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SYNTHESIS BY USING THE SLIDING-MODE CONTROL THEORY FOR THE FUZZY LOGIC CONTROLLER OF THE DIRECT TORQUE CONTROL SYSTEM

Purpose. Improvement of the direct torque control algorithm and thereby increase in the efficiency of the electric drive on the basis of the squirrel cage induction motor.

Methodology. The use of the theory of sliding-mode control and hysteresis regulators allows considering the traditional direct torque control algorithm as a special case, which is obtained for certain values of the weight coefficients of deviation from the given regimes. Changing these coefficients leads to a change in the sector boundaries of the switching table. The analysis of system behavior on the basis of the established quality criterion gives the possibility to determine the necessary changes of sector boundaries for improving the characteristics of the drive and to synthesize a fuzzy controller that implements the sliding mode control with variable weight coefficients. The efficacy of the proposed control algorithm was investigated by use the modified MatLab model of the direct torque control and the necessary computer experiments were performed.

Findings. On the basis of the established criterion, the influences of the change in the switching table sector boundaries on the characteristics of the electric drive with direct torque control were analyzed. The fuzzy controller was synthesized based on the theory of sliding mode control. The behavior of the direct torque control system with fuzzy controller was investigated.

Originality. The scientific novelty of the proposed approach is in further development of the theory of fuzzy controllers synthesis based on the methods of classical control theory and improving the direct torque control algorithm at low speeds, as well as in the high speeds with load close to the nominal.

Practical value. The proposed structure of the fuzzy controller can be easily implemented in existing systems of direct torque control and will provide an improvement of the technical and economic performance of the electric drive.

Keywords: *induction motor*, *fuzzy logic controller, direct torque control, sliding mode control*

Introduction. Modern electric drive systems are characterized by high performance requirements, accuracy of the processing of regime coordinates, robustness as well as efficiency and economy. In view of the widespread use of an asynchronous electric drive in modern industrial production, the improvement of existing control algorithms, in particular, the direct torque control algorithm (DTC), can provide a significant economic effect. Consideration of the DTC as a partial case of the sliding mode control theory makes it possible, by means of changing the weight coefficients of surfaces, at the intersection of which the sliding mode is implemented, to form a controlling influence with regard to the peculiarities of each area of the system state. Taking into account the fact that the change of the weight coefficients of surfaces under the use of hysteresis flux and torque controllers is transformed into the change of the switching table sector boundaries, it is an actual task to find an optimum angle of the sector shift, in terms of increasing the efficiency of the electric drive, as well as the synthesis of adaptive control system, which will provide the necessary change of these angle.

Unsolved aspects of the problem. Direct torque control algorithms, offered in the late 80s of the last century by Isao Takahashi and Toshihiko Noguchi and Manfred Depenbrock, despite their functional simplicity provide high flux and torque performances and robustness to change in the induction motor parameters. However, the DTC switching table (Table 1) is not equally effec-

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Table 1

Direct torque control algorithm switching Table

γ		−30°, +30°	30°, 90°	90°, 150°	150°, 210°	210°, 270°	270°, 330°
$d\Psi = 1$	$dm = 1$	110	010	011	001	101	100
	$dm = 0$	111	000	111	000	111	000
	$dm = -1$	101	100	110	010	001	001
$d\Psi = -1$	$dm = 1$	010	011	001	101	100	110
	$dm = 0$	000	111	000	111	000	111
	$dm = -1$	001	101	100	110	010	011

tive at different rotation speeds and at different load of the induction motor [1, 2].

In particular, the influence of the voltage vector on the stator flux vector decreases substantially in the switching region between sectors, which leads to so-called weakening of the flow at the sector boundaries. This problem is especially noticeable at low speeds.

On the other hand, at high rotational speeds and loads, close to the nominal, efficacy of the use of the voltage vectors, indicated in Table 1, also decreases. This is primarily due to the fact that in the classic DTC algorithm at high speeds, providing of a given value of the flux becomes priority. Decreasing the pulsations of the electromagnetic torque and flow in the steady state regimes also remains important.

