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Sergey Goolak - Juraj Gerlici - Viktor Tkachenko - Svitlana Sapronova - Tomas Lack - Kateryna Kravchenko*

DETERMINATION OF PARAMETERS OF ASYNCHRONOUS ELECTRIC MACHINES WITH ASYMMETRICAL WINDINGS OF ELECTRIC LOCOMOTIVES

This article is devoted to development of a method for calculating the parameters of an asynchronous motor of an electric locomotive with asymmetrical windings of stator and rotor. A method for determining self and mutual inductances of the stator and rotor phases of an asynchronous motor with asymmetric windings and their relations to mechanical variables is proposed. It is based on comparing two equations of stored magnetic energy, one equation calculated through induction, magnetic field strength and geometrical dimensions and another equation calculated through the parameters of the motor circuits. It is shown that the obtained solutions correspond to the previously existing methods, but they give the additional possibilities in mathematical modeling. The proposed technical solution allows higher accuracy developing of a mathematical model of a drive with an asynchronous motor having asymmetrical stator and rotor windings for studying dynamic processes during the operation of the specified drive, in particular, the drive of auxiliary machines for electric locomotive, where an asynchronous motor with asymmetrical stator windings is used as a phase release.

Keywords: *magnetic field induction, mutual inductance, self-inductance, magnetic field strength*

1. Introduction

The search for effective methods for obtaining a picture of dynamic processes in an electric drive with an asynchronous electric motor and the study of the operating modes of electric machines for specific technical applications require a reasonable choice of the most appropriate method for the given case of mathematical modeling of the indicated electric drives. Considering the possibility of building a mathematical model of an asynchronous electric machine, it is necessary to take into account that such a selection should assume the possibility of accounting a number of assumptions [1-7]. First, it shall be deemed that the system of voltage of the asynchronous motor is symmetrical and sinusoidal and the stator and rotor windings are symmetrical. It is also necessary to assume that the stator and the rotor of the asynchronous machine are smooth.

In this regard, one interesting circumstance should be noted. Although the actual supply voltage system is asymmetric and non-sinusoidal and stator and rotor windings of the asynchronous motor are not always symmetrical, the methods for asynchronous machines modeling, when the stator and the rotor windings are symmetrical and the power supply system is sinusoidal, are widely used. The works on the asynchronous machines modeling can be a proof of the same [8-13]. The mathematical models, obtained with the help of these methods, allow to investigate dynamic processes in electric drives with asynchronous motors and to study the operating modes of electric machines under the condition of symmetry of the stator and the rotor windings and with a high-quality power supply system of the electric machine. This is an evidence that the topic of researches devoted to the development of mathematical models of asynchronous motors with asymmetrical windings and with asymmetry and non-sinusoidal of the supply voltage system, as well as the development of methods for determining the parameters of an asynchronous motor applied in these models, is relevant.

2. Analysis of methods for determining the parameters of asynchronous motors

When building each of the models of an asynchronous motor analyzed in [1-13], its own system of motor parameters is required, and, respectively, its own method of determining these parameters.

Calculations of parameters using catalog and reference data of an asynchronous motor have a large inaccuracy and can only be used for the qualitative assessment of the energy, operating and mechanical characteristics of the motor [14]. The calculation of the parameters according to the results of the experiments is highly accurate and can be used to assess the energy efficiency of asynchronous motors, but with the time invariant parameters of asynchronous motors. With an asymmetrical non-sinusoidal power supply system, stator winding induction harmoniously depends on the angle between the phase currents of the stator and the rotor. This angle is variable in the conditions of a poor voltage supply system. This imposes certain restrictions on the use of the solutions proposed in [14]. The method of determining parameters with reference to a specific time interval is based on

