Scientific and technical directions of improvement of electric motors for non-ferrous metallurgy

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Induction motors of classical and special design modifications are used in electric drives of non-ferrous metallurgy shop equipment. Technical requirements for classic induction motors (IM) include high energy efficiency and a high degree of reliability. The most important are the requirements of high starting torque, low starting current and low dependence of startability upon the mains supply voltage fluctuations.

Classic electric motors, both general-purpose and specialized, satisfy the needs of metallurgical industries in terms of starting torque, but they have overestimated values of the locked rotor current ratio by 1.5–2 times. Radical decrease of the locked rotor current ratio presents one of the topical areas of improving the IMs for non-ferrous metallurgy. The design description is given, and technical indicators of the upgraded electric motor with low starting current are pointed out. Linear induction motors (LIM) are considered as a typical example of electric motors of a special design modification.

In the aspect of low material capacity, kinematic simplicity and reliability, LIMs compete with classical IM. The widespread introduction of LIMs into electric drives of workshop equipment will significantly reduce material capacity and increase the reliability of non-ferrous metallurgy. The LIM specificity is analyzed. Description of the design and technical parameters of the LIM with a short carriage are given. Regular assessments of the current technical condition of electric motors and the risk of their operability loss are the measure of significant increase in reliability of the electrical equipment of non-ferrous metallurgy. The assessments of performance risks that could be obtained without significant interruptions in exploitation of the equipment are in demand. The article presents a method for topological IM diagnostics. The electric motor diagnostic testing methodology is described, and quantitative measures of the risk of operability loss are introduced.

Key words: electrical equipment, reliability, material capacity, induction motors, low starting current, linear electric motors, operational diagnostics, diagnostic testing methodology, the operability loss risk assessments.

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Introduction

Induction motors of classical and special design modifications are used in electric drives of non-ferrous metallurgy equipment [1–2]. Classical electric motors operate as part of a three-component drive of the working machine, which includes a rotary movement motor, a reducer and a mechanism for converting the kind of motion. Special electric motors, performed as the linear and arc-type stator modifications, carry out a direct force impact on the working machine units. From this point on we shall use the term "linear motor" to mean "linear and arc-type stator modifications of the induction motor".

The specifications of classical induction motors (IM) for metallurgical industries consist in high energy efficiency and a high degree of their reliability. Besides, the most important requirements are that of high starting torque, low starting current and low dependence of startability upon the mains supply voltage fluctuations.

The existing powerful electric motors have starting torque-to-nominal torque ratio of 0.9–1.7 and starting current-to-rated current ratio of 6–10 [2]. During operation, the corresponding starting parameters are lower because of the voltage drop on the cable that supplies energy to the electric motor and, often, because of the low quality of electricity at powerful metallurgical plants. At that, the secure direct start-up of metallurgical electrical equipment requires the motors with starting torque-to-nominal torque ratio of 1.5–2, and starting current-to-rated current ratio of 3–4. It should be established that the existing electric motors, both general-purpose and specialized, by and large meet the needs of metallurgical industries in terms of starting torque, but have an inflated 1.5–2 times the value of the starting current-to-rated current ratio. In this regard, one of the urgent directions of improving the IMs for non-ferrous metallurgy is radical reduction in the the starting current-to-rated current ratio.

In some cases, the decisive requirement for metallurgical electrical equipment is its low material capacity, kinematic simplicity and reliability. In this aspect, linear induction motors (LIMs) are in competition with the classical layouts of electric drives. In metallurgy, their usage is severely limited. Here we can note only the use of LIMs as a part of manufacturing machines for the liquid metal mixing and MHD-pumps for liquid metals. At the same time, wide introduction of LIMs into electric drives of shop equipment would allow to significantly reduce material onsumption and to increase reliability of non-ferrous metallurgy industries.

The fact that, in some cases, the technological process in metallurgy can not be interrupted or stopped without significant economic loss makes the issue of reliability particularly acute. In this regard, regular assessments of the current technical condition of electric motors and the risk of their operability loss are the measure of significant increase in reliability of the electrical equipment of metallurgical industries. The industry is in great demand for a system of operational risk assessments, which could be obtained on the equipment without significant interruptions in its exploitation.

