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SYNTHESIS OF THE SYSTEM FOR MINIMIZING LOSSES IN ASYNCHRONOUS MOTOR WITH A FUNCTION FOR CURRENT SYMMETRIZATION

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Виконаний математичний опис режимів роботи електропривода ТПН-АД, у яких можливе зменшення втрат потужності. Виконана розробка системи мінімізації втрат асинхронного двигуна. Наведена структурна схема, виконані розрахунки системи керування. Зазначені показники зменшення втрат і показники симетрування при живленні від джерела з несиметричною напругою. Ілюстровані особливості роботи системи та шляхи підвищення її ефективності

Ключові слова: асинхронний двигун, тиристорний перетворювач, електропривод, мінімізація втрат, несиметрія напруг, симетрування

Выполнено математическое описание режимов работы электропривода ТПН-АД, в которых возможно уменьшение потерь мощности. Выполнена разработка системы минимизации потерь асинхронного двигателя. Приведена структурная схема, выполнен расчет системы управления. Указаны показатели уменьшения потерь и показатели симметрирования при питании от источника с несимметричным напряжением. Иллюстрированы особенности работы системы и пути повышения ее эффективности

Ключевые слова: асинхронный двигатель, тиристорный преобразователь, электропривод, минимизация потерь, несимметрия напряжений, симметрирование

1. Introduction

A trend to building-up mass production of controlled electric drives (ED) is observed in the current world practice. By the beginning of the 2000s, leading electrical companies had stopped or significantly reduced production of direct current ED [1]. According to the data of economically developed countries, ED with asynchronous motors (AM), mainly with a squirrel-cage rotor, account for 80 % to 90 % of the total amount of electric power consumed by ED. This is due to their relatively low cost, less need for scarce materials in comparison with electric motors of other types, cost effectiveness, simplicity, and reliability of operation. As applied to asynchronous motors, two systems of ED are widely used: ED with thyristor voltage converters (TVC) and ED with frequency converters (FC). Advantages and disadvantages of both ED systems are known. The use of ED of one or another system is determined by the technical and economic requirements of the driven mechanisms to the ED.

The TVC-AM electric drives are characterized by low cost, simplicity, good weight-to-size indicators, high reliability, and wide functionality (especially when used in closed-loop systems) [2]. Analysis of capabilities of an asynchronous electric drive with the thyristor voltage converter shows that it can successfully compete with the frequency electric drive. TVC-AM is characterized by lower cost parameters and can be recommended in cases where long-term operation at a speed below nominal values is not required. Even though development of TVC-AM electric drives has more than a fifty-year history, one cannot say that all scientific problems have been solved and the reserves of technical perfection exhausted. For example, solution of the problem of practical development of systems and algorithms for controlling energy-saving TVC-AM modes is promising. It is also important to develop electromechanical systems aimed at compensation for the negative properties associated with impairment of the power source quality indicators.

2. Literature review and problem statement

It is known that despite their advantages, asynchronous motors have high energy indicators only when operating under nominal mode. Deviations from the nominal operating mode of AM associated with load reduction lead to a significant deterioration in the energy performance of the motors [3, 4]. Electric drives with a thyristor voltage converter enable solution of this problem. What is at issue is a prolonged work at artificial characteristics in the region of a nominal slip with power losses in asynchronous motors smaller than in the working section of the natural characteristic [4, 5]. The converter output voltage exerts a control action and the asynchronous motor operates at an optimum adjusting mechanical characteristic [6]. The voltage is controlled downward from the rated voltage. The optimum characteristic is calculated proceeding from solution of the problem of extreme control according to the criterion of minimum power losses [7].

The studies carried out by the authors of work [4–7] solve to a significant degree the problem of theoretical substantiation of optimization of the energy parameters of asynchronous motors and synthesis of energy-saving control systems. However, the proposed electromechanical systems were designed and recommended for use with normalized voltage quality indicators of the power supply and are completely invariant to their change. Operation of such systems in conditions of asymmetry of the power source voltages is completely ineffective and does not lead to a reduction of power losses in asynchronous motors.

At the same time, it is known that the normalized indicators of the electric energy quality always correspond to the required ones that determines the possibility of operation of asynchronous motors, for example, under conditions of asymmetry of the power sources [8]. Emergence of asymmetric modes of operation of a three-phase AM may be caused by other factors, for example, asymmetry of resistances in the stator or rotor circuits [8]. Unbalanced operating modes have a negative effect on the motor performance. With voltage asymmetry in electric machines, magnetic fields appear and rotate at a synchronous speed not only in the direction of rotation of the rotor but in the opposite direction as well. As a result, a braking electromagnetic moment and an oscillatory component of the electromagnetic moment with a frequency of oscillation of 100 Hz arise. Active parts of the AM, primarily its stator, are additionally heated because of the phase currents exceeding the nominal value [9]. In the case of voltage asymmetry with a simultaneous voltage drop, the load is distributed unevenly among the phases of the AM windings leading to their overheating even at the load moments significantly lower than the nominal ones. To ensure normal operating conditions when feeding from a source with asymmetrical voltage, it is necessary to overrate the nominal power of the AM or provide measures for symmetrizing voltage of the power source [8, 9].

