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COMPLEX DESIGN TOOLS FOR IMPROVEMENT OF ELECTROMECHANICAL SYSTEMS WITH INDUCTION MOTORS

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The stages, methodology and complex design tools of electromechanical systems with inductions motors are substantiated. A quantitative assessment of the possibilities of increasing their economic efficiency using complex design according to the criterion of maximum income is provided. The expressions of complex criteria of efficiency, complex mathematical models and research methods are substantiated. The change in economic efficiency is determined when the value of design parameters deviates from the optimal value. Using the developed means of complex design can increase economic efficiency by tens of percent is shown. References 22, table 1, figures 2.

Keywords: induction motor, complex design, complex mathematical model.

Complex approaches to all spheres of human activity are a natural step towards minimizing the negative impacts of technical civilization on the environment. Complex approaches are a prerequisite for waste-free production; they can provide the maximum useful result with minimal consumption of energy and material resources taking into account the features of operating conditions. Such approaches are effectively used in many industries, in particular in the analysis and synthesis of objects in the energy sector [1, 2], biotechnology [3, 4], the creation of automatic control systems [5, 6]. Induction electromechanical transducers are the most common type of mechanism for creating mechanical action using electrical energy. This is due to their cheapness, reliability, high enough efficiency. Such motors consume about half of all produced electricity and the perfection of their conditions significantly affects on the efficiency of production activities. Analysis and synthesis of electromechanical system (EMS) parameters with induction motors (IM) according to complex criteria provide the possibility of a significant increase in the efficiency of technological processes and mechanisms according to the final result of their useful action (in some cases - at times, due to the justification and application of new structures and the implementation of synergistic effects of integrated design).

There are two trends in the strategy of scientific research in the design of EMS with IM: the use of universal technical solutions that are produced in large series, or the development of specialized equipment for specific conditions of use. The choice of a universal or specialized technical solution is carried out according to the results of a technical and economic comparison of these design options with the final result of obtaining a useful product. Features of the integrated design are due to its goal: the search for such an optimal set of design and operating parameters of the developed object (in this work, the main attention is paid to the refined accounting of IM operation conditions as part of EMS), which will provide the maximum system efficiency with minimal resource consumption.

The purposes of this work are: substantiation of the stages, methodology and means of EMS complex design with IM; development and research of complex performance criteria, taking into account capital and operating costs and the impact of economic and technical work conditions on the optimal parameters; assessment of the possibilities of increasing the EMS economic efficiency with IM due to the complex design using.

Requirements for the means of design synthesis are determined by the ratio of the needs for universality or specialization of electromechanical equipment. Accordingly, complex design can be classified into three types:

1. Designing system components independently of each other, using the efficiency criteria and limitations of the system (system design). For example, there is no necessity to regulate the multiplicity of currents and moments in starting regimes and at critical slip (overload capacity), when designing induction motors (IM) of frequency control systems, since these regimes are formed by the control system. Removing

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the restrictions of such regulation creates conditions for the IM design with the improvement of energy and mass-dimensional indicators in the main operating conditions [7].

2. Designing system components using the efficiency criteria and limitations of this system according to mathematical models of integrated design is taking into account the mutual influence of the system components and the corresponding change in the operating conditions parameters. For example, if an induction motor of a piston compressor drive is designed according to the methods for stable regimes and with high efficiency in these regimes, then under real operating conditions with a pulsating load, the efficiency can significantly decrease (up to 10% or more) [8]. The reason is the ripple of the speed and currents values. In the process of optimal design, complex mathematical models of the dynamic conditions of the engine-compressor system are used, which makes it possible to bring the efficiency indicators closer to the maximum (the drop in efficiency can be at least halved in comparison with the IM optimized according to the stable regimes).

