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FIELD WEAKENING CONTROL FOR INDUCTION MOTORS BASED ON COPPER AND IRON LOSSES MINIMIZATION

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ABSTRACT

This paper is concerned with the analysis of losses in induction motors. The most significant have been chose for minimization. These are in particular the losses in the windings and in the magnetic circuit due to eddy currents and hysteresis. Equations for the rotor flux linkage and orthogonal components of the stator current in the rotor reference frame dq in the induction motor's vector control system based on the condition of minimizing the total losses in copper and motor steel in the steady state. Here, effects of steel saturation are not taken into account. The limit values of the torque and speed are determined, where the rotor flux linkage control can improve the energy characteristics of the drive outside the magnetic saturation. It is shown that the main difficulty in implementing energy-optimal control is that the rotor flux linkage operates not only energy parameters, but also speed regulation in the field-weakening region. A block diagram of the implementation of energy-optimal control with field weakening mode is proposed. The idea is to switch the control algorithms of the magnetic field of the motor in such a way that in the start-brake modes the rotor flux linkage changes in the speed reference function, and when operating at a steady speed, in the function of the torque. A comparative analysis for a typical and developed drive systems in field-weakening mode by the simulation is carried out. It is shown that with the same transients of the torque and speed in a typical system, the efficiency in steady-state decreases with a decrease of torque load torque, whereas the proposed system it remains unchanged. The change in efficiency in dynamic conditions occurs when the rotor flux linkage changes. With energy-optimal control, there is a slight increase in the stator current peaks when the torque load changes abruptly, but at low torque load an additional field-weakening leads to a decrease in the stator voltage, which carry on a decrease in electricity consumption.

Keywords: Electric Drive; Induction Motor; Speed Regulation; Field Weakening; Rotor Flux; Optimal Control; Loss Minimization; Energy Efficiency

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INTRODUCTION

At present, more than 60 % of the generated electricity is being consumed by electric drives, a significant part of which belongs to induction motors (IM). The reasons for the wide spread of IM are the low cost of maintenance, reliability and low cost in comparison with other motors, as well as extensive operational experience in various fields of application. The advantages include the lack of a collector, which is present in the DC motor.

Currently, the reduction of energy losses in the electric drive at the design stage has reached its peak. High-quality design of the electric machine allows even at the manufacturing stage to perform an electric motor with high efficiency when it is operating in modes close to the nominal.

It is known that the maximum efficiency of IM at the rated speed and at nominal flux of the rotor occurs when it operated with a torque load torque that is from 70 % to 100 % of nominal. At low torque load, motor efficiency is significantly reduced.

Improving the energy efficiency of the drive during its operation with low torque load can be achieved by improving control systems.

The most interesting for research in terms of energy efficiency is a vector-driven induction motor. The efficiency η is defined as:

$$\eta = \frac{P_m}{P_e} \cdot 100\% \,, \quad (1)$$

$$P_e = 3U_s I_s \cos\varphi \,, \quad (2)$$

where: $\cos\varphi$ – the power factor; φ – the electric angle between the voltage vector and the current vector; P_m – the mechanical power on the motor shaft; P_e – the electric power.

Electric power exceeds mechanical power by the amount of total losses in the electric drive system:

$$\Delta P_{\Sigma} = P_e - P_m = \Delta P_{Cu} + \Delta P_{Fe} + \Delta P_{inv} + \Delta P_{mech},$$

where: ΔP_{Cu} – the losses in the stator and rotor windings, or the losses in copper; ΔP_{Fe} – the losses in the magnetic circuit or iron losses (core losses); ΔP_{inv} – rectifier and DC link inverter losses; ΔP_{mech} – mechanic losses, due to the presence of dry and viscous friction.

The main types of losses in the induction motors are illustrated in Fig. 1.

The most significant of these types of energy losses are the losses in the stator and rotor windings, which usually range from 55 % to 60 % of the total losses. The energy of these losses is spent on heating the windings, which occurs when current flows through the conductors of the stator and rotor:

$$\Delta P_{Cu} = 3(R_s I_s^2 + R_r I_r^2) = \frac{3}{2}(R_s i_s^2 + R_r i_r^2),$$
$$I_s = i_s / \sqrt{2}, \quad I_r = i_r / \sqrt{2}, \tag{3}$$

where: I_s, I_r – the current values of stator and rotor currents (*rms-value*); i_s, i_r – the amplitude values of currents (*peak-value*); R_s, R_r – active resistance of the stator and rotor windings.

Losses in core are spent on heating the magnetic circuit. They consist of eddy current losses and losses because of magnetization reversal of the core material due to hysteresis:

$$P_{Fe} = \frac{3}{2}\left(k_{ec}\omega_e^2\psi_m^2 + k_h\omega_e\psi_m^2\right), \tag{4}$$

where: ω_e – the rotation speed of the rotor flux vector ψ_r; ψ_m – magnetization flux; k_{ec}, k_h – eddy current- and hysteresis coefficients, respectively.

Losses in core are not caused by torque load and are produced by 20-25 % of the total losses. Losses in the converter consist of losses occurring when switching the power switches of the inverter, losses in copper of inductors and filters in the DC link, as well as losses from the presence of higher harmonics. The efficiency of modern frequency converters is 95-99 %, i.e. significantly higher than IM efficiency. It follows that the losses to the converters are much smaller than the losses in the IM, and in solving the problems of energy-optimal control they can be neglected.

Losses on mechanical transmission, i.e. losses in the transmission, do not depend on the drive control strategy and, as shown in, they are insignificant. To reduce mechanical losses, worm gears should be avoided. The best solution is to use couplings.

Mechanical losses from dry friction are spent on heating bearings, wheels and kinematic gears. Losses from viscous friction occur during air circulation in the drive and due to resistance to wind or liquid from vehicles and turbo-mechanisms (pumps, fans, wind generators). Mechanical losses make up (8-12) % of the total losses in the electric drive system and cannot be reduced by improving automatic control systems.

Therefore, they can also not be taken into account, but focus on reducing losses in copper and core.

