. The main difference of the study is that the measurements of the electrical parameters required for calculating the inductance are carried out over the entire range of operating currents of the windings. The essence of the proposed technique is to measure the active power in the armature winding, the winding of the main and additional poles, and the compensation winding, as well as in the armature circle as a whole when they are supplied with alternating current. According to the obtained values of active power losses and phase displacement, the corresponding reactive power losses are determined, with the help of which the inductances of the motor windings are calculated. Approbation of the methodology for calculating the conduction inductance for an electric motor of a pulsating current NB-418K6 (country of origin Russia), is used on electric locomotives of the VL80T and VL80k series (country of origin Russia). A scheme for measuring electrical parameters necessary for calculating inductance is proposed. The graphical dependences of the inductance on the armature current, built on the basis of calculations, confirmed the hypothesis about the nonlinear dependence of these inductances on the armature current. For further application of the results obtained in the simulation of the operation of the traction electric motor NB-418K6, a polynomial approximation of the total inductance of the armature circuit was performed.

Keywords: *pulsating current traction motor, armature current, total inductance of the armature winding.*

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1. Introduction

The study of dynamic processes in the traction drive of electric locomotives requires the construction of an adequate model of the drive, with the help of which it would be possible to determine certain characteristics of the drive with a high degree of reliability [1]. The traction motor is an integral part of the traction drive. In a number of AC electric locomotives, pulsating current motors are used as traction motors. Certain difficulties arise when simulating a pulsating current motor. They are related to the fact that some of the engine parameters are provided by the manufacturer, and some must be calculated. The parameters provided by the manufacturer include the active resistances of the motor windings. The moment of inertia and inductance of the field winding can be determined from the geometrical dimensions of the motor [2] and the magnetization curve [3], respectively. The question remains regarding the definition of the inductance of an electric motor, namely: armature winding, main poles, compensation winding and additional poles. In a number of works, these values are calculated for the nominal mode and the data obtained are used in modeling [4, 5]. But the indicated inductances are nonlinear functions of the armature current [6, 7].

Therefore, it is not correct to use a certain fixed inductance value for one mode. Thus, determining the inductance of a pulsating current traction motor is an urgent task. *The object of research* is a pulsating current traction motor. *The aim of research* is to determine the inductance of a pulsating current traction motor as a function of the armature current.

2. Methods of research

The research is based on the approaches given in [8, 9], which indicate that the inductances of an electric motor are nonlinear functions of current. Based on the analysis of the work, taking into account the methodology for measuring the inductance, the proposed circuit for measuring the inductance of a pulsating current traction motor (Fig. 1). When measuring inductance, an indirect measurement method is proposed. The constant voltage U sets the saturation of the corresponding windings. An alternating voltage ~U with a frequency f=50 Hz is used to obtain the parameters necessary for calculating the inductance of the corresponding windings. Since a non-sinusoidal current flows in the circuit, it is recommended to use a spectrum analyzer to isolate the fundamental current harmonic ($f1$=50 Hz).

Inductance measurement technique:

Stage 1. The range of change of the armature current I_a and the step of its change ΔI_a are selected.

Stage 2. A single-phase voltage U with a frequency of 50 Hz is supplied such that the current in the armature circuit I_a would correspond to the initial value. The value of the armature circuit current is monitored using an ammeter A.

Stage 3. With the help of wattmeters W1, W2, W3, the values of active power $P_{1-1'}$, $P_{2-2'}$, $P_{3-3'}$ are obtained, respectively. With the help of phase meters φ1, φ2, φ3 and the phase shift between the armature current and the voltage drop in corresponding points of the circuit (Fig. 1) $\varphi_{1-1'}$, $\varphi_{2-2'}$, $\varphi_{3-3'}$.

Stage 4. Based on the obtained values of the active power and the phase shift between currents and voltages for the corresponding points on the diagram (Fig. 1), reactive powers are calculated for these points by the expression:

$$Q_{i-i'} = P_{i-i'} \cdot \mathrm{tg}\varphi_{i-i'},$$

where $P_{i\text{-}i'}$ – active power between points $i\text{-}i'$, W; $\varphi_{i\text{-}i'}$ – phase shift between armature current and voltage drop at point $i\text{-}i'$, deg.

Step 5. Inductive resistances are calculated for each measuring point in accordance with the expression:

$$x_{i-i'} = \frac{Q_{i-i'}}{I^2},$$

where I – current in the armature circuit, A.