3. This is the design and construction of the system components according to 2 and taking into account the possibility of their functional combination, when one combined element of the system does several functions. For example, an induction motor rotor can be equipped with blades and carry out the functions of a hydraulic pump impeller, in the case of a motor-pump [9]. The simplest case of functional combination the system components can be carried to monoblock structures, for example, the IM and the pump, when the centrifugal pump impeller is located directly on the induction motor shaft. The same bearing suppot applies to both the IM and the pump in this monoblock design. This simplifies the design, improves weight and dimensions, and reduces friction losses (there is a synergistic effect of reducing friction losses in comparison with the shafts of separate IM and the pump connected by the coupling, which is due to the absence of distortions due to the shafts incompatibility).

New directions of science and technology have appeared as a result of appling integrated design. This is mechatronics or electromechanotronics in the field of electromechanical systems. There is some discrepancy in the interpretation of these terms in domestic and foreign technical literature. In the domestic literature, electromechanotronics traditionally studies integrated (functionally and structurally) systems with electromechanical and semiconductor converting parts [10], and the term mechatronics is often referred to as mechanical, hydraulic power actuators with an electromechanical control part [11]. In foreign literature, mechatronics is a definition that often combines both of the above terms. Another direction in the science development based on the integrated design principles, is the design of multifunctional induction motors [12] (for example, the simultaneous realization of mechanical work to move liquid or bulk media and their heating). In this case, the synergistic effect is in useful use of losses in induction motors and intensification of their cooling [13].

Mathematical models of complex IM design are changing in accordance with the needs of the above types of such design. With the first type, the mathematical apparatus for designing AM for stable regimes can be used to a large extent [14,15]. The specificity of such design is associated with the features of the efficiency criteria formation and design synthesis limitations, with a more detailed study of the factors associated with the operating conditions in the system. For example, it is necessary to take into account the increased specific weight of losses from higher temporal and spatial harmonic components, for IM frequency drive [7].

In the second type of integrated design, the requirements for mathematical models, are satisfied the models of electromechanical systems and their components, which are developed using the simulation system (for example, MATLAB) [16, 17], taking into account the mutual influence of the system components. The equations of electrical and mechanical equilibrium of these models are differential equations, they are solved with relatively to the dependences of the immediates values of electrical and mechanical variables.

An IM mathematical models of electromechanotronic systems (EMTS) correspond to the requirements for mathematical models of complex design [18]. They provide analysis taking into account the asymmetry and nonlinearity of electromagnetic parameters, spatial and temporal nonsinusoidality of processes. An increase in the efficiency and adequacy of IM EMTS complex mathematical models are provided by using of nonlinear dependences of electromagnetic parameters, determined by the equivalented of IM field mathematical models by their circular analogies [18, 19].

The IM mathematical models should correspond to requirements for mathematical models of complexed design and often should be multiphysics - should take into account electromagnetic, thermal, hydraulic, acoustic processes (the third type of complexed design).

Comlexed criteria of EMS efficiency. The systems efficiency in complex design directly depends on the applied criterion. For example, maximizing the pumping unit efficiency of a hydraulic system provides a high efficiency of converting electrical energy into hydraulic, but doesn't take into account the features of the consumer's operating conditions, in some cases it reduces the system efficiency with the final result [8]. That is, the system efficiency is determined by the result of its useful final action, which should quantitatively assess the positive system effect in order to find the conditions for its maximum efficiency. The indicator of system efficiency is a value that assesses the useful product, created by the system. The system useful action must be assessed integrally for a certain period, if the system operating condition changes over time. The period for evaluating the system usefulness should cover those stages of the production cycle that are characteristic of the design object and during which the useful action of the system changes as the design parameters of the design object change.

The criterion for the system efficiency (assuming that capital investments apart from energetic and operating costs are unchanged), can be the energy efficiency coefficient is the dividing result of the efficiency indicator, which allows us to assess the system useful effect over a certain period of time, to the energy consumed by the system during this time. For example, for EMS water supply the ratio of the water amount delivered to the consumer to the energy consumed by the system is used as a complex criterion of efficiency. For example, the complexed design of wind or hydroelectric installations, the end product of their functioning is energy delivered to the consumer and the energy efficiency coefficient is the ratio of this energy to the source energy: the energy of the air flow through the area blown by the wind turbine, or the potential energy of the water reservoir.