The purpose of this article is to provide the reader with an overview of the current trends and developments in the above mentioned areas of improvement of electric motors for non-ferrous metallurgy equipment.

The upgraded electric motors with reduced starting current

Electric motors for metallurgical industries of classical design modification are produced in specialized series: AMTK, AP, AF. In recent years, they have been replaced by modernized general-purpose electric motors, which are superior to the specialized ones by starting parameters, but somewhat inferior to them in terms of energy efficiency. To the greatest extent this concerns the segment of electric motors with capacity of 100 or more kilowatts. The development of such electric motors is a contradictory complex scientific and technical problem, which includes physical, methodological and technical aspects. The solution of the problem is based on a compromise between the striving for ensuring high startability and guaranteeing high energy efficiency in nominal conditions.

The effect of current displacement in the squirrel-cage cell of the rotor of an asynchronous motor is used as a physical phenomenon focused on the solution of the problem. The effect is significantly pronounced in the massive parts of the rotor cell of powerful IMs in the starting mode, in which connection the starting current active rotor resistance increases and inductance decreases by 10–30%. In the IM rated duty, the current displacement influence on the rotor cell resistance is negligibly small. However, in classical designs, the technical range of the current displacement effect influence is almost exhausted. The attempt to increase the rotor cell active resistance of such IM more than 2 times fails. The consequence of this fact is the fixation of the locked rotor current ratio of the stock-produced motors at the level of 6–10. Radical reduction of this indicator to the level of 3–4 implies an intensification of the current displacement effect to such an extent that the rotor cell active resistance at the start-up would increase by at least 10–14 times.

According to the authors' study, current displacement in the massive parts of the rotor cell can lead to multidirectional results — decrease, increase and invariance of the starting current. The starting current-to-rated current ratio of IM can be calculated by the known formula [1]:

$$k_i = \frac{k_U}{\sqrt{(r_1 + c_1 k_r r_2)^2 + (x_1 + c_1 k_l x_2)^2}} \qquad (1)$$

where k_U is an IM voltage change at start-up, r_1, x_1 are an active and inductive resistance of the stator winding, r_2, x_2 are an active and inductive resistance of the rotor cell, k_r, k_l are the changing coefficients of the rotor cell active resistance and inductance at start-up, c_1 is a parametric coefficient. Calculation of the starting current-to-rated current ratio has been carried out according to (1) at $k_U = 1$, for characteristic relative parameters of IM as follows: $r_1 = 0.04$, $x_1 = 0.100$, $r_2 = 0.020$, $x_2 = 0.047$, $c_1 = 1.020$.

The calculation results are shown in Fig. 1, which shows the dependence of the the starting current-to-rated current ratio k_i on the change coefficients of the rotor cell active resistance and inductance at start-up k_r, k_l. The plane at the top of the figure separates the areas of increased and decreased values of the locked rotor current ratio. As shown in Fig. 1, the k_r coefficient values at the level of 1.5–2 currently implemented both in general-purpose electric motors and specialized electric motors, contribute to an increase in the locked rotor current ratio, which negatively affects their performance

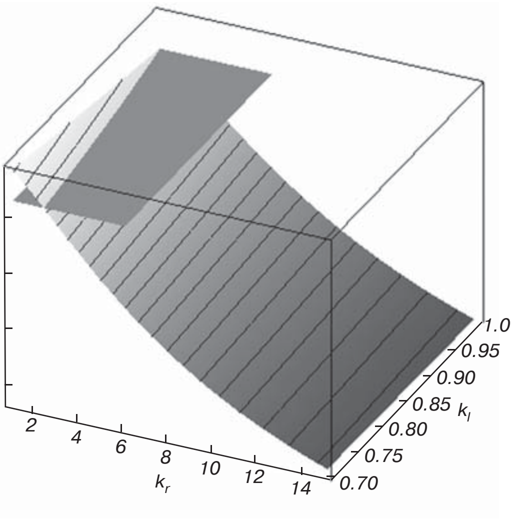

Fig. 1. The induction motor starting current ratio

Table 1.
Comparative technical data of electric motors

No.	Dimention-type	η_n	$\cos\varphi_n$	k_r	k_l	k_i	k_m
1	4A355M2	93.9	0.94	1.96	0.91	5.74	1.33
2	AF355DM2	96.6	0.91	1.90	0.90	7.30	1.90
3	4A355M2Э	92.9	0.81	22.2	0.64	2.77	1.70

