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# EXPERIMENTAL RESEARCH OF THE MAGNETIZATION AND DEMAGNETIZATION PROCESSES OF THE VECTOR-CONTROLLED INDUCTION MOTOR

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*Experimental research of the processes of magnetization and demagnetization for the motionless vector-controlled induction motor was performed, according to a linear law with a variation in the duration of these processes. The methodology of research during which the orthogonal components of the stator and rotor currents were recorded in the rotor flux reference frame, the rotor flux module and the energy of the total losses in the stator and rotor copper is described. The main characteristics and parameters of laboratory equipment and facilities are given. From the point of view of minimizing copper losses, the existence of the optimal duration of the investigated transient processes has been experimentally proven. The results of experimental studies with high accuracy coincide with calculations based on previously obtained analytical dependencies, which confirms the admissibility of the assumptions made during theoretical studies.* References 10, figures 7, tables 2.
***Keywords:*** induction motor, magnetization, demagnetization, power losses, optimization, experiment.

**Formulation of the problem.** Reducing unproductive losses of electricity in electric drives due to the optimization of their control systems is an actual problem, which is discussed in many sources [1]. In vector control drives for induction motors (IM), the processes of controlling the motor's electromagnetic field and its movement coordinates (speed, position) are separated in time. In single-zone speed control and in position control, the rotor flux linkage is changed, as a rule, before the start of the motor movement and after it ends, that is, when the rotor is at standstill [1]. In some cases, the flux linkage of the rotor is also changed during the IM movement at low loads in order to increase the efficiency [1]. When implementing energy-efficient optimal control algorithms, power losses in steady-state modes are usually minimized [2–4]. In this case, losses due to magnetization and demagnetization of IM are not taken into account. Taking into account these losses in the optimization process, it is possible to achieve even better results in terms of energy saving by minimizing the energy losses during the change of the rotor flux, which is accompanied by current transients in both the stator and the rotor.

The scientific papers [5–9] present the research results of various searching [5] and analytical [7–10], structural [7–9] and parametric [7–10] methods of optimal control of the rotor flux of the IM rotor, based on loss models. The article [10] shows that the most rational, from the point of view of ease of implementation and minimization of total electricity losses during magnetization (*magnetization*) and demagnetization (*demagnetization*), is the linear law of changing the rotor flux as follows:

$$\psi_{r\,lin}^{demag}(t)=\psi_{r0}\left(1-t/t_f\right),\qquad \psi_{r\,lin}^{mag}(t)=\psi_{r0}t/t_f\ . \tag{1}$$

with slope

$$\frac{d\psi_r}{dt}=\pm\frac{\psi_{r0}}{t_{f\,opt\,lin}}, \tag{2}$$

$$t_{f\,opt\,lin}=\sqrt{3}\cdot\lambda\tau_r, \tag{3}$$


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where $\psi_{r0}$ is a rotor flux in no-load mode; $\tau_r = L_r/R_r$ is a rotor time constant; $\lambda = \sqrt{(R_s + k_r^2 R_r)/R_s} = \sqrt{1 + k_r^2 R_r / R_s} > 1$; $k_r = L_m / L_r$ is a coefficient of magnetic coupling of the rotor; $L_r$, $L_m$ are the rotor inductance and mutual inductance; $R_r$, $R_s$ are the rotor and stator resistance, respectively; $t_f$, $t_{f\ opt\ lin}$ are the time of changing the rotor flux coupling from 0 to the no-load flux coupling and the optimal value of this parameter during magnetization and demagnetization of the motor according to the linear law.

The minimized losses are

$$\Delta W_{lin\ \min}^{demag} = \Delta W_c \left(2\lambda / \sqrt{3} - 1\right), \qquad \Delta W_{lin\ \min}^{mag} = \Delta W_c \left(2\lambda / \sqrt{3} + 1\right), \qquad \Delta W_c = \frac{3}{2} \cdot \frac{R_s \psi_{r0}^2 \tau_r}{L_m^2}. \tag{4}$$

If the rate of change of flux is not optimal, then the energy losses are determined by the formulas:

$$\Delta W_{lin}^{demag} = \Delta W_c \left( \frac{\lambda \tau_o}{t_f} - 1 + \frac{\lambda t_f}{3\tau_o} \right), \qquad \Delta W_{lin}^{mag} = \Delta W_c \left( \frac{\lambda \tau_o}{t_f} + 1 + \frac{\lambda t_f}{3\tau_o} \right), \tag{5}$$

where $\tau_o = \lambda \tau_r$.