Accordingly, it is necessary to synthesize such an algorithm for induction motor direct torque control which will adapt to the operation conditions. The use of the theory of fuzzy sets is proposed to solve this problem.

Analysis of the recent research. Different approaches are used to eliminate disadvantages and enhance the effectiveness of the classic DTC algorithm [3]. In general, many authors apply the space-vector modulation to solve the problems of the hexagonal flux trajectory and distortion of the current shape at low speeds. A rather detailed analysis of the influence of voltage vectors on flux changes at low speeds and near the switching sectors boundaries is given in [4]. In [5], the advantages of space-vector modulation are proposed to combine with the use of the theory of predictive control in order to improve the electric drive characteristics. However, the application of such an algorithm requires on-line identification of motor parameters and precise estimation of controlled parameters (moment and flux) as well as prediction of their change in a few steps forward. In [6], to improve the quality of the trajectory of the flux vector, it is proposed to use the fuzzy logic controller instead of the hysteresis flux controller and an extended switching table for significant fluctuations of the flux from the given value.

The flow estimation method also has a significant effect on the quality of DTC operation. The efficiency of using a traditional flux estimator, which is based on the stator's voltage and current, decreases at low speeds [7]. However, incorrect flux identification, which leads to erroneous sector identification, in some cases, at low rotational speeds, gives the possibility to avoid the flux and current distortions and thus improves the characteristics of the electric drive. Some researchers try to use this peculiarity to improve DTC. For example, the modified control algorithm with variable boundaries of the switching table sectors is proposed in [8], and in [9], the fuzzy control theory is applied to determine the sector shifts. The complexity of the proposed approaches has not facilitated their further application in the direct torque control systems.

Considerable attention of researchers is also paid to the use of the sliding mode control theory in the direct torque control systems. However, most of these studies focus on the application of classical PI regulators in sliding mode control systems and the synthesis of flux and torque estimators based on the sliding mode control theory [3, 10]. In [11], the influence of the switching table vectors near the switching sector boundaries is considered and on the basis of the theory of fuzzy sets and sliding mode control an algorithm is synthesized which allows reducing the torque pulsations.

In [12], it is approved that the use of the theory of sliding mode control and relay regulators of flux and torque gives possibility to consider the classic direct torque control algorithm as a partial case, obtained with the certain ratio of weight coefficients for the formed switching surface. Change in the ratio of these coefficients, which is equivalent to change in the boundaries of the switching sectors of the classical DTC algorithm, provides the increase in the tracking accuracy of torque and flux.

Objectives of the article. On the basis of the established optimality criterion, the effect of the change of switching sectors of the DTC algorithm at different speeds and with different loads operation will be analyzed. Based on the result of the conducted analysis and applying the theory of fuzzy set, the regulator, which will provide the necessary change in the boundaries of the switching sectors, will be synthesized. The system's behavior with proposed control algorithm will be investigated in different operational regimes.

Presentation of the main research and explanation of scientific results. Let us consider the law of switching of control influences u_A, u_B, u_C for the DTC algorithm, which is synthesized on the basis of the sliding mode control theory (in particular, described in Utkin V. I. "Sliding Modes in Control and Optimization") and realizes the sliding mode on the surfaces

$$S_1 = c_1 \cdot \left(T_z - T\right); \qquad S_2 = c_2 \cdot \left(\Psi_z - \Psi\right);$$
$$S_3 = -\int_0^t \left(u_A + u_B + u_C\right) d\lambda, \tag{1}$$

where T_z and T are the given and real values of the induction motor electromagnetic torque; $|\Psi_z|$ and $|\Psi|$ are the given and real flux vector amplitudes; c_1 and c_2 are the weight criteria coefficients, the equations of which determine the deviation from the given regimes. Taking into account that $u_A + u_B + u_C = 0$ (inverter voltage forms a three-phase symmetric voltage system), the control law mentioned above will be as follows