Determining the optimal parameters of systems with finding a balance between capital and operating costs is of interest to the consumer of equipment with a significant change in capital expenditures by varying the optimization parameters. That is, in general, the consumer is interested in both the energy efficiency of the equipment and the payback period of capital investments. The optimal parameters of systems are determined by finding a balance between capital and operating costs and are often carried out using the value E_r as an optimization criterion. E_r is the minimum yearly reduced costs for the standard operating life (for example, T_{sls} = 7 years) [20-21]:

$$E_r = E_c / T_{sls} + E_{oa} , \quad (1)$$

where E_c, E_{oa} are capital costs (including construction and installation) and yearly operating costs, including materials, maintenance, service, wages.

Design according to criterion (1) provides a balance between capital and operating costs, but doesn't take into account the specific conditions for using the system, in particular: taking into account the profit amount from the sale of production unit, which affects the payback period.

We investigate how the economic efficiency of EMS functioning depends on the applied criterion of its optimal design. In this case, we accept: 1) A unit of a useful product manufactured by the system and delivered to the consumer has a price (if this product is not an independent, then it is necessary to agree its share in the final product and thereby determine its price equivalent c_p); 2) The cost of setting up the system is covered by credit rate on a bank loan δ_l (The percentage on the loan is paid together with the basic amount of the loan when the required amount of profit is accumulated); 3) The system life without accidents and general maintenance is T_{sl} years.

A complex criterion for the EMS effectiveness should take into account the specifics of the technical and economic operating conditions of the system, the design features and operating parameters to improve the design quality with the optimization of capital investments. We use the profit value as a design criterion for optimizing the system parameters, to do this. The case was considered when the operating costs can be determined with enough accuracy by the system energy losses. Moreover, the amount of profit is up to taxation (Pr) is determined according to the expression:

$$\Pr = (V_{pa} c_p - V_{ppa} c_{pp}) T_{sl} - E_c (1 + \delta_l T_{pb}) , \quad (2)$$

where V_{pa}, V_{ppa} are the average yearly volumes of the manufactured product and the primary consumed product; c_{pp} is the cost of the consumed product; T_{pb}, T_{sl} are payback periods of initial investment and operation, in years.

Realization of optimization complex design. The conditions for optimization studies using complex IM mathematical models are enough complicated, which determines the use of appropriate methodologies for finding the extrema of the objective functions. Complicating factors are: nonlinearity and high order of the equations system of the IM mathematical model (especially by the field analysis conditions); there may be a need to study the dynamic conditions, which leads to a significant increase in computer time; problematic presentation of the goal function in an explicit form; taking into account the mutual influence of the system components in the studied regimes.

The features assessment of use the EMS complexed design with IM was carried out in the study of EMS: electric line - IM - load. The EMS with IM ATD-8000 with a rated power of 8 MW and a voltage of 6 kV powering by a line with a length of L = 8200 m is investigated. Stable and variable load variants are investigated. In the first variant, the constant resistant torque on the motor shaft is determined at a motor load factor is 1.2. In the second variant, the torque on the shaft during the operation time varied linearly from the first variant to zero. Research conditions: daily and yearly operating condition are T_d = 20 hours/day and T_y = 200 days/year (number of operation hours per year $T_{oa} = T_\text{d} \cdot T_\text{y}$); base phase voltage at the input of the supply line is $U_{1fL} = 1{,}05 \cdot 6 \cdot 3^{-1/3}$ kV; cost of electricity losses is c_{eb} = 2 UAH/kW·h; a cable with the following parameters was taken as a base: crossing of wires is s_b = 150 mm^2; cost of a running meter is c_{mb} = 1200 UAH/m; active resistance of the core is r_b = 0,122 Ohm/km. When the crossing of wires s changes, the change in operating costs in the line corresponds to a change in resistance $r = r_b s_b / s$, and capital costs change:

$$E_c = c_{mb} L s / s_b . \tag{3}$$

The mathematical model of IM for complex modeling of EMS was developed in the simulation system with nonlinear parameters, which were determined from the results of field analysis [18]. The error in determining the parameters of the design and starting conditions in mathematical modeling doesn't exceed 2% in comparison with the data of the reference book [22]. The complex mathematical model of EMS *electrical line - IM - load* is shown in Fig. 1 for the simulation system. At the same time, the IM mathematical model is presented in the imitation blocks form of stator winding branches with their input and output terminals (n1-k1, n2-k2, n3-k3). At the every step of numerical modelling, the initial information for calculations is transmitted from the simulation system (in Fig. 1 - from the measurer block) of the motor structural model (in Fig. 1 - the ATD_8000 block) in the form of current voltage values. There the IM load torque is set, the angular frequency of the rotor rotation and the instantaneous values of the currents in the branches of the stator winding are calculated. The last control signals for the library blocks of the MATLAB current sources, which are located in the blocks of the stator winding branches. The block for accounting losses in steel (as a function of the magnetization reversal frequency and induction in the IM magnetic circuit) and additional losses are connected in parallel to the input of the IM.

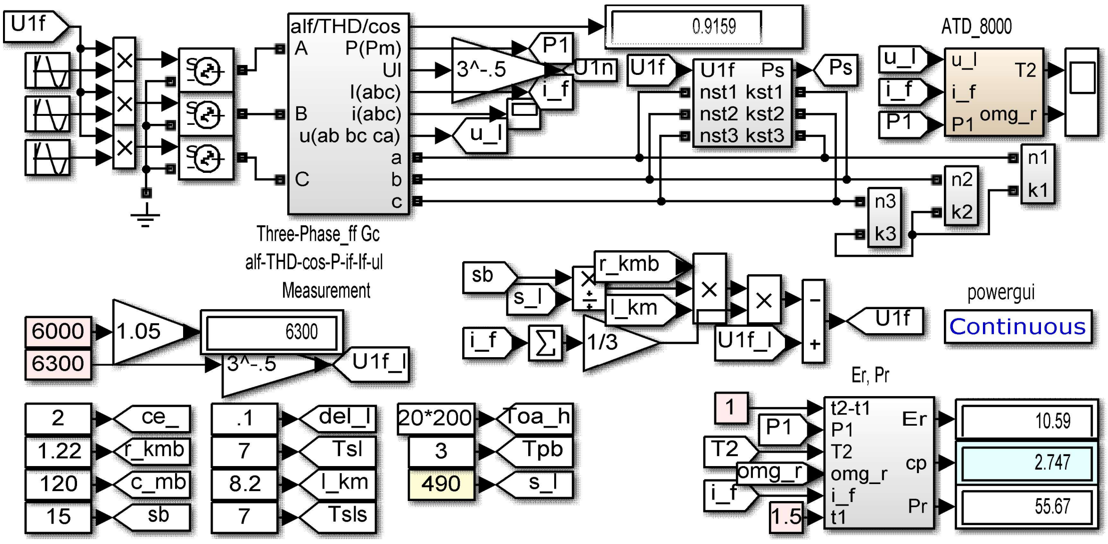


Fig. 1

The parameters of the IM operating condition were calculated taking into account the voltage recession in the line of its power supply. It was assumed that the study regime is symmetrical and constant. In this case, taking into account the change in the crossing of network wires, the phase voltage at the IM input is:

$$U_{1f} = U_{1fL} - I_L r_b s_b / s\,,$$

where I_L is the effective value of the phase current in the electrical network (is determined in the process of modeling the EMS operation condition, Fig. 1).