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* [1]**Sergey Goolak**, [2]**Juraj Gerlici**, [1]**Viktor Tkachenko**, [3]**Svitlana Sapronova**, [2]**Tomas Lack**, [2]**Kateryna Kravchenko**
[1]Department of Traction Rolling Stock, State University of Infrastructure and Technologies, Kyiv, Ukraine
[2]Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Zilina, Slovak Republic
[3]Department of Carriages and Carriage Economy, State University of Infrastructure and Technologies, Kyiv, Ukraine
E-mail: goolak@duit.edu.ua

the processing and recording of available information about a motor such as phase currents and voltages [15]. It provides the ability to select the desired method of determining parameters with reference to time for a specific type of motor model. However, the following question remains, i.e. what parameters of an asynchronous motor can be determined having an information about phase currents and voltages, which is relevant for creating a mathematical model of an asynchronous motor under conditions of power supply from the system with a source of poor-quality electrical energy.

In [16], mathematical relations between the parameters of an asynchronous motor and its phase currents and voltages are given for a model of a generalized two-phase asynchronous machine for coordinates α - β, d - q. But the mathematical tool and the algorithm of its use for determining motor parameters are provided only conceptually. It has been mentioned above that the models in coordinates d - q and x - y are strictly connected to the field speed of the stator or rotor and can be used only in the case of powering the stator with only sinusoidal voltage.

In [17], the authors adapted the model of an asynchronous motor in coordinates d - q to a non-sinusoidal voltage supply by switching from the model in coordinates a, b, c to model in d - q by applying the Park's transformation. The transition to the model in a, b, c from model in coordinates d - q is carried out using the inverse Park's transformation. Model parameters are calculated using equivalent - T. The calculation of the parameters of an asynchronous motor for equivalent - T is given in [18], it does not take into account such phenomena as displacement of the rotor current, steel loss and magnetic circuit saturation. In the study [19], a method was developed for determining the parameters from the catalog data using an equivalent scheme for an asynchronous motor taking into account current displacement and capacity losses of steel, but the authors did not consider the phenomenon of saturation of the motor magnetic circuit. This problem is considered in [20], where reactivity is scrutinized as a function of the saturation level of the magnetic circuit.

The solutions obtained in [18-20] allow one to determine parameters of an asynchronous motor, but under the condition that its stator and rotor windings are symmetrical. The operation of an asynchronous motor with electric or magnetic asymmetry of the stator windings leads to an uneven distribution of losses in copper through the stator phases and the occurrence of variable components of the electromagnetic moment and power consumption [21].

The asymmetry of active resistances and inductances can be considered as their deviation from similar parameters when motor windings are symmetrical [22]. This algorithm will allow us to calculate and build a model of an asynchronous motor with asymmetry of windings. But the question regarding the calculation of parameters of asynchronous motors, which are powered from a single-phase power supply network, which is important for the class of asynchronous motors, used to break down a single-phase power supply system into a three-phase one, still remains open.

In [23] it was assumed that a single-phase motor for transforming parameters could be represented as an ideal transformer and the coefficient of voltage deviation from the symmetrical mode was replaced by the ratio of voltages. However, the mathematical tool and the algorithm of its application are given only conceptually in [23-24].

Determining the parameters of asynchronous motors in the specified modes powered by a single-phase network allows one to build a mathematical model to find the energy, mechanical and performance characteristics of this motor in the given mode with a great accuracy [25]. Due to asymmetry, not only transient processes, but also the established modes are dynamic, therefore, in any coordinate system, they are described by differential equations. To obtain static parameters as a function of a variable, this system is differentiated analytically, after which it is integrated numerically with respect to this variable. When performing differentiation, there may be a question of method convergence. In addition, this technique does not show the dependence of inductance on the geometrical dimensions of the corresponding windings, which is important when the windings of an asynchronous motor are asymmetrical.

When modeling the drive for auxiliary machines of electric locomotives of the series VL-80^{T,K}, the phase release, which is an asynchronous motor with a square-cage rotor powered by a single-phase network, can be replaced by a system of asymmetric voltage sources [26]. To set the asymmetry of voltage sources, vector diagrams of currents and voltages shall be built and the asymmetry parameters shall be determined using a vector diagram of voltages. For building of diagrams, it is necessary to know such parameters of a real asynchronous machine as the active resistances of the stator and rotor windings and the self and mutual inductances of these windings.