Theoretical and practical issues of improving energetics of an AM at its partial loading by the TVC means are given sufficient attention in the scientific and technical literature [4–7, 10]. There are much fewer published sources with information on symmetrization of the AM currents in the case of powering from a source with an asymmetric voltage [11, 12]. Information about simultaneous use of symmetrizing and minimizing of the AM power losses under partial loads is practically absent. At the same time, modern means of TVC-AM electric drive control make it possible to solve the problems of reducing losses in the motor, symmetrize the AM currents and combine these functions.

3. The study objective and tasks

This study objective was the synthesis and analysis of a system for minimizing AM power losses with a function of simultaneous symmetrization of stator currents.

To achieve this goal, the following tasks were accomplished:

– mathematically substantiate possibility of and conditions for reducing power losses in the TVC-AM electric drives;

– perform synthesis of the functional scheme and a mathematical description of the system for minimizing AM power losses;

– integrate the results of minimizing power losses and perform their analysis;

– integrate the results of symmetrization of the AM stator currents and perform their analysis.

4. Materials and methods for studying asymmetric modes of operation of asynchronous motors

4. 1. The experimental study base

The study was carried out both by simulation of the loss minimizing system (LMS) in AM and with the help of its physical model. In simulation, a complete AM model was used taking into account nonlinearity of its parameters with the subsequent simulation of TVC based on logical commutation functions [13]. To determine circuit asymmetry, a unit for forming nonlinear voltages of the power source has been developed with a possibility of varying the coefficient of nonlinearity. Evaluation of the results of symmetrization was carried out on the basis of harmonic analysis of the AM stator currents [12, 14].

In the experimental study, a physical model of the power loss minimization system based on the MOELLER DS4 soft starter and a 2.2 kW, 1500 rpm 4A90L4 asynchronous squirrel-cage motor were used. During the experiment, REFCO Halt-08, Fluke-16, National Instruments NI6009, NI9201-USB9162 control and measuring devices available at the Department of Computerized Electromechanical Systems, Odesa National Polytechnic University, Ukraine, were used.

4. 2. Mathematical substantiation of possibility of and conditions for reducing power losses in the TVC-AM electric drives

The electric drive with a thyristor voltage converter enables minimizing of AM power losses. It was a question of prolonged work at artificial characteristics in the region of nominal slip with the AM power losses lower than in the working section of the natural characteristic that was to be solved. The output voltage of the converter exerted a control action and the motor was operating at an optimum adjusting mechanical characteristic. The voltage was controlled downward from the rated voltage. The optimum characteristic was calculated in advance proceeding from the solution of the problem of extreme control according to the criterion of minimum power losses [4, 5].

In the analytical description of the energy conversion processes, a number of assumptions were taken into account:

– linearity of the AM magnetic circuit;

– linearity of the working section of the artificial mechanical characteristic of the AM;

– account for the first harmonic components of the motor stator currents and voltages.

This allowed us to derive an analytical dependence of the control law corresponding to the optimal mechanical characteristic for any of the known types of asynchronous motors. Four main components of the AM losses were taken into account. For further analysis, it was convenient to divide them into two groups: the losses from loading and the losses from magnetization.

It is known that the losses from loading taking place in the AM under nominal operating conditions are described by two components

$$\Delta P_{l\,n} = \Delta P_{1\text{cn}} + \Delta P_{2\text{cn}}, \tag{1}$$

where $\Delta P_{1\text{cn}}$ stands for losses in the stator copper caused by the load current at the nominal load moment, W; $\Delta P_{2\text{cn}}$ stands for losses in the rotor copper caused by the load current at the nominal load moment, W.

The total motor power losses for magnetization in the rated operating mode are determined as follows:

$$\Delta P_{0\text{n}} = \Delta P_{1\text{c0n}} + \Delta P_{\text{sn}}, \tag{2}$$

where $\Delta P_{1\text{c0n}}$ stands for losses in the stator copper caused by the magnetization current, W; ΔP_{sn} stands for losses in the AM steel, W.

When the AM coordinates are adjusted by variation of the converter voltage, the losses caused by the load and magnetization are determined by the dependences [15]:

$$\Delta P_1 = \frac{M_\text{s}}{M_\text{n}} \cdot \frac{s}{s_\text{n}} \cdot \Delta P_{n\,l},$$

$$\Delta P_0 = \frac{M_\text{s}}{M_\text{e}} \cdot \Delta P_{0\text{n}}, \tag{3}$$

where M_e is the moment at the natural characteristic when slip is equal to the slip at the artificial characteristic with a reduced voltage $U_1 < U_{1\text{n}}$.