$$u = u_0 \operatorname{sign}\left(\frac{1}{3} \cdot \left[\begin{aligned} & \nu \cdot \sin(\gamma) \cdot c_1 \cdot (T_z - T) + \\ & + \nu \cdot \left(\frac{-\sqrt{3}}{2}\cos(\gamma) - \frac{1}{2}\sin(\gamma) \right) \cdot c_1 \cdot (T_z - T) + \\ & + \nu \cdot \left(\frac{\sqrt{3}}{2}\cos(\gamma) - \frac{1}{2}\sin(\gamma) \right) \cdot c_1 \cdot (T_z - T) + \\ & + \mu \cdot \cos(\gamma) \cdot c_2 \cdot (|\Psi_z| - |\Psi|) \\ & + c_2 \cdot (|\Psi_z| - |\Psi|) \cdot \mu \cdot \left(\frac{-1}{2}\cos(\gamma) + \frac{\sqrt{3}}{2}\sin(\gamma) \right) \\ & + c_2 \cdot (|\Psi_z| - |\Psi|) \cdot \mu \cdot \left(\frac{-1}{2}\cos(\gamma) - \frac{\sqrt{3}}{2}\sin(\gamma) \right) \end{aligned} \right] \right), \tag{2}$$

where r_r is the resistance of the rotor winding; L_s, L_r are the inductance of the stator winding and the stator-referred inductance of the rotor winding; L_m is the mutual inductance; p_n is the number of pairs of poles; Ψ_α, Ψ_β, are the components of flux vector;

$$\nu = \frac{-2 \cdot \left(L_s \cdot L_r - L_m^2 \right)}{L_m \cdot p_n \cdot |\Psi|}; \quad \mu = \frac{3 \cdot \left(L_s \cdot L_r - L_m^2 \right)}{2 \cdot L_m \cdot r_r};$$

$$\cos(\gamma) = \frac{\Psi_\alpha}{|\Psi|}; \quad \sin(\gamma) = \frac{\Psi_\beta}{|\Psi|}.$$

By using the torque and flux hysteresis regulators, in which the connection between the output and the input signal is described by the relations

$$dm = 1 \text{ if } T_z - T > \Delta T; \quad d\Psi = 1 \text{ if } \Psi_z - |\Psi| > \Delta|\Psi|;$$

$$dm = 0 \text{ if } |T_z - T| < \Delta T; \quad d\Psi = -1 \text{ if } \Psi_z - |\Psi| < \Delta|\Psi|;$$

$$dm = -1 \text{ if } T_z - T < -\Delta T,$$

we can obtain, as shown in [12], the switching table in which the boundary of the switching sectors depends on the ratio of the coefficients c_1 and c_2.

Evaluation of the efficacy of the proposed modifications of the direct torque control algorithm is traditionally performed using such criteria as the root-mean-square error of the torque or flux (RMSE) and the total harmonic distortion (THD) of the stator current [7, 11]. At the same time, the following criteria apply to assess the energy efficiency of the electric drive: 1 – minimum of stator current; 2 – minimum of total losses; 3 – the maximum of efficiency factor; 4 – maximum of the power factor. In particular, in [14] the advisability of applying the criterion of the maximum of the power factor is substantiated. Taking into account the above mentioned, the following criterion is proposed to be used to evaluate the efficiency of the change of the ratio of weight coefficients c_1 and c_2 for different operation points

$$I = \max_{\substack{with\ \omega=\omega_i \\ T=T_i}} \left(\frac{\cos\varphi}{THD} \right), \tag{3}$$

where ω_i and T_i determinate the operation point of electromechanical system.

