ЭНЕРГЕТИКА

FLAT TWO-PHASE LINEAR INDUCTION MHD MACHINE FOR METALLURGICAL PURPOSES

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ПЛОСКАЯ ДВУХФАЗНАЯ ЛИНЕЙНАЯ ИНДУКЦИОННАЯ МГД-МАШИНА МЕТАЛЛУРГИЧЕСКОГО НАЗНАЧЕНИЯ

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Abstract. Linear induction MHD machines with a low-frequency power inverter form a complex of electromagnetic stirring of liquid aluminum in smelting furnaces. The article discusses the classification features and characteristics of four-zone inductors of a longitudinal magnetic field with two-phase power. To calculate the operating parameters of a linear induction MHD machine, a nonlinear multiphase model of a magnetic circuit was used. As a result of an iterative calculation, the distribution of the integral magnetic fluxes in the tooth zone of a flat inductor is obtained, and vector diagrams of electromagnetic regime parameters are constructed. According to the results of the analysis, the main tasks and the sequence of stages of their solution were formulated when developing energy-efficient induction MHD machines of a longitudinal magnetic field. In the course of the study, directions for optimizing the mode of a low-pole induction machine are shown in order to obtain the best distribution of currents in the windings.

Keywords. Induction MHD machine, inductor of longitudinal magnetic field, electromagnetic stirrer, running magnetic field, multiphase magnetic circuit model, vector magnetic flux diagram, two-phase power supply system, frequency inverter.

Introduction. For stirring metal melts in furnaces, linear induction machines of transverse and longitudinal magnetic fields are used. The cost of each technical solution, along with the technological and energy efficiency of induction machines, is a decisive factor in the decision to modernize production or to develop of new construction of smelting furnaces. As induction machines for stirring aluminum alloys in mixers and furnaces, in addition to the transverse field inductors, high-tech shortened inductors of the longitudinal field are used. Among the simplest flat induction MHD machines, two constructive solutions can be distinguished that determine the type of machine by the number of windings inducing the force (induction zones).

These design features appropriately characterize the polarity of the inductor and the magnitude of the synchronous velocity of the traveling magnetic field in the melt. The following designations are used as constructive and operational parameters in the description:

2p is the number of poles of the inductor;

Z is the number of teeth of the core;

q is the number of grooves of the core per pole and phase;

α is the phase zone of the inductor;

m is the number of phases of a multiphase winding inductor;

Δ is the working gap.

The classical induction MHD machine of a longitudinal magnetic field can have four or three windings (a four-zone or three-zone inductor). In addition, the power supply of induction machines can be provided in a two-phase or three-phase version. Thus, when developing inductors and evaluating their effectiveness, four main options should be considered for constructing shortened low-pole induction machines of a longitudinal magnetic field.

1. Four-zone inductor with two-phase power supply.

$2p = 2$, $Z = 5$, $q = 1$, $m = 2$, $\alpha = 90°$.

2. Four-zone inductor with a three-phase power supply.

$2p = 4/3$, $Z = 5$, $q = 1$, $m = 3$, $\alpha = 60°$.

3. Three-zone inductor with a two-phase power supply.

$2p = 3/2$, $Z = 4$, $q = 1$, $m = 2$, $\alpha = 90°$.

4. Three-zone inductor with a three-phase power supply.

$2p = 1$, $Z = 4$, $q = 1$, $m = 3$, $\alpha = 60°$.

This article discusses some of the classification characteristics and features of four-zone inductors of a longitudinal magnetic field with two-phase power. A sketch of the construction of a shortened induction MHD machine is shown in Fig. 1. The inductor has four windings 1, designated w_1, w_2, w_3, w_4. They are made in the form of two-way disk sections, which are grouped in series or parallel connection. The windings are placed on a steel laminated magnetic core 2. Between the windings 1 are placed steel teeth 3, which serve as magnetic field concentrators. In the windings connected to the inverter, alternating currents with a frequency of about 1 Hz arise, which create a traveling magnetic field in the surrounding space and capacitance 4 with aluminum melt 5.

For such an inductor design, a two-phase power supply from a transistor inverter of a modified voltage can be applied, and the inductor itself becomes a four-pole, with a corresponding change in the traction characteristics. By inversely turning on the phases, a pair of windings change the polarity of the induction machine (IM). The presence of four windings allows to increase the raster of the coating of the molten metal, located in the region of the dentate zone, by magnetic fluxes.