The proposed method for determining the phase and mutual inductances of an asynchronous motor can be applied during the modeling of dynamic processes of drives with asynchronous motors, which have asymmetrical stator and rotor windings and can be powered by poor quality power systems, in particular, to simulate dynamic processes for drive of auxiliary machines of electric locomotives of the VL-80^{T,K} series.

3. Development of requirements for the magnetic structure and phase zones arrangement in a generalized model of an asynchronous motor

Consideration of electric machines in the article is based on the fundamental assumption that machines can be represented by linear circuit systems with lumped parameters that move relative to each other. Since the two elements of the electric machine (the stator is a fixed element, the rotor is a rotating element) are in relative motion, the question arises about the choice of a suitable coordinate system for recording the equations of motion. There is some freedom in choosing a coordinate system for studying any specific devices and a specific task and the desired form of equations of motion usually dictate this choice. The true coordinates shall be used when choosing the Lagrange function to record the equations of motion [27].

In practice, various methods of electric machines building are used, one of which is shown in Fig. 1 [28]. The considered machine consists of six groups of concentrated coils (one coil per group is shown), which are called phase zones. Three of these phase zones are located in the slots of the static magnetic system

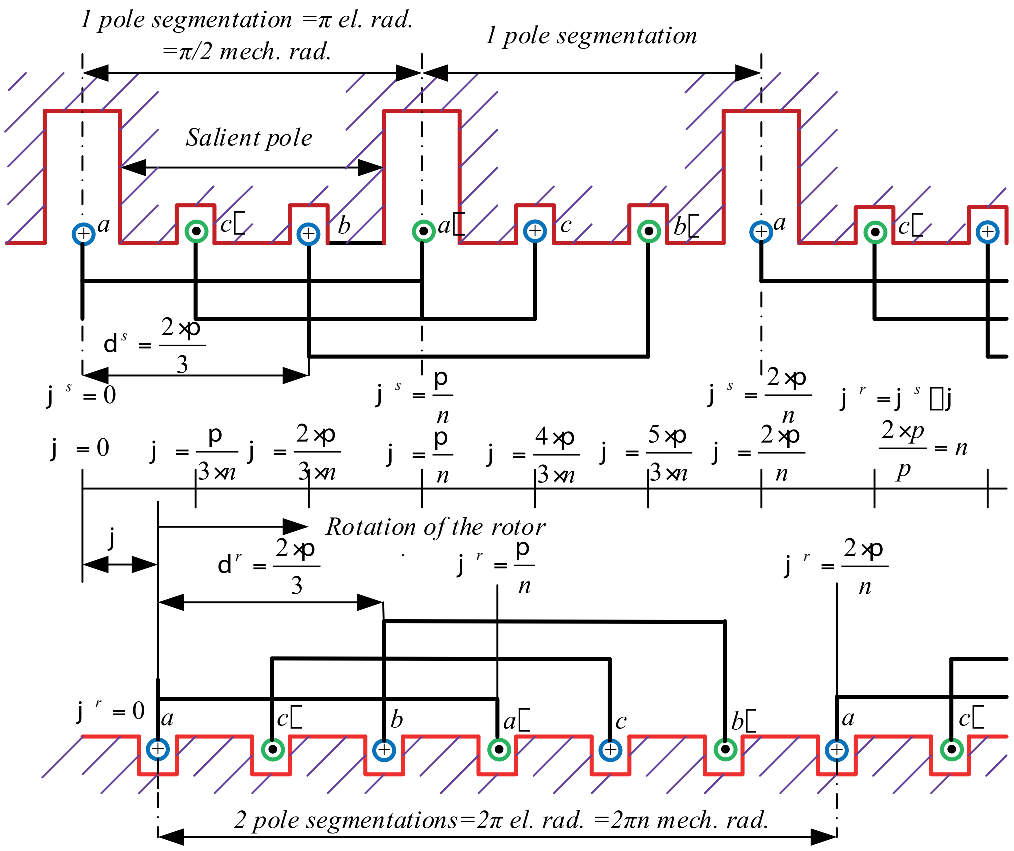

***Figure 1** The salient-pole machine having 3 axels and 2 p poles*

called the stator, the other three - in the slots of the magnetic system, which rotates are called the rotor. For the analyzing tasks, the boundaries of the magnetic system and the phase winding shown in Figure 1 as concentrated will be represented in the form of the continuous structure represented in Figure 2 [28]. Here, the phase zones are sinusoidally distributed main layers and the stator poles projections are shown by radial conductivity, which varies as a function of the angle. It is assumed that the magnetic structure and phase zones arrangement in the generalized physical model (Figure 2) should satisfy the conditions, the main of which are as follows [28]:

1. Electric spatial angle ϕ_{el} and mechanical spatial angle ϕ are related by the following expression:

$$\varphi_{el} = p \cdot \varphi = n \cdot \varphi \tag{1}$$

   where φ_{el} - angle in electrical spatial radians; φ - angle in mechanical spatial radians; p - the number of machine pole pairs; n - the number of periods of the spatial distribution of the current layer.
2. It is assumed that in the generalized model, the coils are sinusoidally distributed in space, so that the current i, connected to the clamps of the phase zone, creates a surface current density $K(\varphi) = i \cdot Z \cdot \cos n \cdot \varphi$, where $Z = w/l$ - the linear density of the conductor current layer, w - the number of turns of the winding, l - the length of the winding.
3. The phase zones of both the stator and the rotor are shifted in space by *120* electrical degrees, i.e. magnetic axes of the phase zones are shifted by *2π/3* of electrical radians or by *2π/3n* mechanical radians.
4. Stator-to-rotor gap is space between the magnetic systems of the stator and the rotor. It is assumed that one side of the stator-to-rotor gap is magnetically "smooth" and the other has magnetic irregularity (pole projections) periodically repeated through π of electrical spatial radians or through $\pi/2$ of mechanical radians.
5. When determining the strength in salient-pole machines, the stator-to-rotor gap will be uniform, which value is g and is equal to the average size of the stator-to-rotor gap for a salient-pole structure. The unevenness of the stator-to-rotor gap will be taken into account in the idealized model, using the radial magnetic inductivity, which is changing in space:

$$\mu_{rad} = \mu - \mu_2 \cdot \cos(2 \cdot \pi \cdot \varphi^{8}). \tag{2}$$

6. Each of the three phase zones, located on the stator, has different number of turns. The rotor phase zones also have different numbers of turns.
7. The stored electrical energy, which is used to describe the machine, is considered only as a zero-order field energy or a static magnetic field energy. The energy of the electrostatic field is neglected, which allows ignoring the effect of capacitors inside the windings and between them. All the electric fields, created by a change in time of magnetic fields or relative motion in a magnetic field, are not included in the energy function describing the system. These electric fields