Formulas (3)–(5) were obtained analytically while neglecting some features of IM, for example, the phenomenon of steel saturation. Therefore, they should be tested experimentally.

**The purpose of the work** is an experimental confirmation of the theoretically determined fact that during magnetization and demagnetization of a vector-controlled induction motor according to a linear law by variation of the magnitude of the rotor flux linkage, it is possible to achieve minimization of the total losses in the copper of the stator and rotor, as well as a comparison of the optimal time of magnetization and demagnetization and minimized thermal losses, calculated according to analytical formulas, with the results of experimental studies.

**Materials and research results.** The experiment was performed in the electric drive laboratory of the Otto-von-Guericke-University Magdeburg at the rapid test station of the IM vector field-oriented control (FOC) system. Technical data and parameters of the investigated Siemens motor are given in the table 1 (parameters of induction motor Simens 1LE10011CB021AA4-Z).

**Table 1**

| Technical data | | | Parameters | | |
|---|---|---|---|---|---|
| Rated power | $P_n$ | 5.5 kW | Stator resistance | $R_s$ | 0.735 Ohm |
| Rated voltage (line-line) | $U_{sn\,lin}$ | 380 V rms | Rotor resistance | $R_r$ | 0.42 Ohm |
| Rated stator current (operating) | $I_{sn}$ | 11.9 A rms | Leakage stator induction | $L_{s\sigma}$ | 0.0066 H |
| No-load current (operating) | $I_{s0}$ | 6 A rms | Leakage rotor inductance | $L_{r\sigma}$ | 0.0066 |
| Nominal electromagnetic torque | $T_n$ | 35.87 Nm | Mutual inductance | $L_m$ | 0.118 H |
| Rated rotor speed | $n_n$ | 1465 rpm | Loss resistance in steel | $R_{Fe}$ | 340 Ohm |
| Rated rotor flux | $\psi_{rn}$ | 0.97 Wb | Inertia | $J$ | 0,0201 kg m$^2$ |

The same loading machine is installed on the same shaft as the machine under study. Both motors are powered by individual frequency converters embedded compatible with the control system in the digital processor EP1C12Q240I7N with Vector Linux 5.8 operating system and real-time extension: RTAI 3.4. Information is displayed on a regular monitor. Current and voltage sensors are included into the frequency converters. The inverters are based on 50 A 1200 V IGBT power modules, driven with space vector PWM, operating with a switching frequency of 5 kHz. The DC-Link is supplied with 560 V. The motors are equipped with 1XP8012-20 1024 encoders.

The general view of the experimental technological installation, the view of the digital processor and the visualization panel are shown in fig. 1, 2 and 3 respectively.