The research was carried out using the MATLAB software for the ratio of the coefficients c_1 and c_2, which ensure the implementation of the classical DTC control algorithm (Table 1) and the algorithms for which the sector boundaries were shifted by ±30 and ±15° relative to the classical algorithm at the given speed values: $\omega = \omega_n$, $0.8\omega_n$, $0.6\omega_n$, $0.4\omega_n$, $0.2\omega_n$, $0.1\omega_n$, and loads: $T = T_n$, $0.75T_n$, $0.5T_n$, $0.25T_n$, $0.1T_n$. The induction motor model, taking into account the magnetic circuit saturation, is used in the research. Necessity to take into account the magnetization characteristic at high speeds operation is shown in [10]. The parameters of the induction motor model and the no-load saturation curve (Table 2) are given below.

Parameters of the induction motor model include:

nominal power – $P = 11$ кW;

nominal voltage – $U = 220$ V;

nominal frequency – $f = 50$ Hz;

the number of magnetic poles – $p = 3$;

moment of inertia – $J = 0.12$ kg × m^2;

resistance of the stator and rotor winding – $R_s = 0.364$ Om, $R_r' = 0.4$ Om;

leakage inductances of the stator and rotor winding – $L_{\sigma s} = L_{\sigma r}' = 0.0032$ H.

The analysis of the results confirms the effectiveness of the changing of the sector boundaries in the classical DTC algorithm switching table according to Table 3. The application of the shifting of sector boundaries by ±30° in most cases leads to a significant distortion in the flux hodograph and only in the case of high speed and large load or at low speeds and small loads makes it possible to obtain a slight improvement in comparison with the shifting by ±15°, respectively.

So, there is a problem of synthesis of the control influences, when the weight coefficients of switching sur-

Table 2

No-load saturation test of induction motor

I, A	0.00	10.16	10.71	11.28	11.92	12.60	13.30	14.12
E, V	3.50	220.5	230.1	240.7	251.0	262.8	272.2	281.3
I, A	15.35	16.41	17.70	19.57	21.87	24.55	27.68	33.85
E, V	292.0	300.5	309.7	320.0	330.4	341.6	351.1	371.4

Table 3

Shifting of the sector boundaries*

M ω	$0.1T_n$	$0.25T_n$	$0.5T_n$	$0.75T_n$	T_n
ω_n	0	0	+15	+15	+15
$0.8\omega_n$	–15	0	+15	+15	+15
$0.6\omega_n$	–15	0	+15	+15	+15
$0.4\omega_n$	–15	0	+15	+15	+15
$0.2\omega_n$	–15	0	0	+15	+15
$0.1\omega_n$	–15	0	0	+15	+15

* 0 – corresponds to the standard DTC system; –15 and +15 – corresponds to DTC systems with shifting the boundaries of sectors in the control vector switching table for the corresponding angle

faces (1) change. As shown in [15], use of the theory of fuzzy sets enables to solve this problem effectively. The structure of a separate rule for the fuzzy controller, which provides adaptation of the control law (2) to the conditions of the induction motor operation, is as follows

$$R^i: \text{IF } \omega \in A^i \text{ and } T \in B^i \text{ then } c_1 = c_1^i \text{ and } c_2 = c_2^i, \qquad (4)$$

where A^i, B^i are linguistic variables that determine the fuzzy sets of the rotational speed ω and torque T of the induction motor; c_1^i, c_2^i are the values of the coefficients that realize the corresponding shift of sector boundaries of the classical switch table for the definite angle.

The outputs of fuzzy controller (4) are the values of the coefficients c_1 and c_2, which, after substitution in (2), form a control influence that fulfills the criterion (3). The implementation of such algorithm requires significant changes in the existing DTC systems.

At the same time, change in the sector boundary of the classical control algorithm by –15° is equivalent to a change by 15° of γ angle, and vice versa. This allows simplifying the implementation of the proposed control algorithm in existing control systems significantly (Fig. 1).

The structure of a separate rule of the fuzzy controller in this case will be as follows

$$R^i: \quad \text{IF } \omega \in A^i \quad \text{and } T \in B^i \quad \text{then } \Delta\gamma = \Delta\gamma^i, \qquad (5)$$

where A^i, B^i are the linguistic variables that determine the fuzzy sets of the rotational speed ω and torque T of the induction motor; $\Delta\gamma^i$ is the corresponding displacement angle of the angle of the flux vector position γ.