The produced value of the useful product V_{pa} (mechanical energy at the output of the blood pressure) and the primary consumed product V_{ppa} (energy consumed by EMS), (2) were determined integrally based on the mathematical modeling results of the operating condition. This determination was carried out at the end of the calculation of the electromagnetic transient processes of IM connecting (time t_1). The operating energy consumption was determined in a similar way by the amount of energy losses in the network E_{oaL} and the IM E_{oaM} (block *Er, Pr,* Fig. 1):

$$V_{pa} = \frac{10^{-3} T_{oa}}{t_2 - t_1} \int_{t_1}^{t_2} T_2 \omega_r dt\,; \qquad E_{oaL} = \frac{10^{-3} T_{oa} r_b s_b c_{eb}}{s(t_2 - t_1)} \int_{t_1}^{t_2} \sum_1^3 I_L^2 dt\,;$$

$$E_{oaM} = \frac{10^{-3} T_{oa} c_{eb}}{t_2 - t_1} \int_{t_1}^{t_2} \left(P_1 - T_2 \omega_r\right) dt\,; \qquad V_{ppa} = \frac{E_{oaL}}{c_{eb}} + \frac{10^{-3} T_{oa}}{t_2 - t_1} \int_{t_1}^{t_2} P_1 dt\,, \tag{4}$$

where P_1 is active power at the IM input; T_2, ω_r is an useful torque on the IM shaft and its angular velocity; I_L is the current effective value of the electrical network phase; t_1, t_2 is the time of the beginning and the end of the integral assessment period of the operating conditions parameters.

Information about the payback time and the price equivalent of the manufactured product is needed to calculate the amount of profit up to taxation by expression (2). These values are interrelated Their connection can be established with (2) taking into account that $T_{pb} = T_{sl}$ there is no profit $\mathrm{Pr} = 0$:

$$T_{pb} = 1/(GP / E_c - \delta_l)\,; \tag{5}$$

$$c_p = [V_{ppa} c_{pp} + E_c (1/T_{pb} + \delta_l)] / V_{pa}\,, \tag{6}$$

where $GP = V_{pa} c_p - V_{ppa} c_{pp}$ is a gross profit.

An optimization study of the dependence of the reduced costs minimum (1), (4) by the crossing of network wires is carried out using the developed mathematical model (Fig. 1). In this case, the operating costs were determined in total both in the line and in the IM:

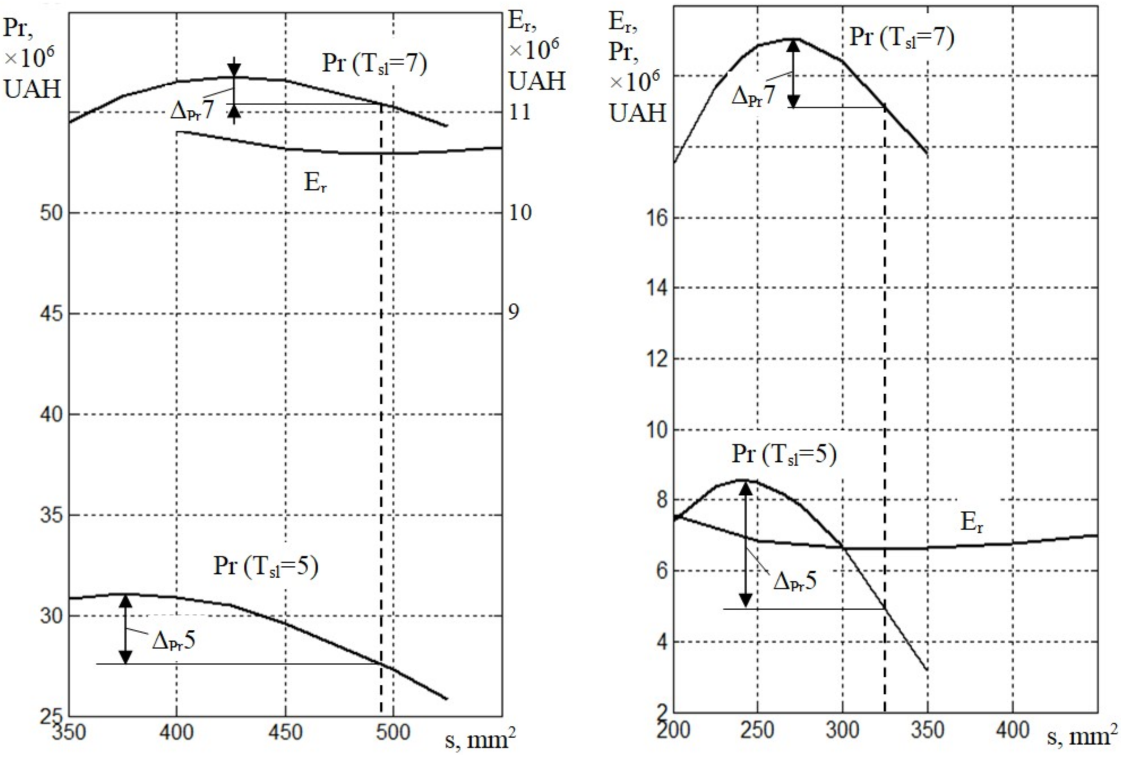
$$E_r = E_c / T_{sls} + E_{oaL} + E_{oaM}\,, \tag{7}$$