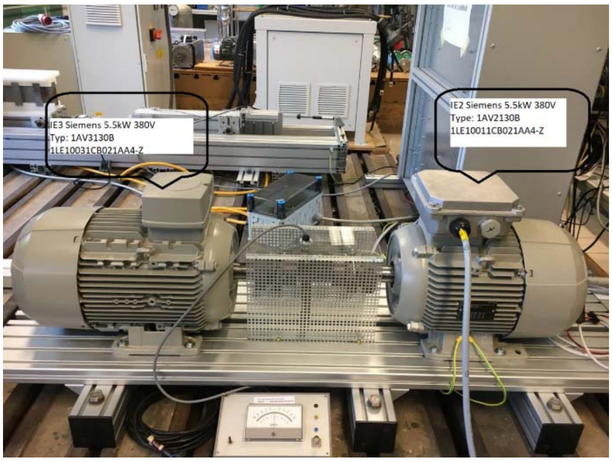


Fig. 1


Fig. 2

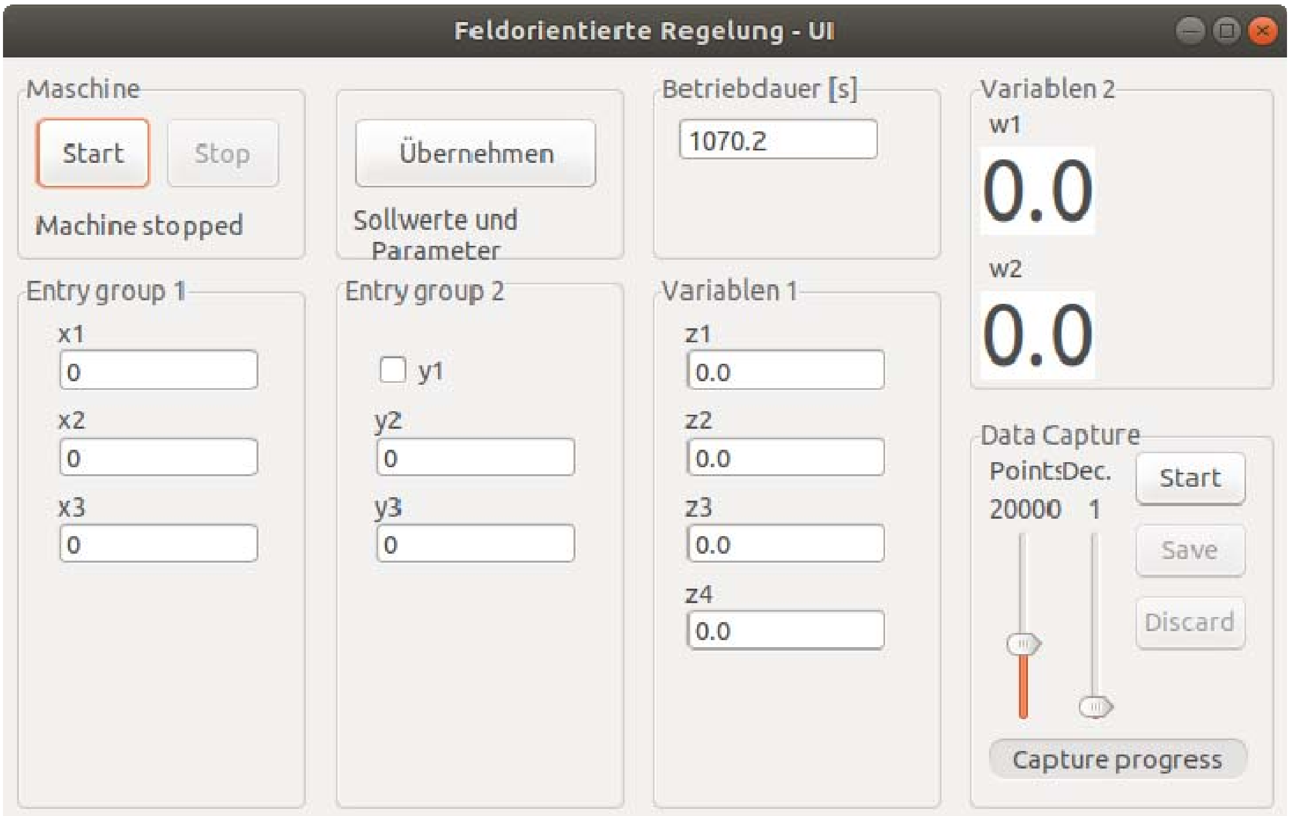


Fig. 3

Control of the flux coupling of the rotor is carried out indirectly by the PI controller of the flux-forming component of the stator current closed loop. Therefore, the structural diagram of such a control channel in the orthogonal rotational coordinate system *d-q*, oriented along the rotor flux coupling vector, looks like fig. 4.

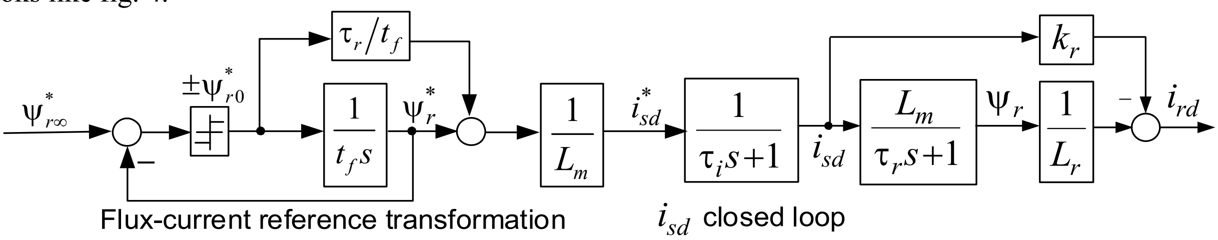


Fig. 4

Rotor reference $\psi_r^*$ formed on the flux-current rate transformation, and its transformation into a reference for the *d*-component of the stator current $i_{sd}^*$ is carried out in accordance with the transfer function