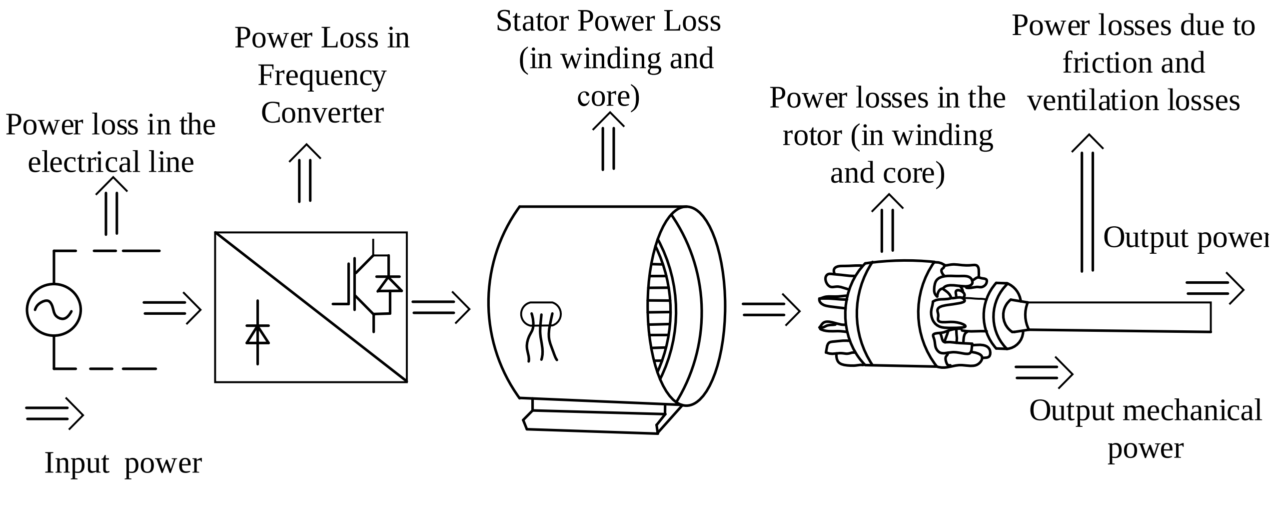

Fig. 1. **Energy losses in the electric drive**
Source: **compiled by the authors**

LITERATURE REVIEW

There are different ways to increase the energy efficiency of electromechanical facilities by means of an electric drive. An incredible number of primary sources are devoted to the discussion of this problem. For an example, you can read the analytical review [1] and the references therein.

Among the known solutions, there are systems synthesized from the conditions of minimizing various types of losses in the motor and converter [2], [3], [4], as well as systems for maximizing efficiency [3-5] and power factor [6], [7], [8]. Among them are methods based on loss models [9], methods using pre-computed lookup tables [10], online search methods [11], [12-13]. The simplest and most popular optimal control methods are those loss model-based controls (LMC).

Loss Model Control is related to the strategies based on formulas of various types of losses or some combination of them. Knowing these formulas, it is possible to synthesize a control law that minimizes losses. For IM, loss reduction is provided by controlling the magnitude of the rotor flux or the ratio of the orthogonal components of the stator current in a coordinate system oriented along the rotor flux vector. The controller in accordance with this algorithm generates a reference for the drive to work at the point of minimum loss. Such systems have high speed because the law of optimal control is formed according to well-known formulas. Control algorithms are complicated when the effect of core saturation and temperature change is taken into account. The main disadvantage of such methods is their high sensitivity to changes in drive parameters. Search Control consists in organizing an iterative online search for the maximum efficiency point [11-12], [13]. The flux of the stator or rotor is gradually reduced until the ratio of the measured output mechanical power to the input electric power corresponds to the maximum possible value. Search on-line maximization of efficiency is very attractive because it is completely insensitive to variations in drive parameters. However, this method makes high demands on the accuracy of measuring equipment over the entire range of changes in speed and torque load. Its disadvantages also include the complexity of search iterative algorithms, their influence on the quality of transients and the high duration of the search. For these reasons, this method is rarely used in industrial electric drives.

Hybrid methods also exist that combine the advantages of two SC and LMC optimization strategies.

To increase energy efficiency, you can also use intelligent control methods [14-15], [16] (neural networks, fuzzy logic, etc.). The disadvantage of these methods is that in the synthesis of control algorithms, many decisions are made intuitively. Thus, the simplest methods for minimizing losses are methods based on their mathematical models. A lot of works has been devoted to their synthesis and analysis. However, they focus on work with rotation speed to nominal value speed control systems. Moreover, sometimes the improvement in energy performance is accompanied with deterioration in the quality of transients. Nevertheless, the regulation of speed above the nominal value due to the weakening of the field is widely used in electric drive systems, in which, with increasing speed, torque load can be reduced. This applies to electric transport drives, hoisting mechanisms, machine feed drives, roll drives of crimping rolling mills. For all the above examples, energy saving is an urgent issue.

THE PURPOSE OF THE ARTICLE

The aim of this work is to develop a system for controlling the speed of induction motor with field weakening as part of a vector field-oriented control (FOC) system, which would minimize losses in the motor windings and magnetic circuit in a steady state without degrading the quality of transients.

MAIN PART. DERIVATION OFOPTIMAL CONTROL LAWS

To describe energy and transient processes in vector-controlled IM, it is convenient to use a mathematical description of the drive in a rotating orthogonal coordinate system do, oriented along the rotor flux vector [17]:

$$\begin{cases} u_{sd} + \dfrac{k_r}{T_r}\Psi_r + \omega_e \sigma L_s i_{sq} = i_{sd} R_{sr}\left(\tau_{sr} s + 1\right), \\ u_{sq} - \omega_e \sigma L_s\, i_{sd} - z_p \omega k_r \Psi_r = i_{sq} R_{sr}\left(\tau_{sr} s + 1\right), \\ L_m i_{sd} = \Psi_r\left(\tau_r s + 1\right), \\ \omega_e = \omega_{slip} + \omega_r = k_r R_r \dfrac{i_{sq}}{\Psi_r} + p\,\omega, \\ T_e = k_T \Psi_r i_{sq}\,, \\ T_e - T_L = J\omega\, s, \end{cases} \quad (5)$$

where: s – Laplace operator; T_e – electromagnetic torque; T_L – load torque; $i_{sd}, i_{sq}, u_{sd}, u_{sq}$ – flow- (d) and torque- (q) orthogonal components of the stator current and voltage, respectively; ψ_r – rotor flux amplitude; R_s, R_r – active stator and rotor resistances; L_s, L_r, L_m – inductors of the stator, rotor and magnetization; p – the number of pole pairs ;

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$\tau_r = L_r / R_r$ – rotor electromagnetic constant; $k_T = 3pk_r/2$ – torque coefficient; $k_r = L_m / L_r$ – rotor magnetic coupling coefficient; J – moment of inertia; ω_e – rotation speed of the coordinate system; $\omega_{slip} = k_r R_r i_{sq} / \psi_r$ – absolute rotor slipping ; ω, $\omega_r = z_p \omega$ – electric and mechanical rotor angular speeds;

$$R_{sr} = R_s + k_r^2 R_r, \quad \tau_{sr} = \sigma L_s / R_{sr},$$
$$\sigma = 1 - \frac{L_m^2}{L_s L_r}. \tag{6}$$

To solve the optimal control problem formulated above, we express the losses in copper and in core as the orthogonal components of the signals in the dq system.