In the case of applying the gravity defuzzyfication method, T-norms of the type of product and membership functions of the linguistic variables represented in Fig. 2, the output signal of the fuzzy controller (5) has the form shown in Fig. 3.

To study the proposed control algorithm, a block which realizes the fuzzy controller (5) is added to the model of the DTC system of the SimPowerSystem extension package of the MATLAB. The output of the fuzzy controller enters the Simulink Sum block, as shown in Fig. 1, and provides corresponding displacement of the angle of the flux vector position, which is equal to shift of the sector boundaries of the classical DTC switching table. Investigations of the system with the fuzzy controller (5) were carried out at low and high speeds and variable loads (Fig. 4). MATLAB software tools are used to analyze the results.

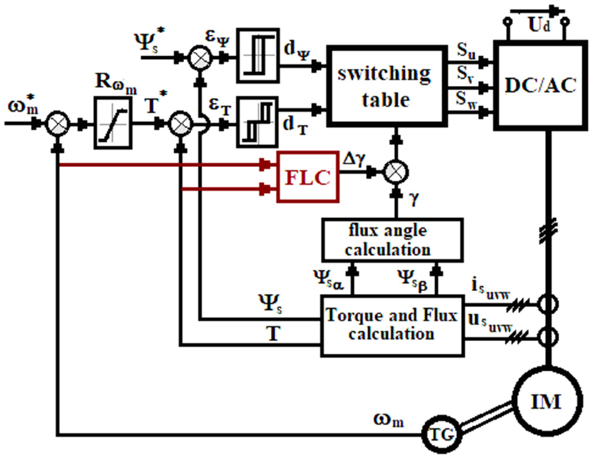


Fig. 1. The structure of the direct torque control system with fuzzy controller, synthesized on the basis of the theory of sliding mode control

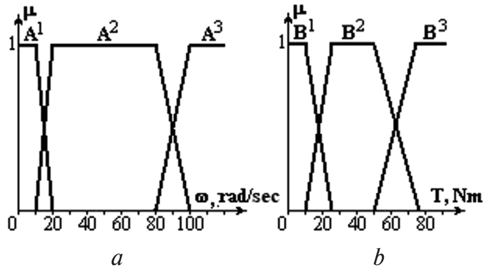


Fig. 2. Membership functions of the linguistic variables: a – the rotation speed; b – the electromagnetic torque

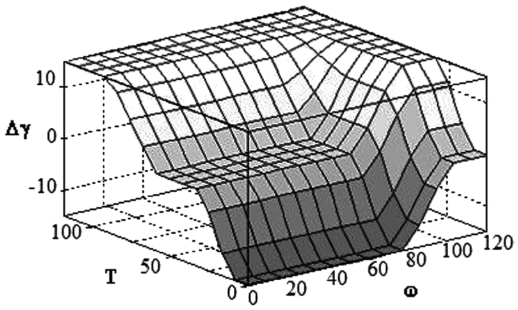


Fig. 3. Output signal of the fuzzy controller

Results of Fourier series analyses of the stator currents (Fig. 5) and the values of the coefficients of total harmonic distortions (Table 4) demonstrate the reduction of harmonic levels, which as outcomes also decreases the level of the torque pulsations and improves

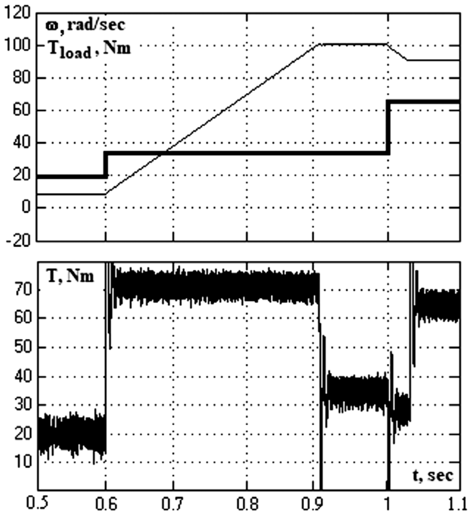


Fig. 4. The change in speed, load and electromagnetic torque of the induction motor in the system with the fuzzy controller