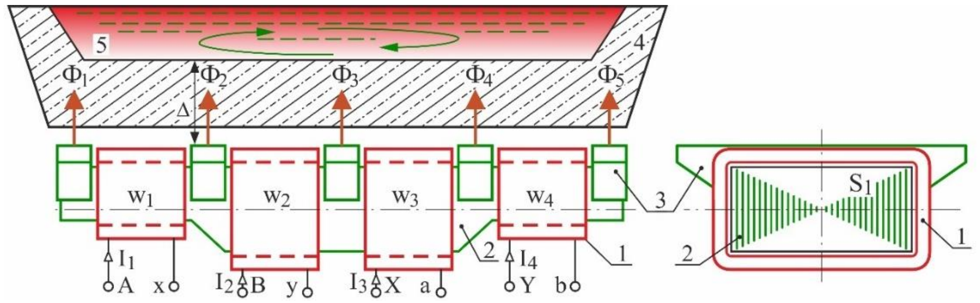
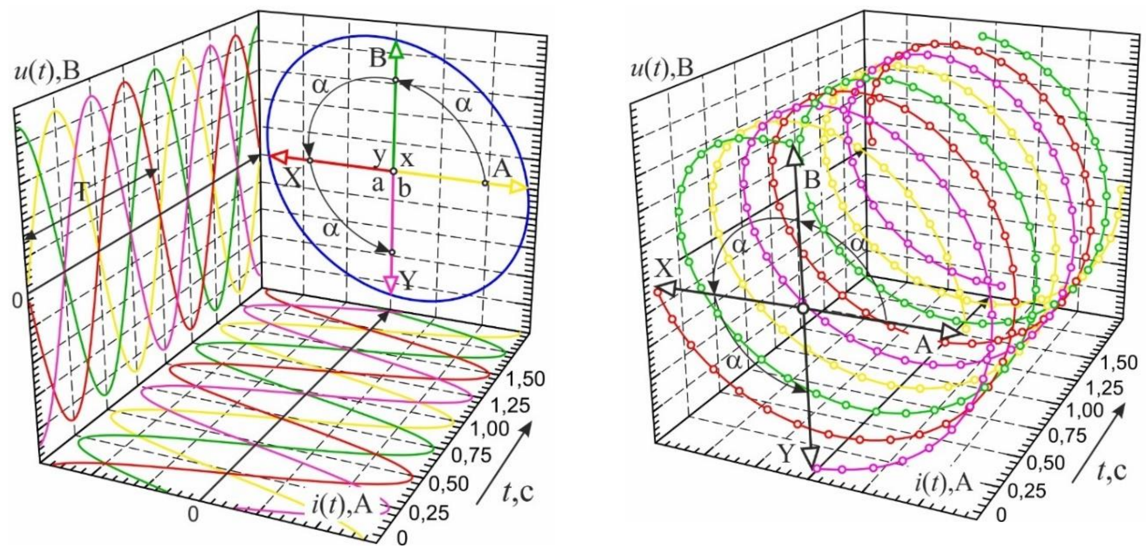


Figure 1

For presented on fig. 1 AxByXaYb winding designations receive a system of balanced voltages in the two-phase variant with a phase shift of voltages of about $\pi/2$. There is an effect of the mutual influence of currents and distortion of the field pattern due to edge effects and the open-ended configuration of the magnetic circuit, as well as the transfer of power between the windings due to mutual inductance. Due to the proximity of the windings on the common magnetic core, the phase shifts of the currents differ from $\alpha = \pi/2$, therefore the refined distribution of magnetic fluxes is estimated by calculation and experiment. To control the amplitude-phase ratios of magnetic fluxes include measures of regime regulation, special circuit solutions and algorithmic control of the state of the transistor inverter.