Then by substitution into equation (3) the expression

$$i_s^2 = i_{sd}^2 + i_{sq}^2 \ldots, i_r^2 = i_{rd}^2 + i_{rq}^2, \tag{7}$$

as a result

$$\Delta P_{Cu} = \frac{3}{2}\left[R_s (i_{sd}^2 + i_{sq}^2) + R_r (i_{rd}^2 + i_{rq}^2)\right]. \tag{8}$$

To reduce the number of variables in (8), we express the components of the currents can see below the flux of the rotor ψ_r and torque T_e. To do this, we write the equations connecting the currents and flux in the steady state:

$$\begin{cases} \psi_r = L_m i_{sd}, \\ \psi_{rq} = L_m i_{sq} + L_r i_{rq} = 0, \\ \psi_{rd} = L_m i_{sd} + L_r i_{rd} = \psi_r, \end{cases},$$

where:

$$i_{sd} = \psi_r / L_m, \tag{9}$$

$$i_{rq} = -k_r i_{sq}, \ldots i_{rd} = 0. \tag{10}$$

Then by substitution (10) into equation (8), we get rid of the equation for calculating copper losses from rotor currents:

$$\Delta P_{Cu} = \frac{3}{2}\left[R_s (i_{sd}^2 + i_{sq}^2) + k_r^2 R_r i_{sq}^2\right] = \frac{3}{2}\left[R_s i_{sd}^2 + R_{sr} i_{sq}^2\right] \tag{11}$$

From the equation of torque (see system (5)), it follows:

$$i_{sq} = \frac{T_e}{k_T \psi_r}. \tag{12}$$

Given (9) and (12), equation (11) takes the form:

$$\Delta P_{Cu} = \frac{3}{2}\left[R_s \left(\frac{\psi_r}{L_m}\right)^2 + R_{sr}\left(\frac{T_e}{k_T \psi_r}\right)^2\right]. \tag{13}$$

Let us carry out similar transformations of the equation for losses in core (4). First, we find the amplitude of the magnetization current and its projection on the d and q axes:

$$i_m = i_s + i_r, \quad i_{md} = i_{sd}, \quad i_{mq} = (1 - k_r) i_{sq},$$

and then the orthogonal components of the magnetization flux and its amplitude, which appears in equation (4):

$$\psi_{md} = L_m i_{md} = L_m i_{sd} = \psi_r,$$
$$\psi_{mq} = L_m i_{mq} = k_r L_{r\sigma} i_{sq} = k_r L_{r\sigma} \frac{T_e}{k_T \psi_r}, \tag{14}$$
$$\psi_m^2 = \psi_{md}^2 + \psi_{mq}^2 = \psi_r^2 + k_r^2 L_{r\sigma}^2 \left(\frac{T_e}{k_T \psi_r}\right)^2,$$

where: $L_{r\sigma} = L_m - L_r$ – the induction of rotor scattering flux.

After substitution (14) into (4) we have:

$$\Delta P_{Fe} = \frac{3}{2}\left\{(k_{ec}\omega_e^2 + k_h \omega_e)\left[\begin{matrix}\psi_r^2 + \\ k_r^2 L_{r\sigma}^2 \left(\frac{T_e}{k_T \psi_r}\right)^2\end{matrix}\right]\right\}. \tag{15}$$

Summing up the losses (13) and (15), we obtain the function to be minimized when solving the problem of energy-efficient control:

$$\Delta P_\Sigma = \frac{3}{2}\left\{\begin{matrix}\frac{\psi_r^2}{L_m^2}(R_s + L_m^2 k_{ec}\omega_e^2 + L_m^2 k_h \omega_e) + \\ + \frac{T_e^2}{k_T^2 \psi_r^2}[R_{sr} + k_r^2 L_{r\sigma}^2 (k_{ec}\omega_e^2 + k_h \omega_e)]\end{matrix}\right\}.$$

We denote

$$R_x(\omega_e) = R_s + L_m^2 (k_{ec}\omega_e^2 + k_h \omega_e), \tag{16}$$

$$R_y(\omega_e) = R_{sr} + k_r^2 L_{r\sigma}^2 (k_{ec}\omega_e^2 + k_h \omega_e). \tag{17}$$

Given these notations

$$\Delta P_\Sigma = \frac{3}{2}\left(\frac{\psi_r^2}{L_m^2} R_x(\omega_e) + \frac{T_e^2}{k_T^2 \psi_r^2} R_y(\omega_e)\right). \tag{18}$$

To minimize function (18), we differentiate it with respect to the flux of the rotor and equate the resulting derivative to zero.

$$\frac{d\Delta P_\Sigma}{d\psi_r}=3\left(\frac{\psi_r}{L_m^2}R_x(\omega_e)-\frac{T_e^2}{k_T^2\psi_r^3}R_y(\omega_e)\right)=0\,. \qquad (19)$$

The solution of equation (19) regarding the rotor flux gives the following result:

$$\psi_{ropt}=\sqrt{\frac{T_e L_m}{k_T}\sqrt{\frac{R_y(\omega_e)}{R_x(\omega_e)}}}\,. \qquad (20)$$

Then by substitution (20) into equation (18), we find the minimum loss:

$$P_{\Sigma\min}=\frac{3T_e}{k_T L_m}\sqrt{R_x(\omega_e)\cdot R_y(\omega_e)}\,. \qquad (21)$$

Using equations (9), (12) and (20), we also determine the optimal expressions for the stator current components along the d axis and q axis and their ratio:

$$i_{sdopt}=\sqrt{\frac{T_e}{k_p k_r L_m}\sqrt{\frac{R_y(\omega_e)}{R_x(\omega_e)}}}\,, \qquad (22)$$

$$i_{sqopt}=\sqrt{\frac{T_e}{k_p k_r L_m}\sqrt{\frac{R_x(\omega_e)}{R_y(\omega_e)}}}\,, \qquad (23)$$

$$\frac{i_{sd}}{i_{sq}}=\sqrt{\frac{R_y(\omega_e)}{R_x(\omega_e)}}\,. \qquad (24)$$

The system efficiency without taking into account mechanical losses and losses in the converter can be calculated by the formula

$$\eta=\frac{T_e\omega}{T_e\omega+P_\Sigma}\,. \qquad (25)$$

The last expression has a maximum when $P_\Sigma = P_{\Sigma\min}$ (21). Then by substitution (21) into (25), we obtain:

$$\eta_{\max}=\frac{\omega k_T L_m}{\omega k_T L_m+3\sqrt{R_x(\omega_e)\cdot R_y(\omega_e)}}\,. \qquad (26)$$

It follows from (26) that, in an optimized system, the efficiency in the steady state does not depend on the magnitude of the torque. Fig. 2 shows the graphs of the dependencies of the torque $\overline{\psi}_{ropt}(\overline{T}_e)$ for different speed values ω_e, and Fig. 3 show the graphs $\overline{\psi}_{ropt}(\overline{\omega}_e)$ for different torque values T_e.