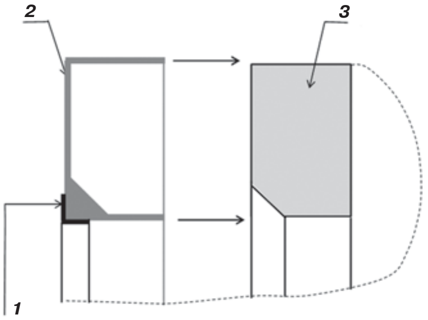

Fig. 2. The double-layer screen of the induction motor rotor cell: *1* — the ring-shaped copper screen layer with a L-type cross-section; *2* — the induction motor steel screen layer with a U-type cross-section and internal bulge; *3* — the rotor cage end ring with trapezoidal cross-section made of aluminium alloy

attributes. For radical reduction of a k_i index, a significant intensification of the current displacement effect is required, providing the k_r coefficient values at the level of 10–14 or more times. This indicator is realized in the upgraded IM [3–4].

In the upgraded IM, the intensification of the current displacement effect is provided by two-layer screens of ferromagnetic steel and copper installed on the rotor cell cage rings. One of them, used in a construction [4], is shown in Fig. 2.

Comparative technical data of three electric motors with a capacity of 315 kW are represented in the Table 1. There are listed the data on a stock-produced general-purpose motor 4A355M2, a specialized crane and metallurgical motor AF355DM2 and an upgraded general-purpose motor 4A355M2Э with screens in Fig. 2 on the rotor cell cage rings.

The Table contains the efficiency factor and the IM power factor rating values, values of the change coefficients of the rotor cell resistances at start-up k_r, k_l, the starting current-to-rated current ratio k_i and the starting torque-to-nominal torque ratio k_m.

As it is evidenced by the data in the Table, the motor 4A355M2Э, ranking below the analogs in energy efficiency, significantly exceeds them by the value of the locked rotor current ratio. Compared to crane and metallurgical motor AF355DM2, this figure is reduced by 2.6 times. Such a low starting current value along with the sufficient starting torque ($k_m = 1.7$), gives the motor a slight decrease of the supply voltage at start-up and, as a consequence, the guaranteed start, self-starting and low dependence of the starting characteristics on the mains supply fluctuations.

Low-speed linear induction motors

A wide target area of LIMs application is formed by intrashop equipment of non-ferrous metallurgy industries, in particular the carnage electric drives, tilters, trolleys, conveyors, switches of the track facilities, contact equipment, pipeline flaps, doors of workshops and processing chambers.

Kinematic simplicity, reliability, functionality, organic unity of the electric motor and working machine are intrinsic to the electric drives with LIMs. In essence, the movement implementation by means of LIMs is an innovative technology for solving the transport problem, which allows to see fulfilled complex travel trajectories of an object in the form of their its piecewise-linear or piecewise-arc approximation. At the same time, the electromagnetic field force effect is often sent on the moving object directly. This feature is essential for the processes of special purity, in particular the vacuumed ones.

In view of the peculiarities of electromagnetic processes, as well as due to the low operating speed of intrashop equipment (1–2 m/s), LIM demonstrates low energy efficiency indicators and, as a rule, has small capacity and is operated in a short-term duty. At the same time, LIM is quite competitive with classic electric drive with asynchronous motor in both the efficiency factor values and material capacity indexes. However, it should be noted that LIM ia able to fully realize its advantages when it is developed for the specific working machine or for the specific group of similar working machines. This factor forces the designers to make original decisions in almost every project.

The longitudinal section of a LIM with short movable carriage for driving and holding the processing chamber doors, developed in the Smolensk branch of MPEI, is presented in Fig. 3 as an example of such design.