Stage 6. The inductances of the main poles (L_{mp}), additional poles and the compensation winding (L_{ap+cw}), the total inductance of the armature circuit (L_a), the inductance of the armature winding (L_{aw}), H are calculated:

$$L_{mp} = \frac{x_{3-3'}}{2\cdot\pi\cdot f};\ L_{ap+cw} = \frac{x_{2-2'} - x_{3-3'}}{2\cdot\pi\cdot f};$$

$$L_a = \frac{x_{1-1'}}{2\cdot\pi\cdot f};\ L_{aw} = \frac{x_{1-1'} - x_{2-2'} - x_{3-3'}}{2\cdot\pi\cdot f},$$

where f – supply voltage frequency, Hz.

Stage 7. By changing the value of the supply voltage U, the next value of the armature current is set, greater by a step of its change ΔI_a. Stages 3–6 are repeated until measurements are taken for the entire armature current range.

The proposed technique and measurement scheme are means for the experimental obtaining of the dependences of the inductance of the armature circuit of the pulsating current motor on the armature current.

3. Research results and discussion

As an example, a pulsating current motor NB-418K6 (country of origin Russia) was chosen, it is used as a traction motor for electric locomotives of the VL-80K and VL-80T series (country of origin Russia). The initial values are: the range of the armature current and the step of the armature current. The armature current variation range was selected based on the following considerations. The rated current of the NB-418K6 motor is 720 A. The traction motor mainly operates in modes (except for the starting mode of the electric locomotive, where the current is slightly higher than the rated one) when the armature current is less than the rated one. Therefore, the range of variation of the armature current was chosen slightly more than the nominal value (I_a=1000 A), and the step of its variation I_a=25 A. In accordance with the proposed method, the necessary electrical values were removed and the inductances of the traction motor armature circuit were calculated for each step of the armature current change. The calculation results are listed in Table 1.

According to the results of the Table 1 let's plot the dependences of the values of the inductance of the armature winding (L_{aw}), the main poles (L_{mp}) and additional poles and the compensation winding (L_{ap+cw}) on the values of the armature current (I_a) (Fig. 2).

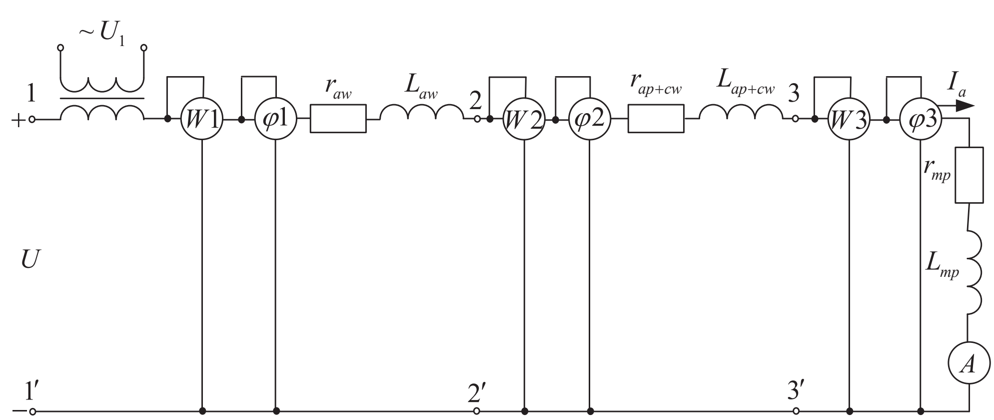

Fig. 1. Scheme for measuring inductance in the armature circuit of a pulsating current traction motor: r_{aw}, r_{ap+cw}, r_{mp} – active resistances of the armature winding, additional poles and compensation winding, main poles, respectively; L_{aw}, L_{ap+cw}, L_{mp} – inductance of armature winding, auxiliary pole winding and compensation winding and main poles, respectively

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Table 1

Dependences of the values of the inductance of the armature winding (L_{aw}), the main poles (L_{mp}) and additional poles and the compensation winding (L_{ap+cw}) and the total inductance of the armature circuit on the values of the armature current (I_a)