When taking into account the accepted assumptions, the relationship $\frac{M_\text{e}}{s} = \frac{M_\text{n}}{s_\text{n}}$, is valid, which makes it possible to express the value of the moment M_e through the slip value. Then the losses are determined by the expression:

$$\Delta P = \Delta P_1 + \Delta P_0 = \frac{\Delta P_{l\,n}}{M_\text{n} \cdot s_\text{n}} \cdot M_\text{s} \cdot s + \frac{\Delta P_{0\text{n}} \cdot s_\text{n}}{M_\text{n}} \cdot M_\text{s} \cdot \frac{1}{s}. \tag{4}$$

Obviously, there is some slip s_{opt} at which total losses in the motor will be minimal. Solution of the problem of finding this optimal slip can be obtained by examining extremum of function (4) and determining the value of s at which the quantity ΔP takes its extreme (minimum) value. For an analytical solution, it is necessary to equate to zero the partial slip derivative of the expression ΔP. The roots of this equation characterize extrema of the function under study.

According to the condition of minimum power losses, it is necessary that the AM work in the first (third) quadrant at an artificial adjusting characteristic with an optimal slip:

$$s_{opt} = s_n \sqrt{\frac{\Delta P_{0n}}{\Delta P_{l\,n}}}. \tag{5}$$

The condition of minimal power losses will be satisfied when working in the range of operating moments from zero to some boundary moment M_{bo}.

$$M_{bo} = M_n \sqrt{\frac{\Delta P_{0n}}{\Delta P_{l\,n}}}. \tag{6}$$

The value of the boundary moment corresponds to the intersection of the adjusting mechanical characteristic with the natural characteristic and does not depend on the running AM load and velocity moments. Fig. 1 shows notion of the mechanical characteristics at which the 4A90L4 motor operates.

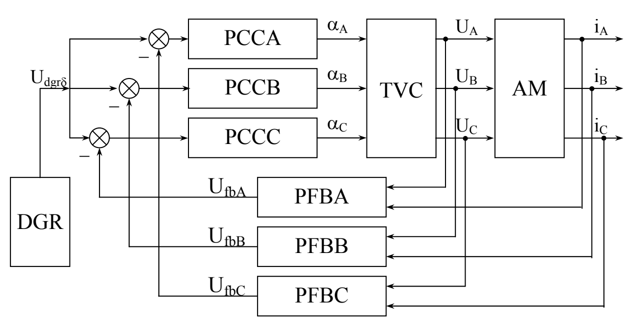


Fig. 1. Mechanical characteristics of the 4A90L4 motor

Curve 1 is a linearized section of the natural mechanical characteristic. Here, the section of the real natural mechanical characteristic of the 4A90L4 AM (characteristic 1') is also given for comparison which allows one to estimate the effect of linearization. The straight line 2 is the adjustment characteristic corresponding to the control law optimal with respect to the criterion of minimum losses. Characteristic 3 corresponds to the adjustment of AM work with a nominal slip. All working points in characteristic 2 correspond to the optimal mode. As the moment increases, this characteristic intersects the natural one at the point b (b') corresponding to the boundary moment M_{bo}. When the load moment is further increased, the mode ceases to be optimal. The position of this point and the width of the working section of the optimum adjustment characteristic depend on the relationship between the loss caused by magnetization and the loss caused by loading in the nominal mode. As follows from (6), the boundary moment for each of the asynchronous motors is determined only by the intrinsic parameters of the motors. In both cases, the motor power losses increase with increase or decrease of the slip relative to characteristic 2. When the slip decreases, the increase in losses is limited by the natural characteristic. In the lower part, when the slip increases, one can draw a conditional boundary where the losses will be equal to the losses at the natural characteristic. This boundary corresponds to line 4 and is called the "the line of equal losses" [4]. The region limited by the section *a–b* of the natural characteristic, the axis of slips and the line of equal losses 4 is the region in which modes can be formed with AM power losses smaller than at the natural characteristic. This area is used in the control optimal by the criterion of minimum losses. Other characteristics encompass a smaller width of this region and characteristic 3 has also a section *c–d* outside the mentioned region. In this section, the motor works not only in a non-optimal mode but with power losses exceeding the losses at the natural characteristic. Graphs of the AM power losses at the natural and adjusting characteristics for the motor under study are shown in Fig. 2. The numerical and letter designations of the curves are equivalent to the notation in the graphs of Fig. 1. Curve 1 represents total losses in the motor when it operates at a natural characteristic. The ideal curves of losses at any adjustment characteristic are straight lines passing through the origin. The straight line 2 corresponds to the losses at an optimum adjusting characteristic. The total losses when the slip is maintained nominal throughout the range of operating moments are represented by the straight line 3. The line of equal losses merges with the section *a–b* of the parabola of losses. The region delineated by the curve *a–b*, the ΔP axis and the graph 2 of losses is the region of saving power losses. Any working point at the natural characteristic, except for the points beyond point *b*, will be obtained at an energetics that is worse than that in the mode of minimization. The losses in the section *c–d* of characteristic 3 are greater than at the natural characteristic.