The electric motor has a flat double-sided inductor 796 mm in length (the inductor front is not shown in Fig. 3), inside of which a movable carriage 298 mm long is traveling. Side overhangs of the LIM make the carriage able to move to the distances up to 1 meter. The designed LIM has the following technical data:

– three-phase supply voltage 220 V, 50 Hz;
– number of poles of the inductor winding 8;
– input current 7A;
– carriage shuttle distance up to 1 m;
– carriage speed 0–4 m/s;
– traction force at start-up 113 N;
– Efficiency factor 31.5%;

– power factor 0.68;

– dimensions 960×159×192 mm.

The LIM carriage is separately shown in Fig. 4. The carriage has four support rollers at the top, which provide its movement on special guides on the LIM frame. Moreover, it has eight spacIng rollers, providing the gaps between the inductor and carriage surfaces. In the carriage chassis an active element 260 mm long is fixed; it represent a hollow box made of steel ST10 6 mm thick, with side coating by aluminum alloy with a thickness of 1 mm. The unified design allows to build up working machines of different power and tractive effort with the same inductor and a set of unified interchangeable movable carriages with different active elements. Such unification expands technical capabilities of LIMs.

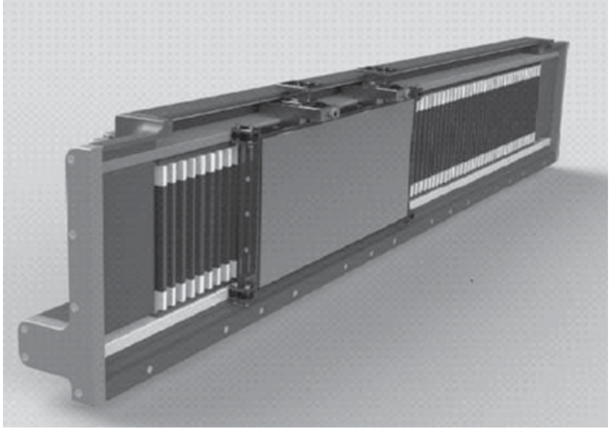

Fig. 3. LIM with short carriage

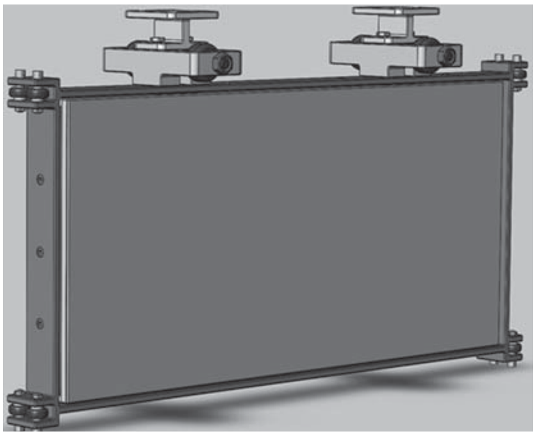

Fig. 4. The LIM carriage

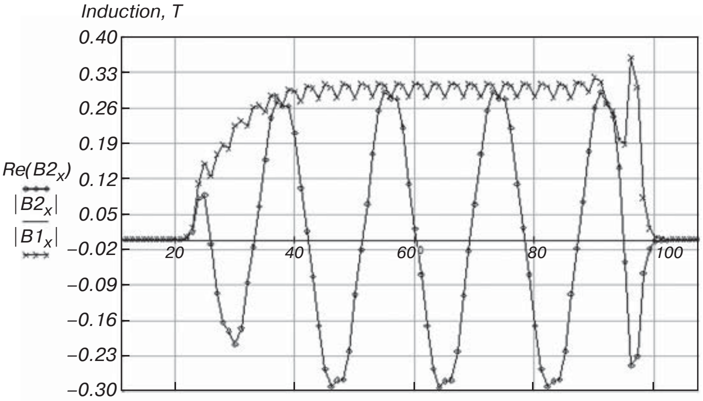

Fig. 5. The master magnetic field distribution in a LIM

The specificity of electromagnetic processes in LIM [5] appears in the fact that the main magnetic field is not a sinusoidal progressive wave, but only contains traveling components. Besides, the main field intensity and space form as well as the proportion of traveling components in it depend on the carriage speed, physical properties of the inductor cores, physical properties of the carriage active element and the exciting current distribution.