The rotor flux linkage values in the graphs of Fig. 2 and Fig. 3 are limited from above at the level of the gearbox in idle mode. From the analysis of the graphs it follows that in order to minimize losses; the rotor flux linkage should be reduced with a decrease in torque and with an increase in speed. Table 1 shows the parameters of the investigated IM

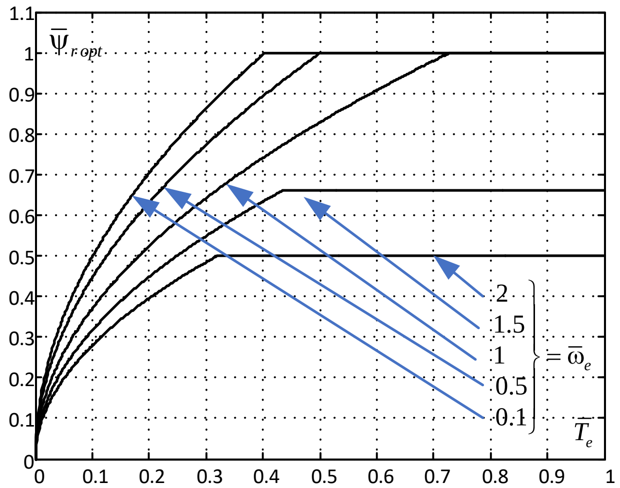

Fig. 2. **Curves of dependency optimal rotor flux on torque**
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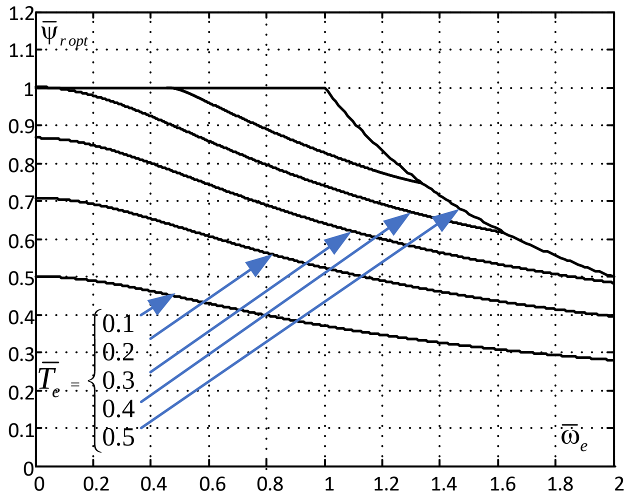

Fig. 3. **Curves of dependency optimal rotor flux on the electric speed of rotor**
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Table. **Data of the motor 4A80B2У3**

Parameter	Values	Parameter	Values
P_n	2,2 *kW*	R_s	3,54 Ω
$U_{sn\ lin}$	380 *V rms*	R_r	2,28 Ω
I_{sn}	4,6 *A*	$L_{s\sigma}$	0,008 *H*
T_{en}	7,4 *Nm*	$L_{r\sigma}$	0,013 *H*
J_{Σ}	0,0042 $kg\ m^2$	L_m	0,407 *H*
p	1	η	0,83
ω_n	297 *rad/s*	k_{ec}	0,0005 Ω^{-1}
ψ_{r0}	0,97 *Wb*	k_h	0,03 H^{-1}

Source: **compiled by the authors**

IMPLEMENTATION OF OPTIMAL CONTROL LAWS

A typical solution to the implementation of the laws of energy-optimal control is represented by a block diagram in Fig. 4, which is based on the use of equations (22) – (24) taking into account expressions (16), (17).

In this scheme, “Speed Slew Rate Limiter” is the speed generator for closed speed loop. Speed controller generate a reference torque T_e^*, and then stator current references i_{sd}^* и i_{sq}^* are formed from this signal. Given that the square root can be extracted only from positive numbers, as well as the fact that i_{sq} must change the sign when the sign of the torque changes while the current i_{sd} is constantly positive, equations (22), (23) need to be changed a little:

$$i^*_{sd\,opt} = \sqrt{\frac{\left|T_e^*\right|}{k_p k_r L_m}\sqrt{\frac{R_y(\omega_e)}{R_x(\omega_e)}}}\,, \qquad (27)$$

$$i^*_{sqopt} = \sqrt{\frac{\left|T_e^*\right|}{k_p k_r L_m}\sqrt{\frac{R_x(\omega_e)}{R_y(\omega_e)}}}\cdot \mathrm{sign}(\,T_e^*\,)\,. \qquad (28)$$

In this form, they are used in the system in Fig. 4.

The disadvantage of this system is the uncontrolled change in the gain of the speed control loop during the formation of the stator current along the q axis, as well as the motor starting at zero flux, which together leads to a significant deterioration in the quality of transients compared to a conventional vector control system [18].

We eliminated this disadvantage by generating the rotor flux as a function of torque and speed according to the formula (20). Such a work with rotation speed to nominal value speed control system is shown in Fig. 5 [18].

In the diagram of Fig. 5, the reference flux linkage of the rotor can be formed both as a function of torque and speed, and independently of them (at a speed close to zero), which makes it possible to separate magnetization-demagnetization modes of the motor and speed control. In addition, the gain of the speed controller adapts to the change in flux of the rotor, which makes it possible to maintain a high quality of transients throughout the entire range of changes in speed and torque.

When implementing energy-efficient control in the field weakening mode the additional problem arises because the rotor flux in such a system controls not only the energy characteristics.

Therefore, in the start-brake modes, it is necessary to control the flux according to one algorithm, and when the torque changes at a steady speed, it should be done in a different way. To implement this idea, it is proposed to generate the reference rotor speed ω^* and reference flux linkage $\psi_r{}^*$ in accordance with the block diagram in Fig. 6.

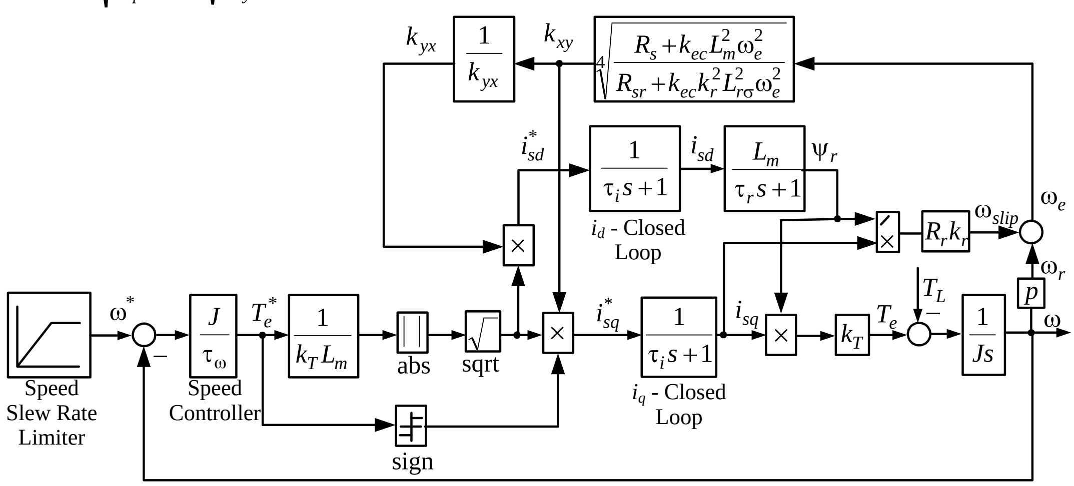

Fig. 4. **Structural diagram of an energy-efficient control system in constant torque region**
Source: **compiled by the authors**