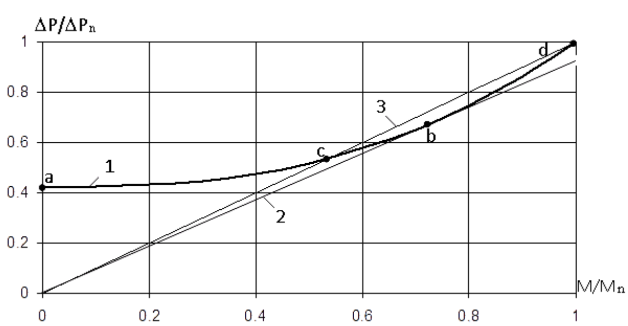


Fig. 2. Graphs of power losses in the 4A90L4 AM

Technical realization of the mode of minimization of losses in the steady-state conditions is only possible in closed-loop ED systems. Moreover, it is not advisable to use slip (speed) feedback since the ED operates in the region close to the nominal slip. This puts requirements to accuracy of the measured values strictness of which is not always justified. The most promising method is based on the property of constancy of the power factor in the loss minimization mode. In this case, the signals of the OS are the angles δ of lag of the end of the AM stator currents. By analogy with the optimal slip, there is δ_{bo} for each AM at which power losses are minimal [15]. This δ_{bo} is determined by:

$$\left.\begin{aligned} &\delta_{\text{opt}} = \text{arctg}\frac{Q_{1\text{n}}}{P_{1bo}}, \\ &P_{1bo} = \omega_0 M_{\text{bo}} + \Delta P_{\text{c}1n}\frac{\Delta P_{0\text{n}}}{\Delta P_{1\text{n}}} + \Delta P_{0\text{n}}, \end{aligned}\right\} \quad (7)$$

where Q_{1n} is the AM rated reactive power, VAr; P_{1bo} is the active power consumed by the AM at the natural characteristic at a load of M_s=M_{bo}, W; ΔP_{c1n} stand for the losses in the AM stator copper at a rated load, W.

It is of interest to study the possibility of minimizing the AM power losses in conditions of asymmetry in the power source voltage. It was established that the mode of minimizing the AM power losses in an explicit form does not bring about the effect of symmetrization. At the same time, symmetrization of the AM stator currents leads to a material improvement in the AM energy parameters. However, the known automatic symmetrizing systems are not invariant to the load variation [12]. The known systems of automatic loss minimization assume their use in the case of phase-symmetrical parameters of the power source and the AM. Such systems use one controller and a symmetrical control and regulation of the TVC thyristors [15]. In the conditions of asymmetry of the power source voltage, it is necessary to use separate phase-by-phase control which requires the use of three control channels and three feedback channels. This makes it possible to solve the problem of minimizing the AM power losses owing to the equality of the load angles to the optimal angle δ_{bo} and obtain a symmetrization effect owing to the equality of the angles δ in the AM phases.

5. Description of the system for minimizing the AM power losses

The functional diagram of the system for automatic minimization of the AM power losses with symmetrization functions is shown in Fig. 3. The electromechanical system includes:

– a thyristor voltage converter (TVC);

– an asynchronous motor (AM);

– a device for generating the reference signal (DGR) which specifies the control signal in the function of the δ_{opt} angle;

– asynchronous motor phase control channels (PCCA, PCCB, PCCC);

– phase feedback channels for each phase (PFBA, PFBB, PFBC).

Each of the control channels includes a PI-regulator of the angle δ (RD) and a pulse-phase control system (PPCS) (Fig. 4, *a*). Each of the feedback channels includes the following (Fig. 4, *b*):

– angle δ sensor (DS) for measuring the angle of the current lag per each

half-cycle of the TVC voltage;

– a memory element (ME) storing the value of the feedback voltage which is updated in the time interval t=0.01 sec.

The action of the LMS begins at the end of the transient process of the AM start. The principle of operation with a symmetrical power source voltage is that when the load on the AM shaft decreases (when the δ angle increases), the feedback effect results in a decrease in the output voltage of the thyristor converter which brings about a decrease in the AM stator currents. As a consequence, it is possible to maintain equality of the δ angles to the optimal value of δ_{bo}. This allows us to solve the problem of power loss minimization. When feeding is realized from a power source with asymmetric voltage, simultaneous minimization of the AM losses and symmetrization of currents is achieved due to the equality of the δ angles in each of the AM phases. In this case, the angles of switching gates of the thyristor converter are essentially asymmetrical.

The system of automatic minimization of AM power losses can be constructed on the basis of the TVC-AM electric drive with synchronization both with the mains voltage and the load current [5, 16]. The main feature of designing an automatic control system is the parameter α or γ with respect to which control is performed. The value of the optimal δ angle can be found on the basis of expressions (6), (7).