The LIM mathematical modelling goal orientation also has its peculiar features. When modeling an IM of classical design, the problems of its behaviour analysis are in the foreground, whereas the LIM modelling is aimed as a rule at synthesis of the construction. Multichoice model calculating different versions with replacements of missing test-operational data allows to substantiately choose the LIM length and width, the inductor windings pole number, the rule of the winding conductors distribution over inductor, voltage and frequency of power supply if they are not rigorously set.

The modelling corresponding to the layout stages of LIM design is usually grounded upon the main magnetic field analytical mathematical models [5]. The final designing stages are based on the detailed replacement schemes of individual short sections of the machine, which usually have the length of one toothed inductor point.

An instantaneous distribution and envelope curve of magnetic induction along the LIM inductor length according to Fig. 3 are shown in Fig. 5. The distributions have been obtained by the detailed equivalent circuit method on 100 elementary sections. Fig. 5 illustrates the longitudinal edge effect in a LIM, that is, the induction decay at the entering inductor edge and its increased values at the leaving edge.

One of the end fields of application of such LIMs in non-ferrous metallurgy is their use in electric drives of electrothermal reactors [6–8].

Diagnostics of the current state of electric motors and assessments of the operability loss risk

The importance of operational diagnostics to maintain the working condition of the non-ferrous metallurgy electrical equipment is very high. This also concerns the asynchronous motors, which are the power element of electrical equipment and largely determine reliability and robustness of technical systems.

The existing methods of operational diagnostics of IM [9–14] are based on fixation and analysis of external energy flows, namely the intensity of electromagnetic, thermal or acoustic field, the values of the consumed currents or the moment on the shaft of electric machine. These diagnostic factors contain reliable information on the existence of internal damages, if any. But, they also poorly indicate the damage place in the internal structure of the machine because of the high degree of information integration. In addition, a significant contribution to the intensity of electromagnetic, thermal or acoustic field can make third-party equipment or random factors. For these reasons, the existing diagnostic techniques are not a foolproof basis to make the conclusions about technical state and residual life of IM.

In this article, the authors present a topological diagnostic technique designed for periodic and detailed analysis of the current technical IM state. The topological method is based on testing single areas of the electric machine vector space and comparing the test results with reference data. The properties of parametric matrices of the electric machine windings and, as a result, the properties of its vector space, change during operation under the influence of service aging and possible operational damage. If these changes are periodically recorded in the operational diagnostics process, the information obtained can be used to assess both current technical condition of the object, and the risk of performance loss. Scientific and methodological foundation of the IM topological diagnostics are presented by the authors in [15].

The vector space corresponding to the parametric matrix of the object is used as a source of information about the IM state. The authors have been called such an approach to diagnostics the topological one. In the vector space, there is information not only about the electric machine integral energy flows, but also about the elements of its structure, their interaction, the degree of homogeneity of individual subspaces, the orientation of the current vectors and EMF in the space, as well as the machine energy fields' configuration. The topological diagnostic technique, unlike the existing methods, operates with much more detailed information on the object features.

As applied to IM, the main indicator of the absence of internal damages caused by poor-quality manufacturing, violation of operating rules and service aging is the parametric homogeneity of the vector space working area.

The vector space working area is the area in which the vectors of electromagnetic quantities are concentrated during property-sheet mode of the damage-free IM. The investigations, the results of which are presented in [15], suggest that the vector space working area is a plane αβ, given in the IM vector space by orthogonal normalized basis:

$$n_\alpha = \sqrt{\frac{2}{3}}\begin{pmatrix} -\frac{1}{2} \\ 1 \\ -\frac{1}{2} \end{pmatrix},\quad n_\beta = \sqrt{\frac{2}{3}}\begin{pmatrix} -\frac{\sqrt{3}}{2} \\ 0 \\ -\frac{\sqrt{3}}{2} \end{pmatrix} \qquad (2)$$

The subspace αβ implements the communication channel between the three-phase stator winding and the squirrel-cage rotor cage. The three-phase stator winding and the rotor cage exchange the energy through a common subspace, realizing the main working process in IM.