$$\frac{i_{sd}^*(s)}{\psi_r^*(s)} = \frac{\tau_r s + 1}{L_m}. \qquad (6)$$

The derivative of the flow coupling task is formed at the output of the integrator of the dispensing device. In the scheme of fig. 4, the following designations are used: $d$- component of the stator current under the condition of compensation of the internal feedbacks of the $dq$- model IM; $\psi_{r\infty}^*$ is a reference for a fixed value of the rotor flux coupling; $i_{sd}, i_{rd}$ are the flux-forming components of the spatial vectors of the stator and rotor currents; $\psi_r$*, $i_{sd}$* are the reference signals for the rotor flux coupling and the flux-forming component of the stator current; $\tau_i$ is a integration time constant of the open current circuit. The time constant of the closed current circuit of the experimental setup is $\tau_i = 0.2$ $ms$, which is significantly less than the time constant of the rotor $\tau_r = 0.3$ $s$. Therefore, the functions and their derivatives are almost non-discontinuous.

For the investigated IM

$$L_r = L_m + L_{r\sigma} = 0{,}125 \text{ H}; \quad i_{sd0} = \sqrt{2} I_{sd0} = 8{,}49 \text{ A}; \quad \psi_{r0} = L_m i_{s0} = 1{,}0013 \text{ Vb}; \quad \tau_r = \frac{L_r}{R_r} = 0{,}3 \text{ s};$$

$$\Delta W_c = \frac{3}{2} R_s i_{sd0}^2 \tau_r = 23{,}55 \text{ J}; \quad k_r = \frac{L_m}{L_r} = 0{,}947; \quad \lambda = \sqrt{1 + \frac{k_r^2 R_r}{R_s}} = 1{,}23; \quad t_{f\,opt\,lin} = \sqrt{3} \cdot \lambda \tau_r = 0.63 \text{ s};$$

$$\Delta W_{lin\,\min}^{demag} = \Delta W_c \left(2\lambda / \sqrt{3} - 1\right) = 9{,}89 \text{ J}; \qquad \Delta W_{lin\,\min}^{mag} = \Delta W_c \left(2\lambda / \sqrt{3} + 1\right) = 56{,}99\ J.$$

In order to check the presence of an extremum and the correctness of formulas (3)–(5), we will gradually magnetize the stationary IM from 0 to $\psi_{r0}$ and demagnetizing it from $\psi_{r0}$ to 0 according to the linear law for 3 time values of these processes: $t_f = [1,\ 0.5,\ 2] t_{f\,opt\,lin} = [0.63,\ 0.315,\ 1.26]$ s. We will measure currents $i_{sd}, i_{rd}$. Based on this information, we will calculate the flux coupling of the rotor, assuming that the flux varies as linearly ratio with the current and calculate the energy loses for magnetization and demagnetization.

The graphs of the obtained transient processes are shown in fig. 5 ($t_f = t_{f\,lin\,opt}$), 6 ($t_f = 0{,}5 t_{f\,lin\,opt}$) and 7 ($t_f = 2 t_{f\,lin\,opt}$).