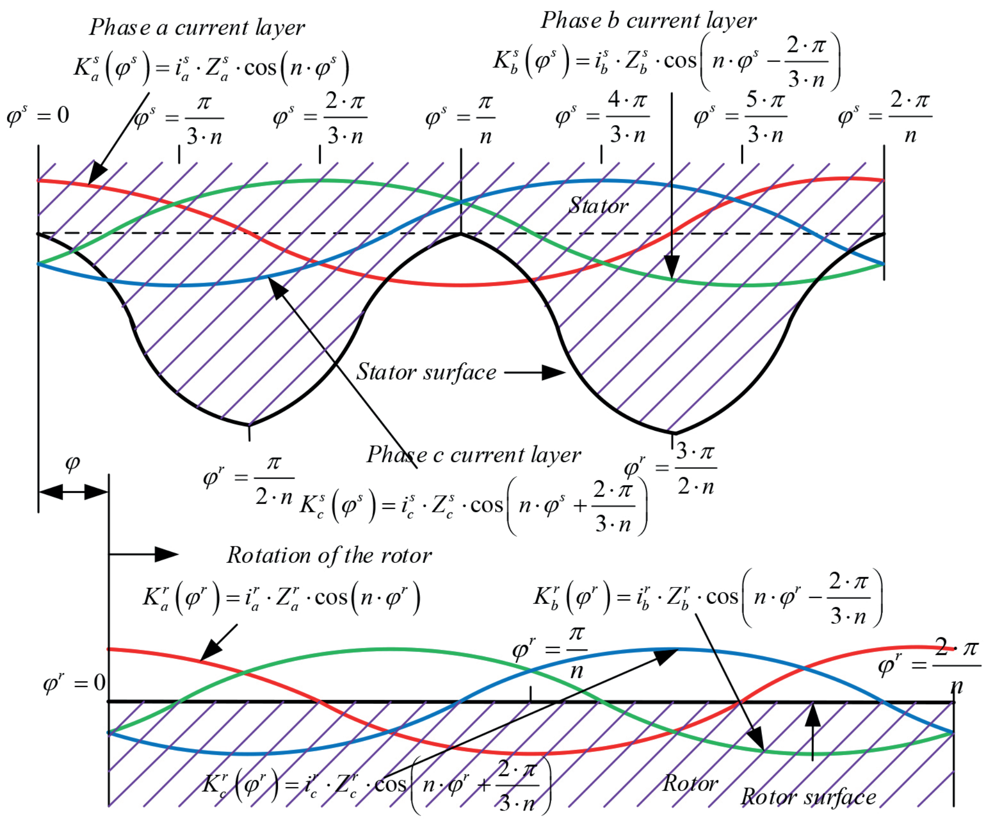

Figure 2 *Current layers created by sinusoidally distributed coils in a generalized machine*

occur when deriving the equations of motion from the energy function of the system written for the magnetic field energy.

4. Development of an algorithm for determining self and mutual inductances of stator and rotor

To determine the inductions of a generalized machine and their connections with mechanical variables, two equations of stored magnetic energy are used, namely, one through the magnetic induction B, the magnetic field strength H and dimensions: $W_m=\frac{1}{2}\cdot\int H\cdot B\cdot dv$ [29] and another one through chain parameters: $W_m=\frac{1}{2}\cdot\sum_i\sum_j L_{ij}\cdot i_i\cdot i_j$ with subsequent equating of these two equations.

The first step to calculate the machine inductance is calculation of the magnetic induction at all the points of the machine. Significant reserve of magnetic energy is only in the stator-to-rotor gap and the inductances can be calculated using the values B and H in the gap, which are obtained from the calculation of the machine static field pattern in accordance with clause 7. Only the influence of the magnetic field existing in the stator-to-rotor gap should be taken into account when considering a generalized machine. In this case, the generalized machine will be a model of a real machine, which reflects its properties related to the transformation of energy.

The presence of the salient-poles is taken into account by the fact that the magnetic inductivity is different at various points in space; therefore, the salient-poles will only affect the magnitude of the magnetic induction B [28]. The magnetic field strength H is found from the assumption of the salient-poles absence. The magnetic field strength H is determined for a system with a uniform stator-to-rotor gap, which is considered in cylindrical coordinates ρ, φ^s, z. At the same time, rotor surface radius is $\rho = r_s$, radial dimension of stator-to-rotor gap $g = r_s - r_r$ and axial length of stator-to-rotor gap l_β. Six current layers determine the six laws of distribution of the surface current density, i.e. three for the rotor and three for the stator. These surface currents flow in the axial direction *(z)*. In accordance with Figure 2 and taking into account the fact that when finding H, the surface of the stator bore is assumed to be smooth and six current layers create the following surface current densities.