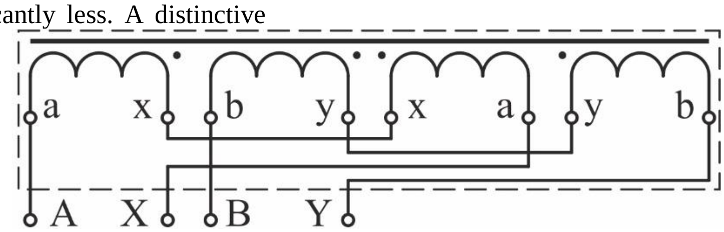
An example of a spatial phase representation of the characteristics for the steady state of an idealized two-phase inductor with a power source is shown in Fig. 2. The use of phase coordinates allows to show vector diagrams of currents, voltages and magnetic fluxes more clearly.



a *b*

Figure 2

The nature of the multi-phase power supply system is largely determined by the wiring pattern of the inducing windings. It should be noted that in the considered two-phase configuration of the MHD inductor, the power supply system, in contrast to the three-phase one, is balanced, therefore the side effects caused by the pulsating component of the magnetic field are substantially weakened. In addition, the power and vibration loads on the metal structures of the inductor and the frequency converter, as well as additional losses, are significantly less. A distinctive feature of the power mode of the windings of a two-phase machine can be considered as a separate pair connection of sections to half-bridges of a transistor source. The phasing of the half bridges of the power link of the inverter is performed in such a way as to ensure a phase shift of about π/2 between the currents of adjacent windings. An example of the connection scheme of the windings of a two-phase induction machine is shown in fig. 3



In addition to the four-pole variant of the inclusion of the windings of the four-zone inductor, for the presented design of IM, a bipolar inclusion is possible. Changing the number of poles is performed by switching the windings and changing the power supply circuit. The change of polarity necessarily leads to a change in traction characteristics, therefore, for each configuration of a longitudinal magnetic field inductor, the effectiveness of the effect on the melt is estimated in advance and recommendations are made for the application of each type of induction machine.

Judging by the scheme of fig. 3 each pair of windings of one phase is connected in series with each other. Such a connection provides the specified character of the distribution of magnetomotive forces (MMF), according to the initial vector diagram, in fig. 2. It should be noted that the presence of edge effects leads to a distortion of the field pattern; therefore, the initial distribution should be considered idealized. If there is a need for advanced regulation of the linear current load of the inductor, the connection diagram of the windings of fig. 3 can be modified and transferred to the mode of separate connection of the phases to the inverter with an increased number of half-bridges, or similar to the parallel connection of the windings.

A sketch of the four-zone inductor model, designed for research in the Maxwell software environment, is shown in fig. 4. When forming the model, the geometry was saved and the main operating parameters of the linear induction machine 2p = 2 were set, for a pair connection of the windings in the ABXY scheme. The spatial description of the model is made in the Cartesian coordinate system.

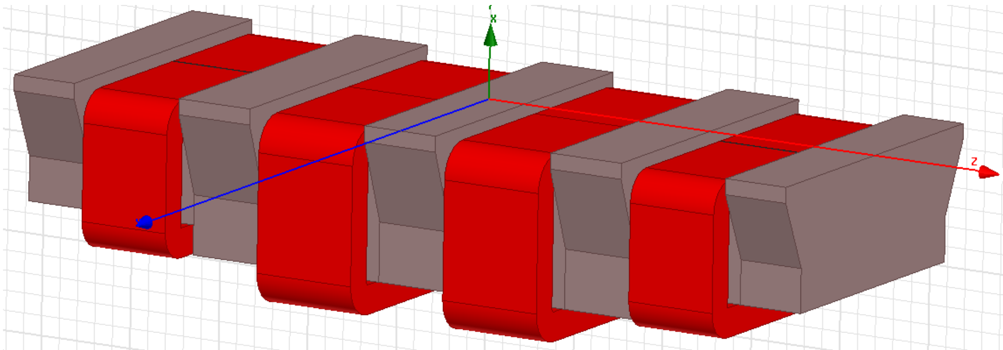


Figure 4

For the two-phase power supply of the field model, a simulated idealized chain model of a transistor inverter is used. The initial configuration of the power source is built using ideal EMF sources, without taking into account the mutual influence of the phases, assuming that the errors from the modified voltage of the PWM inverter are irrelevant. The value of asymmetry of the winding currents is limited to 15%. The resulting picture of the intensity distribution of the magnetic field vector H in the longitudinal section of the two-phase magnetic circuit is shown in Fig. 5. Judging by the color selection, on a scale (A / m), one can estimate the field intensity in the center of the core and take control measures to change the field redistribution with a decrease in saturation and overload.