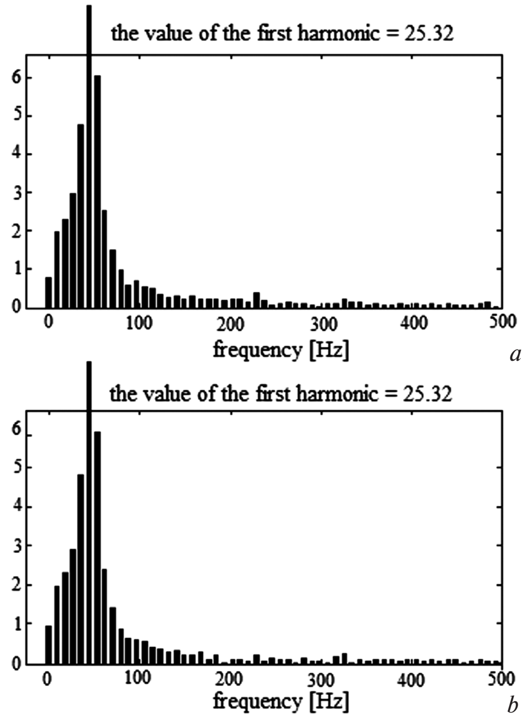


Fig. 5. Stator currents harmonics at the rotational speed of 91 rad/sec and load of 65 Nm:

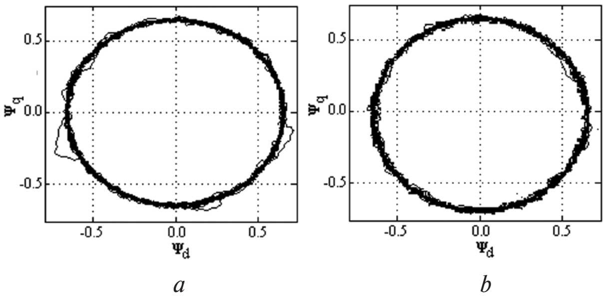
a – classic DTC algorithm; b – algorithm with a fuzzy controller

Table 4

The values of the first harmonic of the stator current and the total harmonic distortion coefficient

	Classical DTC algorithm		Proposed control algorithm	
	I, A	THD, %	I, A	THD, %
ω = 8.4 rad/sec T_{load} = 20 Nm	12.25	21.02	12.09	19.18
ω = 91 rad/sec T_{load} = 65 Nm	25.32	4.48	25.32	4.20

the accuracy of maintenance of the given flux value, especially at low frequencies (Fig. 6). It should also be noted that there is a slight change in the stator current frequency compared with the classic DTC algorithm, which is more pronounced at high speeds. This can be explained by the change in the type of mechanical characteristics of the induction motor on which the operating point is placed.



a *b*

Fig. 6. Hodographs of the flux vector at the rotational speed of 8.4 rad/sec and load of 20 Nm:

a – classic DTC algorithm; b – algorithm with a fuzzy controller

The obtained results confirm the efficiency of the synthesized fuzzy controller in transient and steady state modes of operation.

Research conclusions and recommendations for further research. The equivalency of the change in coefficients in the control law by the corresponding correction of the determined angle of the flux vector position enabled to substantially simplify both the structure of the fuzzy controller and the implementation of proposed control algorithm in existing systems.

The use of modified algorithm of direct torque control of induction motor provides a reduction in the harmonic distortion up to 10 % depending on the operating point and thereby improves the efficiency of electric drive.