Internal stator surface is $(\rho = r_s)$:

$$k_a^s(\varphi^s)=a_z\cdot i_a^s\cdot Z_a^s\cdot\cos(n\cdot\varphi^s), \tag{3}$$

$$k_b^s(\varphi^s)=a_z\cdot i_b^s\cdot Z_b^s\cdot\cos n\cdot\left(\varphi^s\frac{2\cdot\pi}{3\cdot n}\right), \tag{4}$$

$$k_c^s(\varphi^s)=a_z\cdot i_c^s\cdot Z_c^s\cdot\cos n\cdot\left(\varphi^s\frac{2\cdot\pi}{3\cdot n}\right), \tag{5}$$

where Z_a^s, Z_b^s i Z_c^s are linear densities of conductors of the three stator current layers.

Similarly, the magnetic field strength on the rotor surface $(\rho = r_r)$ is determined with taking into account that $\varphi^r=\varphi^s-\varphi$.

Using the conclusion given in [16], the equation for finding the magnetic field strength of *a* phase can be written as follows:

$$H_a^s \approx -a_\rho \cdot \frac{r_r}{n \cdot g} \cdot i_a^s \cdot Z_a^s \cdot \sin(n \cdot \varphi^s). \tag{6}$$

The magnetic strengths for the other two phases of the stator and the three phases of the rotor are determined similarly.

The resulting field in the stator-to-rotor gap is found by adding:

$$H_\rho = H_a^s + H_b^s + H_c^s + H_a^r + H_b^r + H_c^r. \tag{7}$$

The equation for magnetic induction B is obtained from equation for *H* and the magnetic inductivity is taken as a variable. Then

$$B = a_\rho \cdot (\mu - \mu_2 \cdot \cos(2 \cdot n \cdot \varphi^s)) \cdot (H)_\rho, \tag{8}$$

where *(H_ρ)* is given in Equation (7).

Equations (7) and (8) can be used to determine the accumulated energy by the spatial integral over volume of the stator-to-rotor gap. The stator-to-rotor gap of an idealized model of a salient-pole machine corresponds to a change in the axial coordinate *z* from O to l_β, angle φ^s from 0 to *2π*, coordinate ρ^r from 0 to *g*, moreover, g is the average value of the stator-to-rotor gap of a salient-pole machine.

Total energy in the stator-to-rotor gap is as follows:

$$W_m = \int_0^{l\beta} \int_0^{g} \int_0^{2\pi} \frac{1}{2} \cdot B \cdot H \cdot (r_r d\rho^r d\varphi^s dz) = \int_0^{l\beta} \int_0^{g} \int_0^{2\pi} \frac{1}{2} \cdot \\ \cdot \left[(\mu - \mu_2 \cdot \cos(2 \cdot n \cdot \varphi^s)) \cdot (H)_\rho^2\right] \cdot (dz \cdot r_r d\rho^r \cdot d\varphi^s). \tag{9}$$

Substituting Equations (7) and (8) into Equation (9), the energy in the stator-to-rotor gap is determined by integration.

The accumulated energy, determined by Equation (9), can be equated to the stored energy expressed through the following circuit parameter:

$$W_m = \frac{1}{2} \cdot \sum_i \sum_j L_{ij} \cdot i_i \cdot i_j. \tag{10}$$

Adjusting Equations (9) and (10) and assuming that the mutual inductance L_{ij} shall be equal to L_{ji} in the assumption of a linear system, the following equations for inductance is obtained:

$$L_{aa}^{ss} = L_{aa\mu}^{ss} + L_{aa\mu 2}^{ss}, \tag{11}$$

$$L_{bb}^{ss} = L_{bb\mu}^{ss} + L_{bb\mu 2}^{ss} \cdot \cos\left(\frac{4 \cdot \pi}{3}\right), \tag{12}$$

$$L_{cc}^{ss} = L_{cc\mu}^{ss} + L_{cc\mu 2}^{ss} \cdot \cos\left(\frac{4 \cdot \pi}{3}\right), \tag{13}$$

$$L_{ab}^{ss} = L_{ba}^{ss} = (L_{ab\mu}^{ss} + L_{ab\mu 2}^{ss}) \cdot \cos\left(\frac{2 \cdot \pi}{3}\right), \tag{14}$$