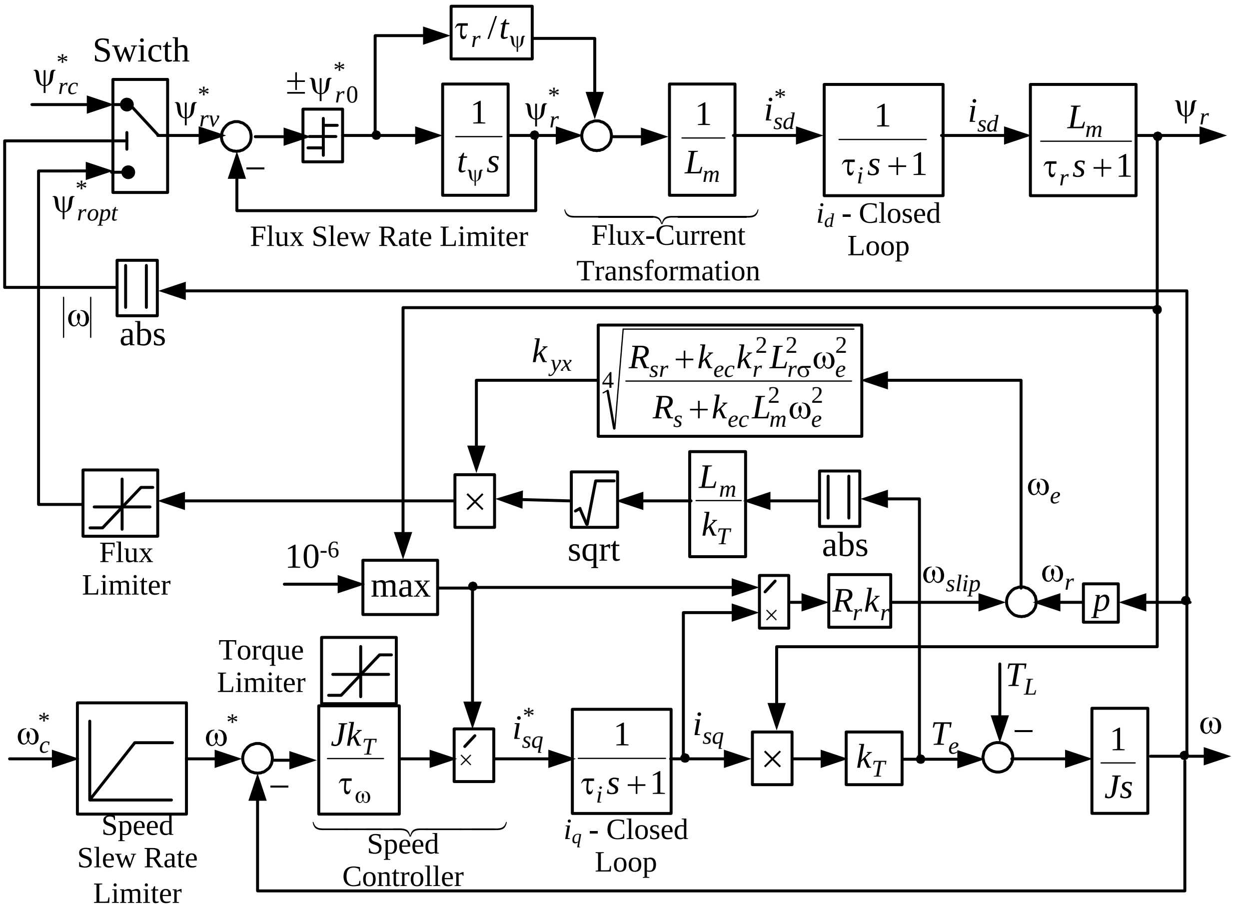

Fig. 5. **Structural diagram of an energy-efficient control system in constant torque region with pre-magnetization IM**

Source: **compiled by the authors**

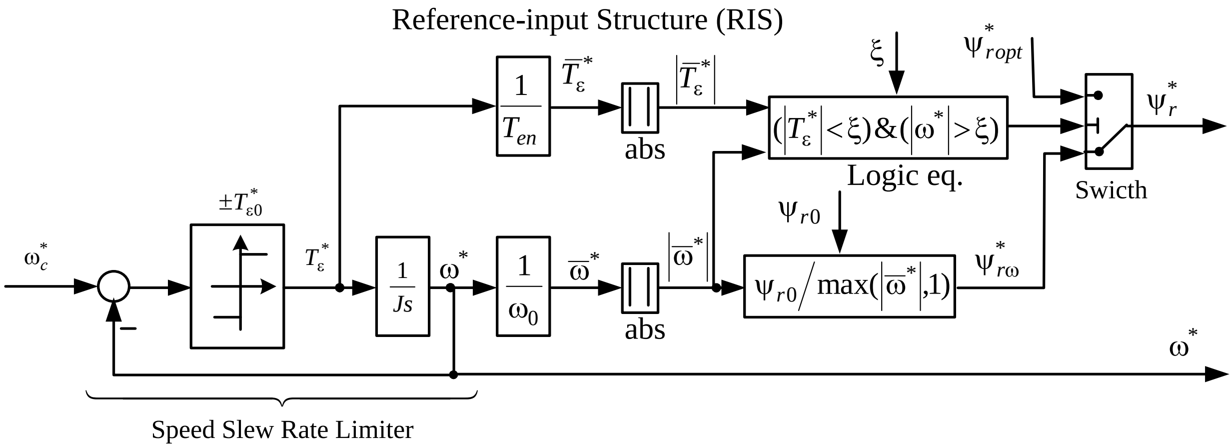

Fig. 6. **The structural diagram for generating of the reference speed and reference flux linkage**

Source: **compiled by the authors**

The "Switch" block is controlled by the signals of the reference dynamic torque T^*_ε and reference speed ω^*. The switching condition forms a "Logic Expression" block. If

$$(|T^*_\varepsilon|<\xi)\&(|\omega^*|>\xi),$$

where $\xi<<1$ – the small number, the upper channel of "Switch" works, i.e. the rotor flux linkage controls the amount of efficiency ($\psi^*_r=\psi^*_{ropt}(T_e,\omega)$).

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Otherwise, the lower channel of "Switch" works, and this flux controls the speed

$$\psi_r^* = \psi_{r\omega}^* = \frac{\psi_{r0}}{\max(\left|\overline{\omega}^*\right|,1)} . \quad (30)$$

Blocks "Norm1" and "Norm2" move reference dynamic torque and reference speed from SI units T_ε^*, ω^* to p.u. units $\overline{T}_\varepsilon^*$, $\overline{\omega}^*$. Block "Divide" forms reference flux linkage for speed control due to field weakening, and block "Max" prevents this operation if the reference speed does not exceed the synchronous motor speed.