and only in line. In both cases, the extrem values of the line intersection coincide. Graphical dependences of the obtained results E_r (T_{sls} = 7 years) are shown in Fig. 2 for the above both regimes of constant load (Fig. 2, *a*) and variable (Fig. 2, *b*).

To compare the design results according to the criteria of the minimum reduced costs (7) and the maximum profit, we transform expression (2) taking into account (5):

$$\mathrm{Pr} = GP \cdot T_{sl} - E_c \left(1 + \frac{\delta_l}{GP / E_c - \delta_l} \right). \tag{8}$$

To calculate dependence (8), one must have information at the price equivalent of the manufactured product c_p. Its value is determined in accordance with the specific design conditions. In this work, for a comparative study, the c_p was determined by expression (6), provided that the payback time $T_{pb} = 3$; the values V_{pa}, V_{ppa}, E_c were determined relative to the optimal crossing of network wires according to the minimum of the reduced costs (Fig. 2, *a*): $s = 490$ mm^2. Under these conditions, the value c_p = 2,747 UAH/kW·h.



a ***b***

Fig. 2

The dependence of the profit change (8) with an area change s is calculated for the operating time T_{sl} = 5 and 7 years for stable (Fig. 2) and variable load regimes (Fig. 2, *b*). Figure 2 shows the dependence of the reduced costs E_r and profit dependencies $\Pr$ for two values of a given system operation time T_{sl}, for which the profit is estimated when the crossing of network wires changes. The profit amount at the optimal crossing of network wires, which corresponds the criterion of the minimum of reduced costs, can be determined at the intersection of the vertical dashed line (through the dependence extremum E_r) with the dependence $\Pr$. The size of the profit increase when optimization design parameters according to the criterion of maximum profit compared to optimization according to the minimum of reduced costs in Fig. 2 is marked by Δ_{Pr5}, Δ_{Pr7}, respectively, for 5 and 7 years of system operation. The increase in profit is 6 ... 15% for a stable load and 12 ... 70% for a variable one, in the carried out research.

A numerical experiment shows that the optimal crossing of network wires of the supply line changes significantly with a change in the criterion and conditions for extremum searching. Optimization of design parameters according to the criterion of maximum profit, taking into account the specifics of operating conditions, provides a possibility to improve the economic efficiency of the system. The magnitude of the improvement Δ increases with an increase in the difference between the service life of the system: standard and specified T_{sls} and T_{sl}, as well as with an increase in the yearly interest rate δ_l (at a zero rate and equal values of T_{sls} and T_{sl}, optimization by both criteria gives the same result).

Optimization studies in Fig. 2 are carried out by varying one parameter, it is enough simple to realize a search of its values. The search of the goal function extremumis much more difficult with an increase in the number of optimization parameters. It can be effectively carried out by the sequential quadratic programming algorithm using the Optimization Toolbox package of the Matlab system using the developed complex mathematical model. A series of regimes calculations takes place according to this algorithm, which are investigated with a change in the optimization parameters. According to the chosen optimization method, the parameters are varied and the extremum of the goal function is found.