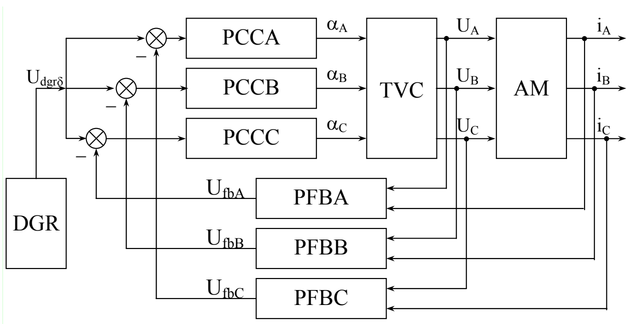
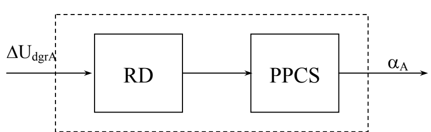
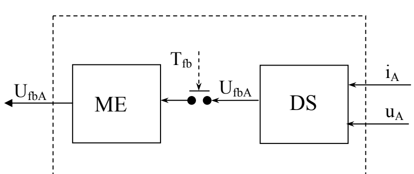


Fig. 3. Functional diagram of the system of automatic minimizing the AM losses



a



b

Fig. 4. Functional diagrams: control channel (*a*); feedback channel of phase A of the system of automatic AM power loss minimization (*b*)

$$M_{bo} = 14.8 \cdot \sqrt{\frac{187.3}{364.7}} = 10{,}6 \ \text{Nm}; \tag{9}$$

$$P_{1bo} = 157 \cdot 10.6 + 304.7 \cdot \frac{187.3}{364.7} + 187.3 = 2007.9 \ \text{W}; \tag{10}$$

$$\delta_{opt} = arctg \frac{1680.1}{2007.1} = 39.9 \ \text{el. deg.} \tag{11}$$

The dependence of the control angle on the control voltage is expressed as

$$\alpha = 0 - K_{ppcs\,\alpha} U_{out\ rc}, \tag{12}$$

where $K_{ppcs\,\alpha}$ is the PPCS transmission coefficient.

$$K_{ppcs\,\alpha} = \frac{\alpha_{\max}}{U_{\text{out rc}}} = \frac{120}{10} = 12 \frac{rad}{V}. \tag{13}$$

It is assumed that the feedback channel is described by an amplifying circuit with a transmission coefficient

$$K_{fb} = \frac{U_{fb\max}}{\delta_{\max}}, \tag{14}$$

where U_{fb}=10 V is maximum feedback voltage.

The angle $\delta_{\max}$ does not exceed 90 el. deg. under normal operating conditions in the first quadrant but when there is a significant asymmetry of the power source voltage, its values can reach 120 el. deg. in individual phases.

The voltage of the input signal generator is determined proceeding from the condition that the input voltage and the feedback voltage are equal when the value of the angle δ is equal to the optimal value δ_{bo}.

$$U_{dgr\,\delta} = \delta_{opt} \cdot K_{fb}. \tag{15}$$

Each of the angle δ controllers is a PI controller which is described by the transfer function

$$H_{r\delta}(p) = \frac{\dfrac{1}{K_m \cdot K_{tvc}} \cdot J_\Sigma}{K_{fb} \cdot 2 \cdot T_e \cdot K_\delta} + \\ + \frac{\dfrac{1}{K_m \cdot K_{tvc}} \cdot J_\Sigma}{4 \cdot T_e p \cdot K_{fb} \cdot 2 \cdot T_e \cdot K_\delta} = K_p + \frac{K_i}{p}, \tag{16}$$

where K_p and K_i are the coefficients at the proportional and integral components, respectively.

For the 4A90L4 motor taken as an example for the studies, the calculated values of coefficients of the angle δ regulators are K_p=0.46 and K_i=16.2, respectively.

6. Discussion of the results obtained in minimization of losses and symmetrization of the AM currents

The study of performance of the automatic AM loss minimization system was carried out for several 4A series asynchronous motors of a general industrial make [17]. For each of the AM, conditions for reducing power losses and the parameters of the automatic loss minimization system were calculated. The typical parameters of the studied electric motors are summarized in Table 1. For the case of feeding the TVC-AM electric drive from a power source with a symmetrical voltage, the results of minimization in the form of graphs of losses in asynchronous motors are shown in Fig. 5. The curves show power losses in AM expressed in relative units when working at natural and adjusting characteristics in the minimization mode at different load moments.

The results show that the LMS provides a significant reduction of AM losses in the range of operating moments $0 \le M \le M_{bo}$. The slight discrepancy between the experimental values of the boundary moments and the calculated values can be explained by the taken assumptions and, in particular, linearity of the AM mechanical characteristics (Fig. 2). The discrepancy does not exceed 4 %.

Table 1

Representative parameters of the studied electric motors

AM type	P_1, kW	ΔP_Σ, kW	M_{bo}/M_n, rel. un.	δ_{opt}, deg.
4A90L4	2.2	0.58	0.72	39.9
4AC132M8	6.0	1.87	1.07	45.7
4AP160M8	11.0	2.03	0.93	41.6
4A315S12	45.0	6.20	1.08	41.1