The range of operation of the efficiency maximization algorithm in field-weakening mode for control system is limited by the maximum possible value of the flux necessary to work out a given speed. Therefore, the rotor flow restriction link is constant $\psi_{r\max} = \psi_{r0} = \text{const}$ in the system where IM work with nominal rotation speed using the control system which show on the Fig. 5 when system with field-weakening mode must be replaced by a link with *"Dynamic flux limiter"* block at $\psi_{r\max} = \psi_{r\omega} = \text{var}$.

The block of *"Torque Limiter"* in the system with field-weakening mode should also be dynamic because speed regulation in the field weakening occurs with constant power:

$$T_{\max} = \frac{T_{mc}}{\max(\left|\overline{\omega}^*\right|,1)} . \quad (31)$$

Taking into account the above features, a variant of the structural scheme with switching algorithms for controlling the rotor flux with field weakening mode speed control system. The resulting system is shown in in Fig. 7.

Let us carry out a simulation of this system and compare them with the results of modeling a typical work in field weakening mode system without loss minimization elements.

Fig. 8, Fig. 9 and Fig. 10 shows the transients in a typical system (a) and in the developed optimal control system (b).

All signals on the graphs are presented in relative units: $\overline{\omega} = \omega/\omega_n$, $\overline{T}_e = T_e/T_{en}$, $\overline{\psi}_r = \psi_r/\psi_{r0}$, $\overline{i}_s = i_s/i_{sn}$, $\overline{u}_s = u_s/u_{sn}$.

Fig. 8 shows the speed, torque, flux of the rotor and efficiency, Fig. 9 – the amplitude of the stator current and its components in the rotor reference frame dq, and Fig. 10 – the amplitude of the stator voltage and its components in this reference frame. Stator currents and voltages in the stationary reference frame αβ in the compared systems are shown in Fig. 11 and Fig. 12, respectively.

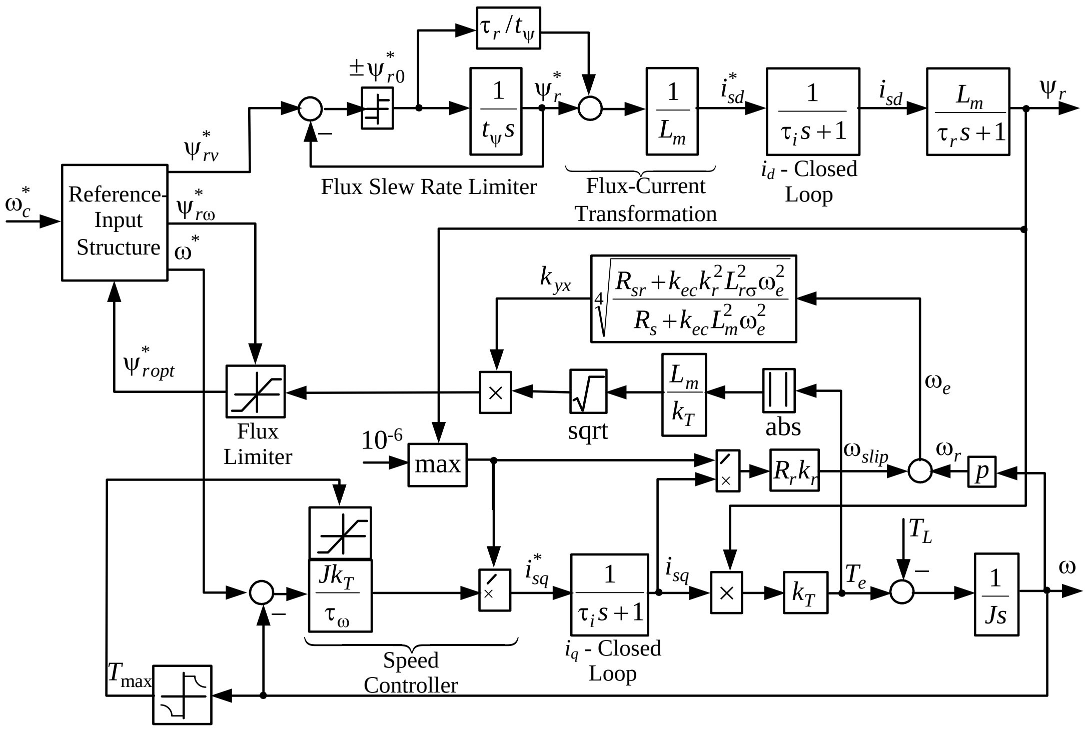


Fig. 7. **The structural diagram of an energy-efficient system for IM with variation of rotor flux**
Source: **compiled by the authors**

A comparative analysis of the presented graphs shows that in a typical system the efficiency at low torque load decreases, and in the energy-optimal one it remains constant. In this case, the quality of transients of the torque and motor speed does not deteriorate (Fig. 8).

As can be seen from Fig. 8b, in the acceleration and braking diapason, the change in the rotor flux occurs as in the standard system, provides a linear change in speed to a predetermined value and in the sections of the static torque change, it ensures stabilization of efficiency at low torque load. With increasing torque load, the rotor flux does not exceed the level corresponding to a given speed.

In both systems, the torque-forming component has a predominant effect on the amplitude of the stator current. Its behavior in the energy-efficient system has changed significantly: it is characterized by the presence of peak surges in areas of sharp changes in torque with a weakened field of the IM.

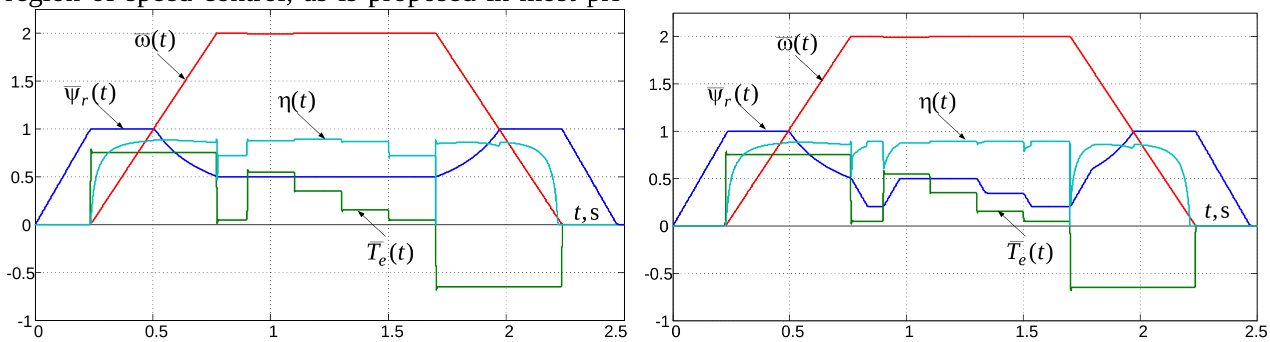
As for the voltage amplitude of the stator, in an energy-efficient system it decreases significantly in areas where additional attenuation of the field occurs with a decrease in torque load.