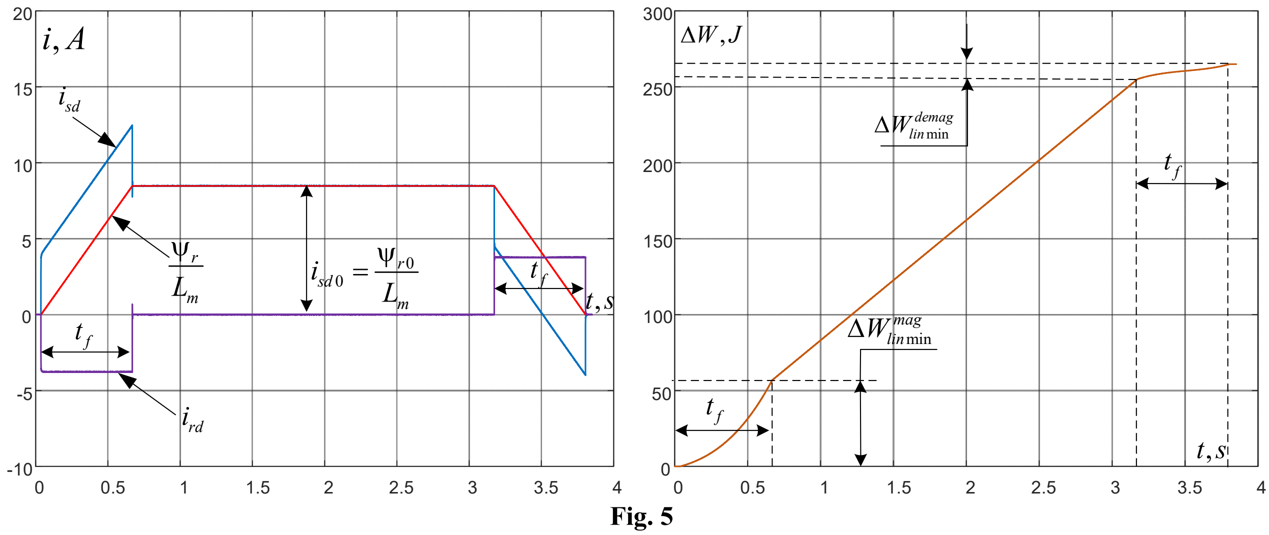


**Fig. 5**

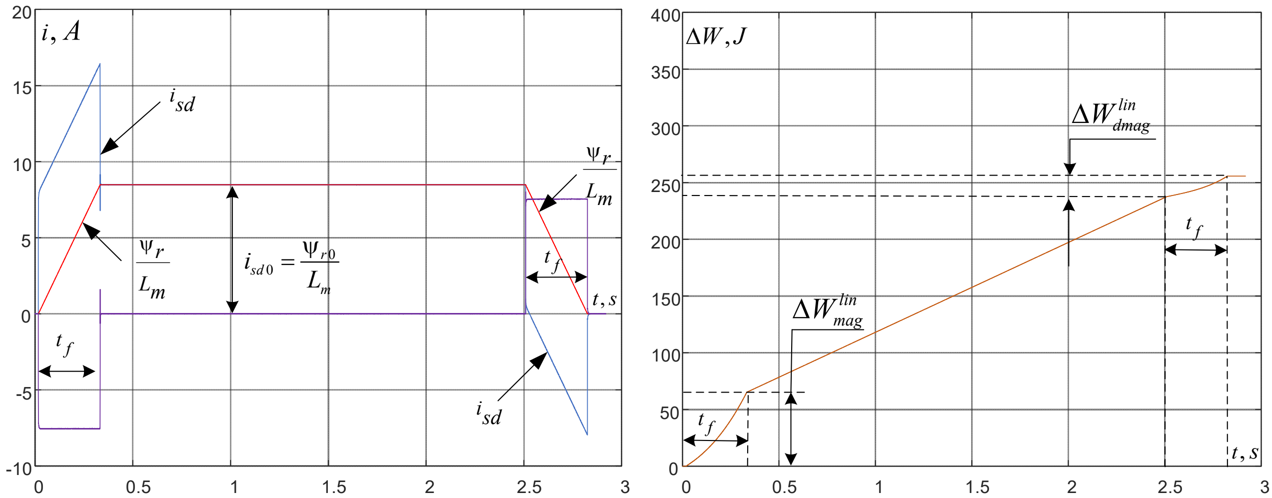


**Fig. 6**

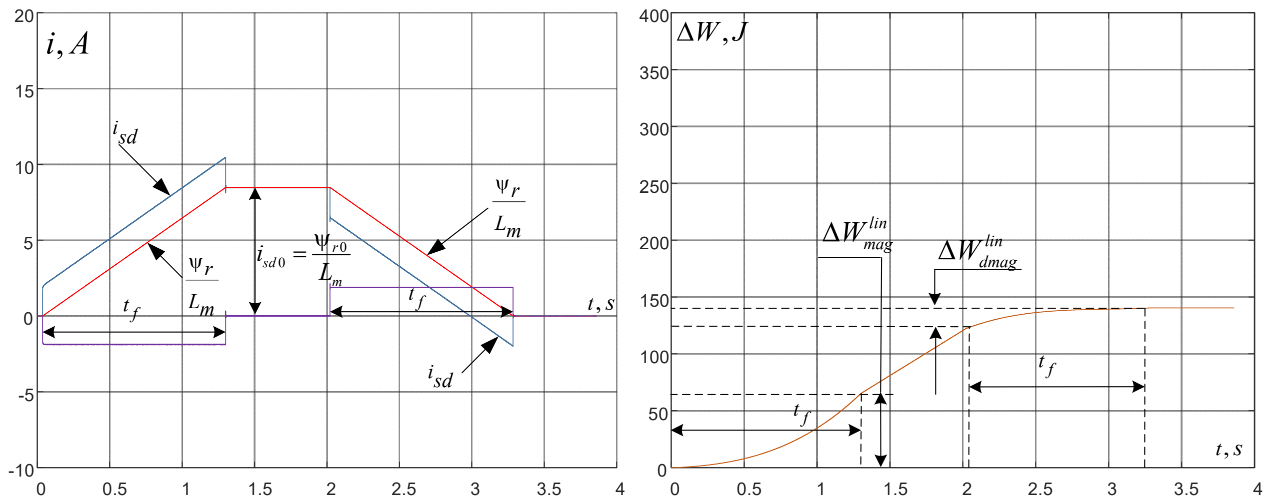


**Fig. 7**

The main numerical results of the experiment and calculations based on analytical expressions are summarized in the table 2 (results of comparison of mathematical modeling and experiment).

**Table 2**

| Electricity losses in copper $\Delta W / \Delta W_c$ , J | | |
|---|---|---|
| Mode \ Research | Analytical | Experimental |
| $t_f = t_{f\,opt\,lin} = 0,63$ s | | |
| Demagnetization | 9,92 | 9,92 |
| Magnetization | 57,19 | 57,19 |
| Total (mag.+demag) | 67,11 | 67,11 |
| $t_f = t_{f\,opt\,lin} / 2 = 0,3$ s | | |
| Demagnetization | 18,31 | 18,32 |
| Magnetization | 65,57 | 65,56 |
| Total (mag.+demag) | 83,88 | 83,88 |
| $t_f = 2t_{f\,opt\,lin} = 1,22$ s | | |
| Demagnetization | 18,31 | 18,31 |
| Magnetization | 65,57 | 65,57 |
| Total (mag.+demag) | 83,88 | 83,88 |

From the examination and comparison of these graphs, it follows that indeed the smallest heat losses of electric power due to magnetization and demagnetization of the motor are observed at linear change of rotor flux coupling from 0 to idling flux coupling in the forward and reverse directions in a time of 0,63 s. Both a decrease and an increase in the rate of change of the rotor flux coupling lead to an increase in losses. It is characteristic that both the increase and decrease of the parameter $t_f$ in the same number of times relatively $t_{f\,opt\,lin}$ give the same result in terms of increased losses in copper.

The difference between the values of losses obtained in the calculation according to the formulas derived in [8] and the same values obtained as a result of the experiment is 0.1 %.

Therefore, the assumptions made when deriving the formulas for calculating the optimal and current indicators of transient processes during demagnetization and magnetization of IM according to the linear law, practically do not affect the accuracy of numerical calculations.