As an example and to study the patterns of change in the profit value, the case of two optimization parameters (supply voltage at the network input and the crossing of network wires) is considered. The limitation on the value of the allowable heating loss in the motor refers to the optimization conditions. Optimization was carried out by varying the optimization parameters within U = (6000 ÷ 9500) V, crossing of wires s = (150 ÷ 550) mm^2. Profit on taxation according to expression (8) is accepted as the goal function of the optimization task. Mechanical energy on the motor shaft is taken as a useful product, its price equivalent is determined with the payback of the cable costs during 3 years of operation with a stabl load, c_p = 2,747 UAH/kW·h. The maximum of the goal function is found for two load variants, due to the above: with constant and time-varying powers. This optimization results, in comparison with the previous results, are summarized in the table.

Parameters	Optimal parameter values according to the criterion: Maximum profit (U_{1L} = var, s = var) Maximum profit (U_{1L} = const, s = var) Minimum consolidated costs			
	$P_{\text{н}}$=const		$P_{\text{н}}$= var	
	T_{sl} = 7	T_{sl} = 5	T_{sl} = 7	T_{sl} = 5
s, mm^2	325 425 490	285 375 490	225 270 320	195 240 320
U_{1L}, V	9250 6300 6300	9100 6300 6300	8000 6300 6300	8100 6300 6300
Pr, 10^6 UAH	81.96 56.8 51	52.09 31.1 27.5	28.92 21 19.1	15.76 8.56 5

Optimization studies with varying supply voltage made it possible to determine the degree of change in the optimal parameters and profit. The magnitude of the increase in the optimal voltage depends on the IM degree of loading. Direct practical application of certain voltage levels requires justification by the criterion of dielectric strength, with the considered stable state loading.

Studies have shown that with a decrease in the degree of IM loading, the optimal voltage value decreases and the practical advisability of developing recommendations for using such variant increases. That is, the expected value of the increase in profits must be weighed against costs on adaptation of the design parameters the transformer and IM to the optimal values, which will provide determination of the appropriateness of this adaptation.

Conclusions. The EMS design with IM provides increase of efficiency of design decisions thanks to: using the complex criteria of efficiency, as the relation of EMS efficiency indicator on final action to the consumed resources; application of complex design mathematical models, taking into account the mutual influence of the system components and the refined definition of the EMS efficiency indicator in the process of optimization study of the system operating conditions; justification and application of search way of an extremum of goal function at complex modeling.

The applying of profit magnitude as a criterion of efficiency increases the quality of design solutions by taking into account data on payback and operation periods, investment conditions.

Optimization studies of EMS with using the IM complex mathematical models provide an increase in the efficiency of design solutions as a result of refined accounting for changes in the EMS operating conditions parameters when changing the indicators of IM operating conditions, including when using field analysis.

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ЗАСОБИ КОМПЛЕКСНОГО ПРОЕКТУВАННЯ ДЛЯ ВДОСКОНАЛЕННЯ ЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМ З АСИНХРОННИМИ ДВИГУНАМИ

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Обгрунтовано етапи, методологію та засоби комплексного проектування електромеханічних систем з асинхронними двигунами. Надано кількісну оцінку можливостей збільшення їхньої економічної ефективності із застосуванням комплексного проектування за критерієм максимуму доходу. Обгрунтовано вирази комплексних критеріїв ефективності, комплексні математичні моделі, методи дослідження. Визначено зміну економічної ефективності за відхилення величини проектних параметрів від оптимальної величини. Показано, що застосування розроблених засобів комплексного проектування може збільшувати економічну ефективність на десятки відсотків. Бібл. 22, табл. 1, рис. 2.

Ключові слова: асинхронний двигун, комплексне проектування, комплексна математична модель.

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