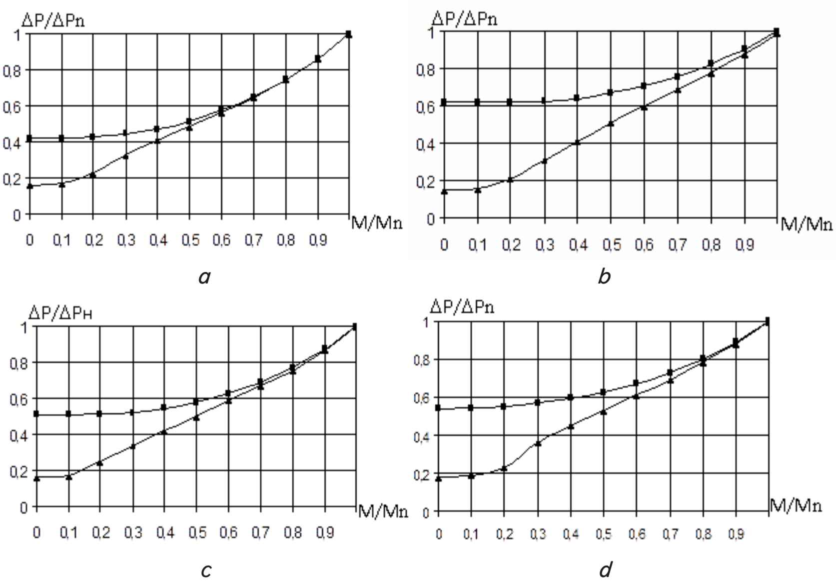


Fig. 5. Graphs of power loss in asynchronous motors: —■— at a natural mechanical characteristic; —▲— at an adjusting optimum characteristic; 4AC132M8, *Ku*=0 (*a*); 4A315S12, *Ku*=0 (*b*); 4AC132M8, *Ku*=5 % (*c*); 4A315S12, *Ku*=5 % (*d*)

Nonlinearity of the optimal characteristics in the region of small loads and the absence of intersection with the origin are due to the natural restrictions of the TVC in the modes close to idling. The mode of minimization of power losses has the greatest effect in those cases when the power indices of electric motors turn out to be low due to their specificity. The assertions that the loss minimization mode is only possible in the region of the load moments $0 \leq M \leq (0.4...0.6)\ M_n$ are correct and refer to the AM of a normal make, with "good" energetics [4]. At the same time, there exists a number of AM for which the values of the boundary moments M_{bo} are within the range 0.6...2.0 M_n. First of all, this applies to the motors with low efficiency and power factors, i. e. multipolar motors, motors with increased slip, starting torque, air gap, etc. This was confirmed by the study results.

The best indicators of improvement in power parameters of the TVC-AM electric drives were observed in the XX mode and at low load moments. This was expressed in a reduction of total losses due to a decrease in the AM power loss for magnetization owing to the reduced stator voltage. Reduction of losses for magnetization leads to smaller reactive power consumed by the AM and, consequently, to an increase in the power factor. In operation of the studied LMS, asynchronous motors get rid of one of their main drawbacks: a significant fall of the power factor when the load is reduced. For the asynchronous motors under investigation, the power factor was more than doubled under small loads.

When the TVC-AM electric drive was fed from a source with asymmetrical voltage, the basic principles of the loss minimization system were preserved. The results of minimization are conveniently presented in a form of histograms of relative AM power losses. The results are presented for several values of the power supply asymmetry during operation of the AM at main and adjusting characteristics. They are shown in Fig. 6. In this case, the 'main' is understood as the characteristic at which the AM operates at an asymmetrical power supply voltage and fully open TVC gates. In addition, Fig. 6 shows the histograms of the relative losses obtained in the process of operation of the previously developed system of automatic symmetrization of the AM currents for the same conditions [12].

At the power source voltage asymmetry determined by the coefficients K_u<5...7 %, the LMS provided the best indicators of power loss reduction for all investigated motors which is especially indicative for small load moments. The system of automatic symmetrization of currents is most effective at a significant asymmetry exceeding the maximum permissible value by more than 2 times (K_u>8 %) for medium- and high-power motors. With an increase in asymmetry of the PS voltage determined by the coefficients K_u>2 %, a certain decrease in the boundary moments (on the average by 5...20 % relative to M_{bo}) was observed in the case of feeding by a symmetrical voltage depending on the AM type and the magnitude of the asymmetry. And, what is especially important, the minimization regime begins at load moments larger than M_{bo}. Denote this value of the load moment as the moment of the start of the system operation, M_{sso}. Losses in the region of moments $M_{bo} \leq M \leq M_{sso}$ exceed losses in the main characteristic, and the quantitative indices of this excess are determined by the AM type, the magnitude of asymmetry and the current load on the shaft. The greater the asymmetry of the power supply, the higher the load moments at which the minimization mode begins. For the majority of AM under study, the variance of losses during operation at the main and adjusting characteristics did not exceed 5 %. At the voltage asymmetry coefficients K_u>4...5 %, the values of the load moments at which the LMS starts work reached and exceeded the values of the rated moments. At a theoretical assumption of the AM operating at this load, the variance of losses can be 20 % or more.

The LMS operation in conditions of power supply from a source with an asymmetric voltage allows not only to minimize the AM power losses but also obtain the symmetrization effect inherent in automatic symmetrization systems. This is illustrated in Fig. 7 by the oscillograms of the 4A90L4 motor stator speeds and currents when operating as a part of the LMS.