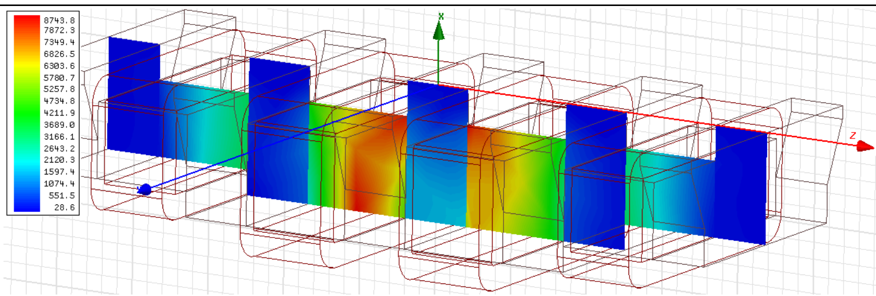


Figure 5

Taking into account the characteristics of the steel, the field is corrected in such a way as to limit the magnitude of the losses in the yoke of the magnetic circuit for the steady state at induction values B <1.9 T and maintaining an acceptable traction force in the tooth zone outside the magnetic circuit. The distribution pattern of the x-components of the magnetic field vector outside the core in the axial section of the induction machine magnetic circuit is shown in Fig. 6

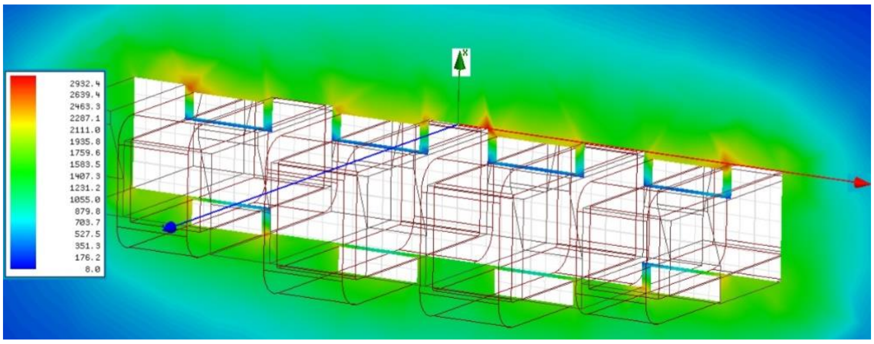
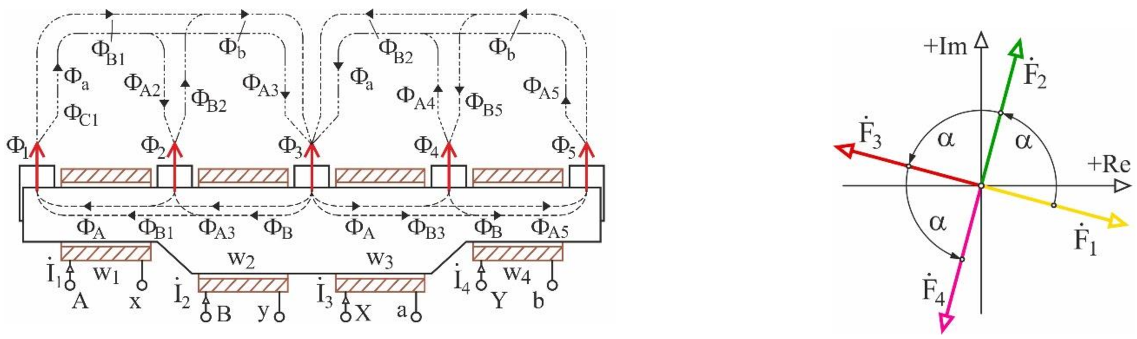


Figure 6

By the nature of the color selection, using the scale it is easy to judge the intensity of the components, the force vectors of the field. By the numerical values in the tables of calculated results, it is easy to get an idea of the differential parameters of the mode. At the same time, the possibility of representing integral mode parameters in many cases in such modeling systems is limited. Therefore, it is convenient to apply circuit simulation of the magnetic system of an induction machine, presented in a chain configuration, for evaluating integral tooth magnetic fluxes.