$$L_{ac}^{ss} = L_{ca}^{ss} = (L_{ac\mu}^{ss} + L_{ac\mu 2}^{ss}) \cdot \cos\left(\frac{2 \cdot \pi}{3}\right), \tag{15}$$

$$L_{bc}^{ss} = L_{cb}^{ss} = L_{bc\mu}^{ss} \cdot \cos\left(\frac{4 \cdot \pi}{3}\right) + L_{bc\mu 2}^{ss}, \tag{16}$$

$$L_{aa}^{rr} = L_{aa\mu}^{rr} + L_{aa\mu 2}^{rr} \cdot \cos 2 \cdot n \cdot \varphi, \tag{17}$$

$$L_{bb}^{rr} = L_{bb\mu}^{rr} + L_{bb\mu 2}^{rr} \cdot \cos 2 \cdot n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{18}$$

$$L_{cc}^{rr} = L_{cc\mu}^{rr} + L_{cc\mu 2}^{rr} \cdot \cos 2 \cdot n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{19}$$

$$L_{ab}^{rr} = L_{ba}^{rr} = L_{ab\mu}^{rr} \cdot \cos \frac{2 \cdot \pi}{3} + L_{ab\mu 2}^{rr} \cdot \\ \cdot \cos 2 \cdot n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{20}$$

$$L_{ac}^{rr} = L_{ca}^{rr} = L_{ac\mu}^{rr} \cdot \cos \frac{2 \cdot \pi}{3} + L_{ac\mu 2}^{rr} \cdot \\ \cdot \cos 2 \cdot n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{21}$$

$$L_{bc}^{rr} = L_{cb}^{rr} = L_{bc\mu}^{rr} \cdot \cos \frac{4 \cdot \pi}{3} + L_{bc\mu 2}^{rr} \cdot \cos 2 \cdot n \cdot \varphi, \tag{22}$$

$$L_{aa}^{sr} = L_{aa}^{rs} = (L_{aa\mu}^{sr} + L_{aa\mu 2}^{sr}) \cdot \cos n \cdot \varphi, \tag{23}$$

$$L_{ab}^{sr} = L_{ba}^{rs} = (L_{ab\mu}^{sr} + L_{ab\mu 2}^{sr}) \cdot \cos n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{24}$$

$$L_{ac}^{sr} = L_{ca}^{rs} = L_{ac\mu}^{rs} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right) + \\ + L_{ac\mu 2}^{rs} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{25}$$

$$L_{ba}^{sr} = L_{ab}^{rs} = L_{ba\mu}^{rs} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right) + \\ + L_{ba\mu 2}^{rs} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{26}$$

$$L_{bb}^{sr} = L_{bb}^{rs} = L_{bb\mu}^{sr} \cdot \cos n \cdot \varphi + L_{bb\mu 2}^{sr} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{27}$$

$$L_{bc}^{sr} = L_{cb}^{rs} = L_{bc\mu}^{ss} \cdot \cos n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right) + L_{bc\mu 2}^{ss} \cdot \cos n \cdot \varphi, \tag{28}$$

$$L_{ca}^{sr} = L_{ac}^{rs} = L_{ca\mu}^{sr} \cdot \cos n \cdot \left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right) + \\ + L_{ca\mu 2}^{sr} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{29}$$

$$L_{cb}^{sr} = L_{bc}^{rs} = \left(L_{bc\mu}^{sr} \cdot \cos n \cdot \left(\varphi - \frac{2 \cdot \pi}{3 \cdot n}\right) + L_{bc\mu 2}^{sr} \cdot \cos n \cdot \varphi\right), \tag{30}$$

$$L_{cc}^{sr} = L_{cc}^{rs} = L_{cc\mu}^{sr} \cdot \cos n \cdot \varphi + L_{cc\mu 2}^{sr} \cdot \cos n\left(\varphi + \frac{2 \cdot \pi}{3 \cdot n}\right), \tag{31}$$

Equations (11)-(31) determine all the self and mutual inductances with respect to six pairs of electrical terminals. The nature of these inductances is of the considerable interest. Inductances that have index $\mu(L_\mu^s, L_{\mu 2}^{sr})$ are functions of magnetic inductivity μ, while an index $\mu(L_{\mu 2}^s, L_{\mu 2}^{sr})$ correspond to inductances, which are functions of inductivity μ_2.