In the time interval $0 \leq t < 0.2$ sec, the 4A90L4 motor operated as a part of the TVC-AM electric drive at the main characteristic with the load moment $M=0.2M_n$, the total moment of inertia $J_\Sigma=2J_{AM}$ and voltage asymmetry determined by K_u=5 %. Time t=0.2 sec corresponds to the start of the LMS. Further operation of the system leads to a significant decrease in the manifestation of asymmetry of the power source voltage. This makes it possible to assert that the equality of the angles δ in the phases of the AM leads to an "equalization" of the values of the stator currents and enables solution of the problem of simultaneous minimization of the AM power losses and symmetrization [12].

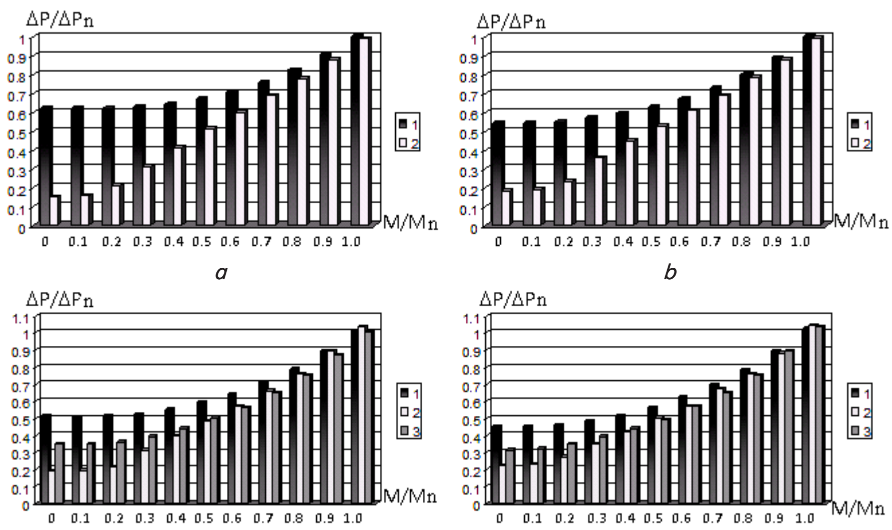


Fig. 6. Histograms of relative power losses: at the natural characteristic (1); at the optimal characteristic with a feedback relative to δ (2); during operation of the stator current symmetrizing system (3); 4AC132M8, K_u=0 (*a*); 4A315S12, K_u=0 (*b*); 4AC132M8, K_u=5 % (*c*); 4A315S12, K_u=5 % (*d*)

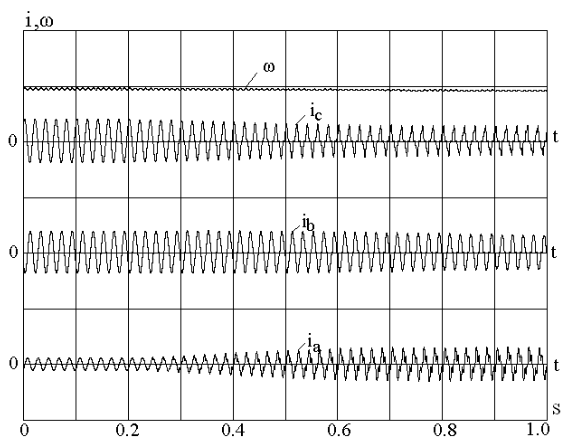


Fig. 7. Oscillograms of speed and currents of the 4A90L4 AM operating as a part of the LMS

There was a decrease in the speed variation at the load moments $0 \le M \le M_{bo}$ caused by the voltage asymmetry for all motors under study. This was because of a decrease in the component of the AM working moment having frequency of 100 Hz. The greatest effect was achieved at the power source asymmetry determined by the coefficients K_u<5 %, namely a decrease by 20...300 %. At a greater asymmetry, the power source indicators were somewhat worse.

The parameters of the AM current symmetrization expressed by the change of the asymmetry coefficients for the example of operation of the LMS with a 4A90L4 motor are presented in Table 2.