An example of the distribution model of the integral working flows of the dentate zone in a longitudinal axial section of the inductor is shown in Fig. 7, a. The distribution diagram for the teeth of the MMF vectors of the balanced system in the reverse order of the phase rotation is shown in Fig. 7, b.



a *b*

Figure 7

The flow distribution down is not considered, since it does not affect the molten metal in the bath. The calculated values of the flows down are less than the useful tooth flows directed into the melt (Fig. 1), due to the presence of ferromagnetic teeth on top of the core, which serve as magnetic field concentrators.

The calculation of the electromagnetic modes of the induction machine of the longitudinal magnetic field is conveniently carried out using the multiphase model of the magnetic circuit [12]. The structure and parameters of the model are determined by the actual geometry of the inductor and the winding mode. The indicated magnetizing forces take the values of equivalent sinusoidal currents taking into account saturation for a fixed inductor mode. Increased values of MMF of the side windings are applied according to the results of the parametric optimization of the distribution of integral gear waves [11] under the condition of the greatest achievable homogeneity in a circular raster.

A fragment of the spatial circuit model of a two-phase nonlinear magnetic circuit is shown in Fig. 8. The construction and determination of parameters of a detailed magnetic circuit model are considered in [8, 9].

A feature of the presented model can be considered the use as magnetizing sources, controlled sources. The matrix description of the controlled source of magnetic voltage corresponds to the traditional four-pole element of the theory of circuits, referred to as a voltage source controlled by current. Here the principle of analogy of electric and magnetic circuits is used. The magnetization control mode allows changing the coefficients k_1, k_2, k_3, k_4 to take into account the changing harmonic composition when magnetizing the steel magnetic circuit. It should be understood that, by the principle of analogy of electric and magnetic circuits, we are talking about sources of magnetic voltage (MMF) controlled by magnetic flux or magnetic voltage.

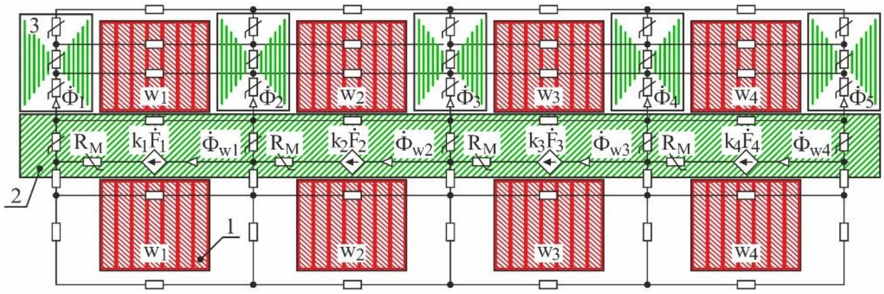


Figure 8

Practical iterative calculations showed that in the steady state in the center of the magnetic circuit, the relative magnetic permeability can be reduced to 20–30 units with a corresponding increase in the magnetic resistance (H – 1) of the circuit. The order of complexity of the model can be very significant, however, the study showed that an increase in the number of nodes, for example from 200 to 1000, with correct determination of the integral parameters of the model, does not lead to a significant increase in the accuracy of the calculation. The description of the mathematical model is formed manually, in the ASCII code, similar to some versions of the Ansys software.

The results of the iterative calculation of electromagnetic mode of IM are presented in the form of a vector diagram. The distribution diagram of the amplitude vectors of working magnetic fluxes is shown in Fig. 9. The diagram shows an expanded raster of the magnetic field above $7\pi/6$, as the sum of the phase angles (φ1-2, φ2-3, φ3-4, φ4-5). The equivalent raster of magnetic fluxes can be estimated by the arrangement of the vectors of the fluxes Φ_1, Φ_2, Φ_3, Φ_4, Φ_5 with a circular movement counterclockwise from the vector Φ_1 to the Φ_5 vector. This indicates the magnetic poles raster expansion for four-zone inductor with a two-phase supply beyond $2p = 2$ when moving counterclockwise along a spiral path between points n and m.

Regulation of the magnetizing forces of the windings F1 and F3 on the value of ΔF_1 and ΔF_3 redistribute the tooth flows Φ_1, Φ_2, Φ_3, Φ_4, Φ_5, changing their intensity and phase shifts. Naturally, with a pair-wise counter-switching windings of different phases, the possibilities of regulation are limited, even if there is the possibility of program-algorithmic control of the inverter mode.