When performing operational diagnostics, the main task is to test the vector space working area — the subspace αβ. The Green functional matrix [13—14] is a characteristic of the current IM technical state, the columns of which are Green impulse vector-functions. Each of them represents the reaction of the stator winding three phases to the effect of the phase voltage vector U_s along one of the axes x, y, z of the plane αβ:

$$u_{sx} = \delta(t)\begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix},\quad u_{sy} = \delta(t)\begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix},\quad u_{sz} = \delta(t)\begin{pmatrix} -1 \\ 0 \\ 1 \end{pmatrix}, \qquad (3)$$

where $\delta(t)$ is the Dirac function. The Green matrix, formed by the results of testing under the number k and correlated with the testing time t_k, counted from the start of operation $t_0 = 0$, has the form

$$G(t, t_k) = \begin{pmatrix} g_{xx}(t, t_k) & g_{xy}(t, t_k) & g_{xz}(t, t_k) \\ g_{yx}(t, t_k) & g_{yy}(t, t_k) & g_{yz}(t, t_k) \\ g_{zx}(t, t_k) & g_{zy}(t, t_k) & g_{zz}(t, t_k) \end{pmatrix} \qquad (4)$$

To assess the current IM technical condition, the Green matrix is compared with the reference plane:

$$G(t, t_0) = \begin{pmatrix} f(t) & \varphi(t) & \varphi(t) \\ \varphi(t) & f(t) & \varphi(t) \\ \varphi(t) & \varphi(t) & f(t) \end{pmatrix} \qquad (5)$$

in which functions $f(t)$ and $\varphi(t)$ are formed by the results of output tests at the factory. According to the results of successive tests at the time $t_0, t_1, \ldots, t_k$, the deviation matrices are being formed

$$\Delta G(t, t_k) = abs(G(t, t_k) - G(t, t_0)), \qquad (6)$$

they are stored in technical documentation of the product within all the IM operating period.

Numerical matrices $G(t_0)$, $\Delta G(t_k)$, composed of the amplitude absolute values of corresponding time functions, are convenient to be used for practical estimates instead of functional matrices $G(t, t_0)$, $\Delta G(t, t_k)$.

With relation to the current technical condition assessing and forecasting the IM residual life, matrix $\Delta G(t_k)$ has a number of useful properties. It contains deviations of the IM vector space parameters from the reference values characterizing the product, the performance of which is trustworthy positive. Deviations occur, to a large extent, under the influence of random factors. For these reasons, the elements of the matrix $\Delta G(t_k)$ can be regarded as absolute characteristics of the risk of the product performance loss. The observance, even approximate, of the equation:

$$\Delta G(t_k) = n \cdot G(t_0), \qquad (7)$$

where $0 < n < 1$ is a proportionality coefficient, testifies parametric homogeneity of the vector space workspace and indicates the IM homogeneous service aging. The presence of drastic changes in single elements of the matrix $\Delta G(t_k)$ that have occurred over time $t_k - t_{k-1}$, is an evidence of appearance or rapid development of the IM construction operational damages.

Let ΔG is a $\Delta G(t_k)$ matrix element deviation, corresponding to so called "limiting state", or the IM state in which its further exploitation have to be stopped due to unavoidable parameters leaving beyond the limits set by technical documentation. The value ΔG can be determined by expert evaluations or to be contained in the normative and technical documentation of the product.

The matrix elements

$$P(X, t_k) = \frac{\Delta G(t_k)}{\Delta G} \tag{8}$$

may be used as current estimates of the rates of event X, which consists in the IM operability loss. It is essential that the risk assessments $\Delta G(t_k)$, $P(X, t_k)$ are given in three different directions of the IM vector space working area and become defined more accurately as the product operation time grows.

Conclusion

For electric drives of technological and intrashop equipment of non-ferrous metallurgy, the modernized induction motors with low starting current are promising, providing, providing the guaranteed start-up and self-starting of electrical equipment as well as a weak dependence of the starting parameters on the mains supply fluctuations.

Linear induction motors with high reliability and low material capacity are promising for electric drives of auxiliary shop equipment of non-ferrous metallurgy.

One of effective measures to improve the reliability of non-ferrous metallurgy electrical equipment is periodic operational diagnostics of electric motors on the base of topological technique. The topological technique features the sufficient detailedness for operational diagnostics and allows to adequately estimate the electric motor current technical condition and it's risk of operability loss.

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