When load moments on the AM shaft were smaller than the boundary moment, the coefficients of asymmetry of the AM currents decreased with respect to the coefficients during operation of the AM at a basic mechanical characteristic. The greatest effect was achieved when working in the modes close to the ideal idling. The values of the boundary moments decreased and amounted to no more than (0.57...0.62) relative to the nominal torque M_n. The moments at the beginning of the LMS operation at different values of asymmetry of the power source voltage were K_u=2,5 %, $M_{sso} \approx 0{,}88\, M_n$; K_u=5 %, $M_{sso} \approx 0{,}96\, M_n$; K_u=10 %, $M_{sso} > M_n$, respectively. The physical process of absence of transition to the basic mechanical characteristic at a load exceeding the boundary moment M_{sso} is explained by a significant inequality of the angles δ by the AM phases in conditions of asymmetry of the power source voltage. While the angles δ of the two phases did not exceed the value δ_{opt}, the angle of the third phase could be initially larger than this value. This led to the beginning of the operation of the feedback channels and the control of this phase and, as a consequence, the LMS as a whole. Like in the studies of power losses, operation of the power loss minimization system at load moments $M_{bo} \le M \le M_{sso}$ led to a rise of asymmetry of the AM currents. These circumstances enabled expansion of the load moment range in which normal operation of the AD was possible for motors with a "good" energetics only if the PS voltage was substantially asymmetrical. For example, for the studied asynchronous motor 4A90L4 at asymmetry of the power source voltage determined by coefficient K_u=10 %, the LMS action ensured the upper limit of possible working load moments at a level close to $M_{bo} \approx 0.62\, M_n$. On the contrary, at an asymmetry of the power source with K_u<8 %, operation of the system led to a limitation of the range of the AM operating moments. If the load on the AM shaft exceeded the value of $M_{bo,}$ it resulted in activation of thermal protection and shutdown of the motor [4]. For motors with a "bad" energetics, these problems are not relevant since they have large enough values of the boundary moments that provide for the start of the loss minimization and current symmetrization mode. Transition to the main characteristic by means of a control system does not solve the problem of symmetrization but when there is asymmetry of the power source voltage determined by the coefficients K_u<5...7 %, it turns out to be useful. The LMS control system must be supplemented with a logic block. It will make it possible to start operation of all feedback channels. This is only possible if the value of the reference voltage U_{bas} exceeds the value of voltage $U_{g\delta}$ of the setpoint generator. In this case, the setpoint voltage is fixed and corresponds to the optimal angle δ_{opt}. Formation of the reference voltage can be performed in several ways. Current control of the ED output values is commonly assumed. The most simple and promising method is based on taking into account angles δ of all AM phases. The value of the reference voltage is formed from the current feedback voltages by the angle δ based on expression

$$U_{\text{str}} = \frac{U_{fb\,A} + U_{fb\,B} + U_{fb\,C}}{3}. \qquad (17)$$

Table 2

Indicators of the AM current symmetrization

M_s/M_n	K_u=2.5 %		K_u=5 %		K_u=10 %	
	K_{io}^{*}	$K_{i\,LSM}^{**}$	K_{io}	$K_{i\,LSM}$	K_{io}	$K_{i\,LMS}$
0.9	0.131	0.131	×	×	×	×
0.8	0.147	0.180	×	×	×	×
0.7	0.165	0.240	0.314	0.390	×	×
0,6	0.188	0.191	0.358	0.345	0.678 (×)	0.686
0.5	0,214	0,164	0,411	0,321	0,767	0,686
0,4	0.243	0.129	0.472	0.262	0.922	0.722
0,3	0.275	0.108	0.539	0,221	1,083	0,779
0.2	0,303	0,077	0,604	0.160	1.257	0.810
0.1	0.320	0.065	0.649	0.155	1.398	0.831
0	0.322	0.063	0.658	0.157	1.456	0.830

*Note: * – K_{io} is coefficient of asymmetry of the AM currents in the open TVC-AM electric drive system; ** – $K_{i\,lms}$ is coefficient of asymmetry of the AM currents of in a closed-loop system of automatic minimization of power losses; × – a prolonged operation of the open TVC-AM electric drive system is impossible because of AM heating*

For all studied motors, the reference voltage at K_u≤5 % (17) begins to exceed the reference voltage at loads close to the values of the corresponding boundary moments. The feedback channels of the LMS do not work at loads larger than the values of the boundary moment M_{bo}, and the AM operates at the basic mechanical characteristic.

7. Conclusions

1. The structure of the automatic power loss minimization system with simultaneous symmetrization functions was proposed for the case of powering from a power source with an asymmetric voltage. In this system, separate phase-by-phase control is implemented which determines use of three control and three feedback channels.

2. The problem of minimizing the AM power loss was solved by maintaining equality of the angles δ to the optimal value. When powering from a source with an asymmetric voltage was provided, simultaneous minimization of power losses in the AM and symmetrization of currents was achieved due to the equality of the angles δ in each of AM phases. In this case, the angles of switching gates of the TVC were not fundamentally symmetrical.

3. When the LMS was powered from a power source with symmetrical voltage, the system ensured a reduction of power losses in the range of operating moments 0≤M≤M_{bo} by 5...45 % relative to the losses taking place in operation at the main mechanical characteristic;

– energy saving in the mode of minimum power losses was achieved owing to reduction of losses for magnetization at a decrease of voltage in the AM stator. The consumed reactive power reduction occurred which led to a higher AM power factor;

– the automatic loss minimization system had the greatest effect in cases when the power indices of asynchronous motors were unsatisfactory.

4. When the LMS was fed by a power source with an asymmetric voltage:

– the effect of minimizing power losses in the AM preserved;

– the effect of symmetrization was observed characterized by a reduction of asymmetry of currents by 1.5...6 times, and a reduction of the negative consequences caused by asymmetry of the power supply voltage which was typical for all 4A series motors under study;

– the proposed system for minimizing power losses is advisable to use for AM powered from a power source with asymmetry of voltage determined by coefficients K_u≤6...7 %.

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