The advantage of the system is the possibility of increasing the efficiency during operation of the electric drive system, not only in the torque constant region of speed control, as is proposed in most primary sources, but also in the field weakening, in which the core losses become significant in relation to total losses.

The disadvantage of the studied system, as well as all energy-optimal systems based on loss models, is their high sensitivity to parameter changes and the uncertainty of the coefficients k_{ec} and k_h in formulas for core loss. It is known that these coefficients can be expressed in terms of fictitious resistance. R_{ec} and dummy inductance L_h, which should be included in the T-shaped equivalent IM circuit in parallel with the magnetization inductance:

$$k_{ec} = \frac{1}{R_{ec}}, \quad k_h = \frac{1}{L_h}. \tag{32}$$

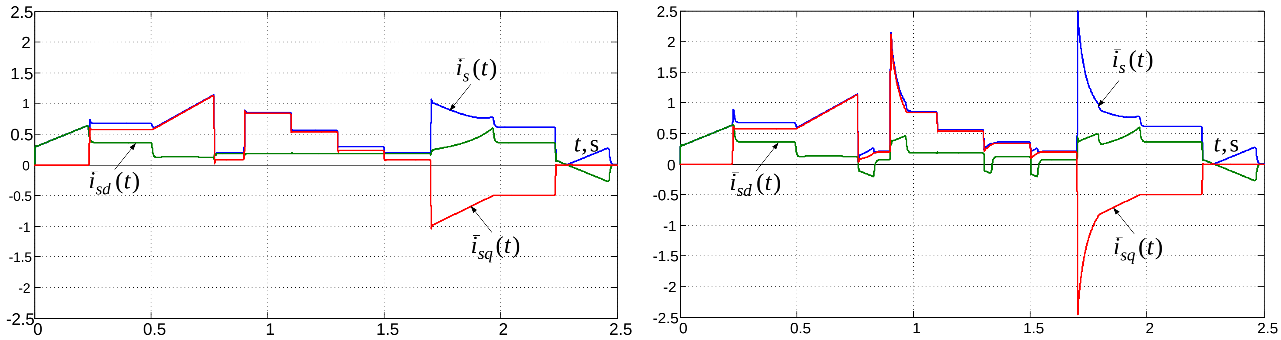
Taking into account the phenomena of eddy currents and hysteresis significantly complicates the mathematical model of IM and the study of control systems using the method of mathematical modeling. In addition, the parameter values R_{ec} and L_h can only be determined experimentally. There are techniques for conducting such experiments [19-20], but the accuracy of the results obtained is not always satisfactory.



a b

Fig. 8. **Transients in typical (a) and optimal (b) vector control systems**

Source: **compiled by the authors**



a b

Fig. 9. **Transients of stator currents and its orthogonal dq-components in typical (a) and optimal (b) vector control systems**

Source: **compiled by the authors**

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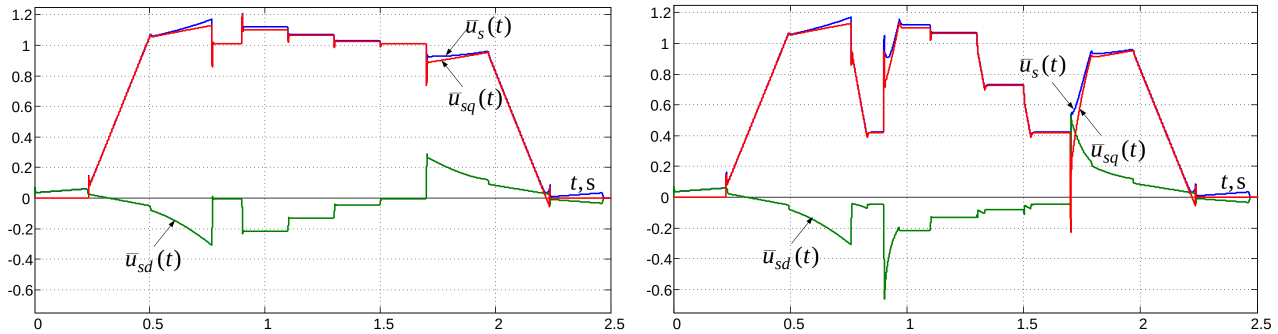
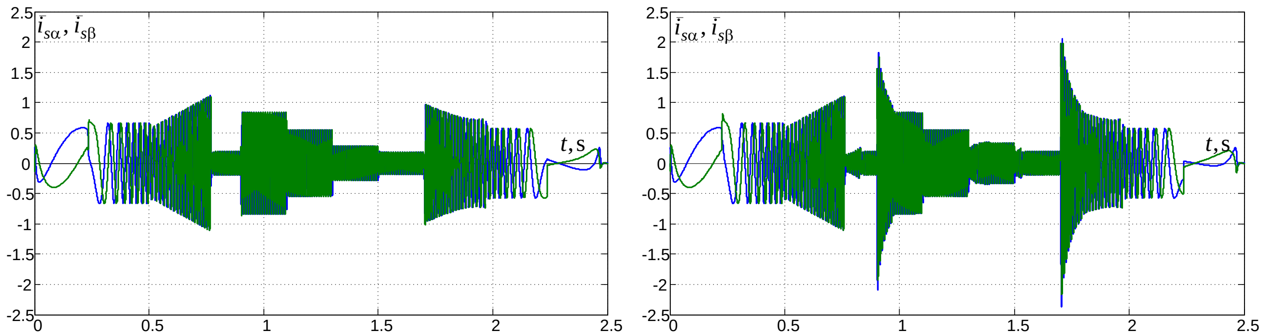


a b

Fig. 10. **Transients of the voltage of the stator and its orthogonal dq-components in typical (a) and optimal (b) vector control systems**

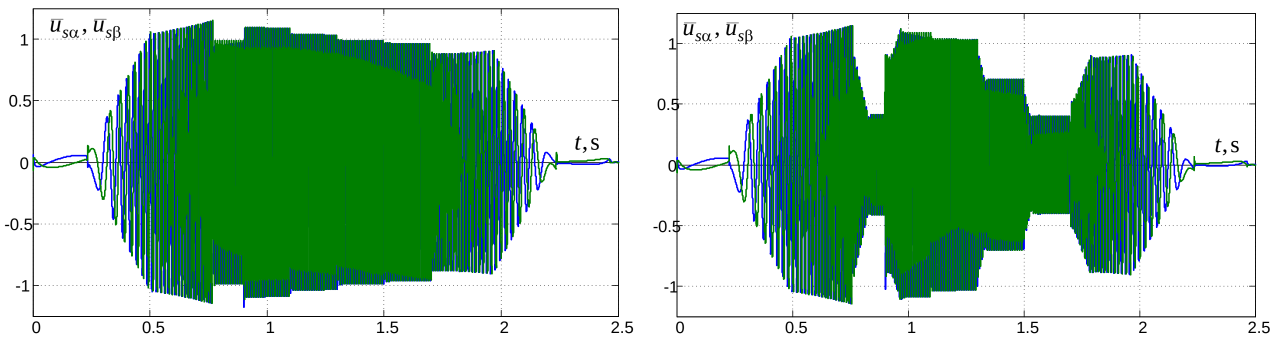
Source: **compiled by the authors**



a b

Fig. 11. **Transients of stator currents in a stationary reference frame in typical (a) and optimal (b) systems of vector control for induction motor**

Source: **compiled by the authors**



a b

Fig. 12. **Transients of stator voltages in a stationary reference frame in a typical (a) and optimal (b) vector velocity control systems for induction motor**

Source: **compiled by the authors**

CONCLUSIONS

The article proposes a strategy for maximizing efficiency in field weakening mode speed control system based on mathematical models of losses in copper and core. It is shown that this method is effective in small torque load.