The method of expressing magnetic inductivity (8) allows one to conclude that all the terms with index μ will be present in equation for any machine with a uniform stator-to-rotor gap, while terms with index μ_2 will occur in the case of a salient-pole machine, that is, a machine with uneven stator-to-rotor gap. In equations for the non-salient-pole machine, all these terms will be equal to zero. Obviously, for a machine with a uniform stator-to-rotor l_β gap, all the self-inductances are constant and all the mutual inductances are cosine-shaped functions of the spatial angle *n·ϕ* between the respective coils on the stator and the rotor. This kind of spatial change in mutual inductance can be expected when sinusoidally distributed coils rotate relative to each other. Terms appearing due to the presence of the salient poles are similar to terms included in the equations for the non-salient-pole machines, except for the rotor self- inductances. The

***Table 1** Comparison of the results of the calculation of inductance carried out by using the proposed method and data obtained experimentally*

ℓ	Parameter	Calculated	Experimental	Inaccuracy
1	Phase inductance of stator winding for phase A	0.242 mH	0.235 mH	-2.97%
2	Phase inductance of stator winding for phase B	0.694 mH	0.684 mH	-3.31%
3	Phase inductance of stator winding for phase C	0.822 mH	0.836 mH	1.67%
4	Phase inductance of rotor winding for phases A, B, C	0.076 mH	0.079 mH	3.95%
5	Mutual inductance	0.391 mH	0.39 mH	-2.56%

self-inductances of stator are constant and the mutual inductances of the stator and the rotor are changed in proportion to the cosine of the spatial angle $n \cdot \phi$. This follows from the fact that the rotor is magnetically smooth and, accordingly, the stator inductances should not depend on its position and the mutual inductances of the stator and rotor should be similar to those for machines with a uniform stator-to-rotor gap. The latter is a consequence of the energy conservation law, which leads to equality of mutual inductances. It is easy to see that the self inductance of the rotor due to the salient polarity is a function of the rotor position and varies according to the cosine law of the double electrical spatial angle $2 \cdot n \cdot \phi$. This is a consequence of the fact that the angular coordinate of the full cycle of changes in the size of the stator-to-rotor gap is equal to half the phase zone. Thus, the change in the mechanical spatial angle ϕ to 2π corresponds to $2 \cdot n$ cycles of change of the rotor induction due to the presence of salient poles at the stator.

Thus, inductances are shown as functions of an independent coordinate φ.

To verify the adequacy of the method, the phase and mutual inductances of the asynchronous motor NB-455A, which is used as a phase release on electric locomotives of VL-80^{T,K} series were calculated and compared to results obtained experimentally [13]. This motor has symmetrical rotor windings and asymmetrical stator windings. The results are listed in Table 1.

As can be seen from the Table 1, inaccuracy of inductance calculations does not exceed 5% of the data obtained experimentally. This indicates that the proposed method for determining the inductance of an asynchronous motor with a square-cage rotor having asymmetrical windings is adequate.

5. Conclusion

The problem of finding the phase and mutual inductances of an asynchronous motor with asymmetrical stator and rotor windings is considered in the article. The method for determining the phase and mutual inductances of asynchronous motor stator and rotor phases of asynchronous motor with asymmetric windings and their relations with mechanical parameters has been improved. The method is based on a comparison of the two equations of stored magnetic energy:

- the equation written through induction, magnetic field strength and geometrical dimensions;
- the equation written through the parameters of the motor circuits.

Comparison of results of an asynchronous motor parameters calculation to results obtained experimentally indicates a high accuracy of the proposed method.

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