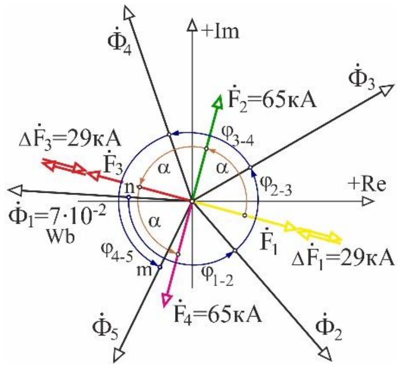


Figure 9

Somewhat better regulation results can be obtained for powerful electromagnetic melt-mixing complexes using separate control of the windings of the induction machine. For such a solution, it is possible to obtain a different coordinated mode of separate power supply in phases, varying the voltage and current of the power transistor link in accordance with the complex requirements for power supply. You need to understand that this option is somewhat more expensive, so it is accepted after the feasibility study. An example of the scheme of a separate connection of the windings of the inductor 1 to a two-phase transistor inverter 2 is shown in Fig. 10.

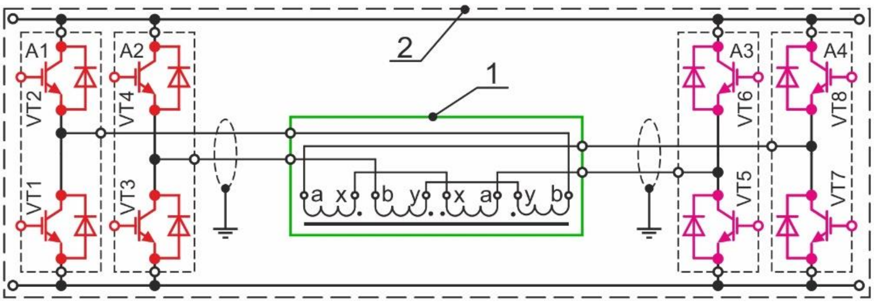


Figure 10

With this approach, there is another consequence of the new circuit design. Compared to the three-phase connection of the inductor windings, 4 copper connection cables (195 mm^2 each) must be used for separate control. This is greater than in the original three-wire circuit. Given the large currents, and sometimes the considerable length of the cable line, they receive a slight increase in voltage losses, which can reduce the efficiency of the complex as a whole.

A way out of the situation can be considered a constructive solution with the combination of an induction machine and a power source in a single structure, when placing such a complex under the furnace. Thus, the wires can be shortened, and to maintain the thermal conditions in harsh temperature conditions under the furnace, in the IGBT inverter, you should use the air conditioning system with air conditioning and air cleaning.

It should be noted that a detailed study of the possibility of controlling the shifts of magnetic fluxes is the subject of parametric optimization. In this case, the optimization criteria can be set substantially different, both for uniform distribution of the prong flows, and for extremely non-uniform. The main parameter in the design of the optimization objective function should be the amount of traction in the melt developed by these flows. It is noteworthy that it is in the two-phase power supply system that there are expanded possibilities for separate control of the windings of the induction machine, while the three-phase system is limited in control capabilities, since it is coherent.

It should be noted that the results presented here should be considered as a statement of the problem and the first approximation to the calculation of the electromagnetic mode in the development format of the induction MHD machine of the above configuration.

Conclusion. When building energy-efficient two-phase induction MHD machines, several interrelated problems should be solved. Evaluation of the effectiveness of the effect of inductors on the molten metal when changing the operating characteristics is the essence of the magnetohydrodynamic problem. The study of the characteristics and features of the electromagnetic field of an induction machine, as well as the methods of controlling the redistribution of magnetic flux, relates to the field of mathematical modeling and optimization of the inductor magnetic system. Creating an effective winding scheme, controlling the number of poles and the speed of a traveling magnetic field should also be considered as a task in the field of research of the field of flat induction machines of a longitudinal magnetic field. In addition, it should be understood that the standard three-phase inverters rotating asynchronous electric drive are not suitable for powering two-phase machines. Therefore, when building complexes of different dimensions, intended for electromagnetic mixing of the melt, it is necessary to create a series of economical and reliable power sources for induction machines, with a different number of phases and various circuitry of winding activation. For each of the designated tasks and the whole variety of designs of induction machines it is necessary to devote a separate study.

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