**Conclusions.** The result of experimental research of the magnetization and demagnetization processes of a motionless vector-controlled induction motor were performed using indirect control of the rotor flux according to the linear law. As a result of research, the possibility of minimizing losses in copper by change the magnitude of rotor flux and analytically obtained formulas for determining the optimal time of magnetization and demagnetization for IM has had approbation. Consequently, the experimentational result minimization of energy losses in copper and calculation by formulas have been confirmed. The high accuracy of the coincidence of the results of analytical and experimental results indicates that the factors not taken into account during the performance of analytical studies (for example, the effect of magnetization of steel) are really not significant and practically do not affect the energy indicators.


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**ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ПРОЦЕСІВ НАМАГНІЧУВАННЯ ТА РОЗМАГНІЧУВАННЯ АСИНХРОННОГО ДВИГУНА З ВЕКТОРНИМ КЕРУВАННЯМ**


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*Проведено експериментальне дослідження процесів намагнічування та розмагнічування нерухомого асинхронного двигуна з векторним керуванням за лінійним законом зі зміною тривалості цих процесів. Описано методику дослідження, під час якої фіксувалися ортогональні складові струмів статора та ротора в системі відліку потоку ротора, модуль потоку ротора та енергія повних втрат у міді статора та ротора. Наведено основні характеристики та параметри лабораторного обладнання. З точки зору мінімізації втрат міді експериментально доведено існування оптимальної тривалості досліджуваних перехідних процесів. Результати експериментальних досліджень з високою точністю збігаються з розрахунками на основі раніше отриманих аналітичних залежностей, що підтверджує допустимість зроблених припущень під час теоретичних досліджень.* Бібл. 10, рис. 7, табл. 2.



***Ключові слова***: асинхронний двигун, намагнічування, розмагнічування, втрати потужності, оптимізація, експеримент.

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