Consideration of the direct torque control algorithm as a separate case obtained from the sliding mode control theory for the certain ratio of weight coefficients for the formed switching surface allows expanding further research to improve performance of electric drive with induction motor, in particular, use of a three-position flux controller and the replacement of zero voltage vectors in the switch table of the classical algorithm.

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Синтез на основі теорії розривного керування нечіткого регулятора системи прямого керування моментом

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Мета. Покращення алгоритму прямого керування моментом і тим самим підвищення ефективності роботи електроприводу на базі асинхронного двигуна з короткозамкненим ротором.

Методика. Застосування теорії розривного керування та гістерезисних регуляторів дає змогу розглядати традиційний алгоритм прямого керування моментом як окремий випадок, що отриманий для певних значень вагових коефіцієнтів відхилення від заданого режиму. Зміна цих коефіцієнтів призводить до зміни меж секторів. Аналіз поведінки системи на основі сформованого критерію якості дав змогу визначити необхідні зміни меж секторів для покращення характеристик приводу й синтезувати нечіткий регулятор, що реалізує розривне керування зі змінними ваговими коефіцієнтами. Для дослідження ефективності запропонованого алгоритму керування модифікована наявна в середовищі системи MatLab модель прямого керування моментом і виконані необхідні комп’ютерні експерименти.

Результати. На основі сформованого критерію проаналізовано вплив зміни меж секторів на характеристики електроприводу з прямим керуванням моментом. На основі теорії розривного керування синтезовано нечіткий регулятор. Досліджена поведінка системи прямого керування моментом з нечітким регулятором.

Наукова новизна. Полягає в подальшому розвитку теорії синтезу нечітких регуляторів на основі методів класичної теорії керування та вдосконаленні методу прямого керування моментом при роботі на малих швидкостях обертання, а також у зоні високих швидкостей обертання й близького до номінального навантаження.

Практична значимість. Запропонована структура нечіткого регулятора може бути достатньо легко реалізована в існуючих системах прямого керування моментом і забезпечить покращення техніко-економічних показників роботи електроприводу.

Ключові слова: *асинхронний двигун, нечіткий регулятор, пряме керування моментом, теорія розривного керування*

Синтез на основе теории разрывного управления нечеткого регулятора системы прямого управления моментом

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Цель. Улучшение алгоритма прямого управления моментом и тем самым повышение эффективности работы электропривода на базе асинхронного двигателя с короткозамкнутым ротором.

Методика. Применение теории разрывного управления и гистерезисных регуляторов дает возможность рассматривать традиционный алгоритм прямого управления моментом как частный случай, который получен при определенных значениях весовых коэффициентов отклонения от заданного режима. Изменение этих коэффициентов приводит к изменению границ секторов. Анализ поведения системы на основании сформированного критерия качества позволил определить необходимые изменения границ секторов для улучшения характеристик привода и синтезировать нечеткий регулятор, который реализует разрывное управление с переменными весовыми коэффициентами. Для исследования эффективности предложенного алгоритма управления модифицирована имеющаяся в среде системы MatLab модель прямого управления моментом и выполнены необходимые компьютерные эксперименты.

Результаты. На основании сформированного критерия проанализировано влияние изменения границ секторов на характеристики электропривода с прямым управлением моментом. На основе теории разрывного управления синтезирован нечеткий регулятор. Исследовано поведение системы прямого управления моментом с нечетким регулятором.

Научная новизна. Научная новизна предложенного в работе подхода заключается в дальнейшем развитии теории синтеза нечетких регуляторов на основании методов классической теории управления и совершенствовании метода прямого управления моментом при работе на малых скоростях вращения, а также в зоне высоких скоростей вращения и близкой к номинальной нагрузке.

Практическя значимость. Предложенная структура нечеткого регулятора может быть достаточно легко реализована в существующих системах прямого управления моментом и обеспечит улучшение технико-экономических показателей работы электропривода.

Ключевые слова: *асинхронный двигатель, нечеткий регулятор, прямое управление моментом, теория разрывного управления*

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