Armature curren, I_a, A	Inductance, H					Approximation error, |δ|, %
	armature windings, L_{aw}	main poles, L_{mp}	additional poles and compensation winding, L_{ap+cw}	full armature chain, L_a	approximation of the inductance of the armature circuit, L_{an}	
0	0.00007	0.00314	0.0008	0.00401	0.004003	0.174564
25	0.00007	0.00313	0.00077	0.00397	0.003993	0.579345
60	0.00007	0.00312	0.00073	0.00392	0.0039	0.510204
75	0.00008	0.00311	0.0007	0.00389	0.003877	0.33419
100	0.000095	0.0031	0.000665	0.00386	0.003856	0.103627
125	0.00011	0.003075	0.00063	0.003815	0.003835	0.524246
150	0.00013	0.00305	0.00059	0.00377	0.0038	0.795756
175	0.00015	0.003025	0.00055	0.003745	0.00374	0.133511
200	0.00017	0.003	0.00051	0.0037	0.00368	0.540541
225	0.00019	0.00295	0.000475	0.00363	0.00361	0.550964
250	0.000205	0.0029	0.00044	0.003555	0.00354	0.421941
275	0.000215	0.00285	0.000405	0.00348	0.00348	0
300	0.000225	0.0028	0.00037	0.0034	0.003412	0.352941
325	0.00023	0.00272	0.00034	0.00329	0.003328	1.155015
350	0.00023	0.00265	0.00032	0.0032	0.003217	0.53125
375	0.00023	0.00254	0.00031	0.00308	0.003073	0.227273
400	0.00023	0.0024	0.0003	0.00293	0.002893	1.262799
425	0.00023	0.00216	0.0003	0.00269	0.00268	0.371747
450	0.00023	0.00192	0.0003	0.00245	0.002445	0.204082
475	0.00023	0.00168	0.0003	0.00221	0.002203	0.316742
500	0.00023	0.00144	0.0003	0.00197	0.00197	0
525	0.00023	0.0012	0.0003	0.00173	0.00176	1.734104
550	0.00023	0.00103	0.0003	0.00156	0.001585	1.602564
575	0.00023	0.00093	0.0003	0.00146	0.001453	0.479452
600	0.00023	0.000840	0.0003	0.00137	0.001363	0.510949
625	0.00023	0.00079	0.0003	0.00132	0.00131	0.757576
650	0.00023	0.00077	0.0003	0.0013	0.001287	1
675	0.00023	0.00076	0.0003	0.00129	0.00128	0.775194
700	0.00023	0.00075	0.0003	0.00128	0.001281	0.078125
725	0.00023	0.00074	0.0003	0.00127	0.00128	0.787402
750	0.00023	0.00073	0.0003	0.00126	0.001273	1.031746
775	0.00023	0.000720	0.0003	0.00125	0.00126	0.8
800	0.00023	0.00072	0.0003	0.001245	0.001245	0
825	0.00023	0.00071	0.0003	0.00124	0.001231	0.725806
850	0.00023	0.0007	0.0003	0.00123	0.001222	0.650407
875	0.00023	0.00069	0.0003	0.00122	0.001218	0.163934
900	0.00023	0.00068	0.0003	0.00121	0.001215	0.413223
925	0.00023	0.00067	0.0003	0.0012	0.001207	0.583333
950	0.00023	0.00066	0.0003	0.00119	0.001191	0.084034
975	0.00023	0.00065	0.0003	0.00118	0.001172	0.677966
1000	0.00023	0.00064	0.0003	0.00117	0.001173	0.25641

The nature of the change in the inductance of the armature winding, the main poles and additional poles and the compensation winding from the change in the armature current (Fig. 2) confirmed the hypothesis of the nonlinear nature of these dependencies.

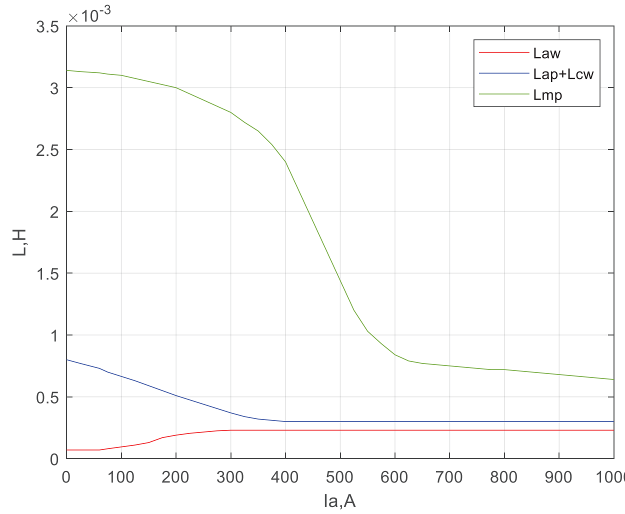

Fig. 2. Dependences of the inductance of the armature winding (L_{aw}), the main poles (L_{mp}) and additional poles and the compensation winding (L_{ap+cw}) on the armature current (I_a)

The obtained inductances, as a function of the armature current, can be useful in modeling the diagnostic systems of the pulsating current traction motor [10]. For modeling a traction motor in order to study electromagnetic processes in its circles, the dependence of the total inductance of the armature circuit on the armature current will be more useful (Fig. 3). As can be seen from Fig. 3, the dependence of the total inductance of the armature circuit on the armature current is also non-linear.