A structural implementation has been developed in which the change in rotor flux in dynamic (start and brake) modes is used to control speed, and in static ones – to maximize efficiency.

The study of the proposed system was performed by simulation.

From the results of comparing a typical system of work in field weakening mode control of induction motor and optimal system, it can be seen that the work in field weakening mode energy-optimal system of vector speed control provides the maximization of efficiency by changing the rotor flux, while maintaining the high quality of transition of torque and speed.

To go into the field-weakening mode for the speed control, the system ignores the optimal flux and generates the flux necessary for working out the given speed. After reaching the steady state, the drive again switches to energy-efficient control.

It is advisable to use the system under study in drives with field-weakening control of induction motors that operate for a long time with light load torque, for example, in electric vehicles and in electric drives of hoisting-and-transport mechanisms.

For the practical implementation of this control system, it is desirable to analyze the duration of operating modes with a constant or slowly changing torque and apply efficiency optimization only when the energy loss for controlling the magnetic flux of the machine is less than the loss for maintaining it at a constant level.

In hoisting installations, it is possible to include an energy-optimal strategy when moving an empty or lightly loaded device.

The disadvantage of the system is the need to identify loss models parameters.

For a conclusion on the effectiveness of the proposed electric drive system, it is necessary to develop a software implementation of the control system on a digital signal processor and conduct its experimental research.

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МІНІМІЗАЦІЯ ВТРАТ В СИСТЕМІ ДВОЗОННОГО РЕГУЛЮВАННЯ ШВИДКОСТІ АСИНХРОННОГО ДВИГУНА

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АНОТАЦІЯ

У статті проаналізовані види втрат в асинхронному двигуні, в результаті чого прийнято рішення мінімізувати найбільш суттєві з них: втрати в обмотках і втрати в магнітопроводі від вихрових струмів і від гістерезису. Виведено рівняння для розрахунку значень потокозчеплення ротора і ортогональних складових струму статора у обертовій системі координат ротора dq в системі векторного керування асинхронним двигуном з умови мінімізації сумарних втрат в міді і сталі двигуна в статичному режимі. При висновку не врахований ефект насичення сталі. Визначено граничні значення електромагнітного моменту і швидкості, при яких регулювання потокозчеплення ротора здатне поліпшити енергетичні характеристики приводу, не входячи в зону насичення кривої намагнічування. Показано, що основною складністю при реалізації енергооптимального керування системою двозонного векторного керування швидкістю асинхронного двигуна є те, що потокозчеплення ротора керує не тільки енергетичними параметрами, але і регулюванням швидкості в другій зоні. Запропоновано структурну схему реалізації енергооптимального керування потокозчеплення в системі двох-зонного регулювання швидкості. Ідея полягає в перемиканні алгоритмів керування магнітним полем двигуна таким чином, щоб в пуско-гальмівних режимах потокозчеплення ротора змінювалося в функції завдання швидкості, а при роботі на сталій швидкості - в функції електромагнітного моменту. Виконано порівняльний аналіз типової і розробленої енергоефективної систем двозонного регулювання швидкістю методом математичного моделювання. Показано, що при однакових перехідних процесах електромагнітного моменту і швидкості в типовій системі ККД в сталих режимах при зменшенні навантаження падає, а в запропонованій системі залишається незмінним. Зміна ККД в динамічних режимах відбувається при зміні потокозчеплення ротора. При енергооптимальному керуванні спостерігається деяке збільшення піків струму статора при різкій зміні навантаження, але при малих навантаженнях додаткове ослаблення поля призводить до зменшення напруги статора в сталому режимі, що призводить до зниження споживання електроенергії.

Ключові слова: електропривод; асинхронний двигун; регулювання швидкості; ослаблення поля; потокозчеплення ротора; оптимальне керування; мінімізація втрат; енергоефективність

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МИНИМИЗАЦИЯ ПОТЕРЬ В СИСТЕМЕ ДВУХЗОННОГО РЕГУЛИРОВАНИЯ СКОРОСТИ АСИНХРОННОГО ДВИГАТЕЛЯ

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АННОТАЦИЯ

В статье проанализированы виды потерь в асинхронном двигателе, в результате чего принято решение минимизировать наиболее существенные из них: потери в обмотках и потери в магнитопроводе от вихревых токов и от гистерезиса. Выведены уравнения для расчета значений потокосцепления ротора и ортогональных составляющих тока статора во вращающейся системе координат ротора dq в системе векторного управления асинхронным двигателем из условия минимизации суммарных потерь в меди и стали двигателя в установившемся режиме. При выводе не учтен эффект насыщения стали. Определены граничные значения электромагнитного момента и скорости, при которых регулирование потокосцепления ротора способно улучшить энергетические характеристики привода, не входя в зону насыщения кривой намагничивания. Показано, что основной сложностью при реализации энерггоптимального управления системой двухзонного векторного управления скоростью асинхронного двигателя является то, что потокосцепление ротора управляет не только энергетическими параметрами, но и регулированием скорости во второй зоне. Предложена структурная схема реализации энергооптимального управления потокосцеплением в системе двухзонного регулирования скорости. Идея состоит в переключении алгоритмов управления магнитным полем двигателя таким образом, чтобы в пуско-тормозных режимах потокосцепление ротора изменялось в функции задания на скорость, а при работе на установившейся скорости – в функции электромагнитного момента. Выполнен сравнительный анализ типовой и разработанной энергоэффективной систем двухзонного регулирования скорости методом математического моделирования. Показано, что при одинаковых переходных процессах электромагнитного момента и скорости в типовой системе КПД в установившихся режимах при уменьшении нагрузки падает, а в предложенной системе остается неизменным. Изменение КПД в динамических режимах происходит при изменении потокосцепления ротора. При энергооптимальном управлении наблюдается некоторое увеличение пиков тока статора при скачкообразном изменении нагрузки, но при малых нагрузках добавочное ослабление поля приводит к уменьшению напряжения статора в установившемся режиме, что приводит к снижению потребления электроэнергии.

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Ключевые слова: электропривод; асинхронный двигатель; регулирование скорости; ослабление поля; потокосцепление ротора; оптимальное управление; минимизация потерь; энергоэффективность

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