For the convenience of implementing the simulation model, an approximation of the total inductance of the armature circuit is performed. The approximation was performed by a 12th degree polynomial [11], since in software packages this type of approximation is the most convenient for implementation, and the 12th degree polynomial showed a fairly high degree of convergence of the results.

The resulting approximating function has the form:

$$L_{an} = -1.022\cdot10^{-34}\cdot(I_a)^{12} + 6.704\cdot10^{-31}\cdot(I_a)^{11} -$$
$$-1.916\cdot10^{-27}\cdot(I_a)^{10} + 3.131\cdot10^{-24}\cdot(I_a)^{9} -$$
$$-3.221\cdot10^{-21}\cdot(I_a)^{8} + 2.169\cdot10^{-18}\cdot(I_a)^{7} -$$
$$-9.627\cdot10^{-16}\cdot(I_a)^{6} + 2.776\cdot10^{-13}\cdot(I_a)^{5} -$$
$$-5.006\cdot10^{-11}\cdot(I_a)^{4} + 5.244\cdot10^{-9}\cdot(I_a)^{3} -$$
$$-2.782\cdot10^{-7}\cdot(I_a)^{2} + 3.967\cdot10^{-6}\cdot I_a + 0.00401,$$

for which the values of the approximating function are calculated. The data obtained are listed in Table 1. For the obtained approximation data, a graph of the approximating function is constructed (Fig. 3). The standard deviation of the approximation error of the total inductance from the armature current is calculated by the formula:

$$\sigma = \sqrt{\frac{1}{N}\cdot\sum_{i=1}^{N}\left(|\gamma_{av}|-|\gamma_i|\right)^2} = 0.39\ \%,$$

where γ_{av} – arithmetic mean of the error of determining the total inductance using the approximating polynomial.

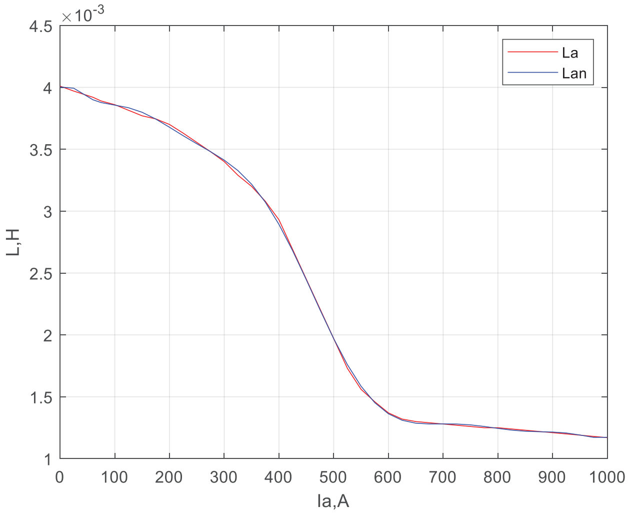

Fig. 3. Dependence of the total inductance (L_{aw}) and the approximating function (L_{an}) on the armature current (I_a)

The obtained value of the standard deviation of the error of approximation of the total inductance from the armature current, as well as the construction of the graphs shown in Fig. 3, indicate the high reliability of the approximation results.

4. Conclusions

A scheme for measuring the inductance of a pulsating current electric motor by an indirect method is proposed. A method is proposed for calculating the inductance of the traction motor armature circuit based on the measured electrical values. Dependences of the inductance of the electric motor as a function of the armature current are obtained on the basis of the proposed technique for the NB-418K6 traction motor. The approximation of the dependence of the total inductance of the armature circuit as a function of the armature current by a fifth-order polynomial is carried out. Calculation of the root-mean-square deviation of the approximation error of the total inductance of the armature circuit showed a high convergence of the approximation results with the calculated data. The average deviation did not exceed 0.04 %.

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