УДК 62-83

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STRUCTURAL REALIZATION OF THE MAXIMUM TORQUE PER AMPERE STRATEGY FOR THE VECTOR SPEED CONTROL SYSTEM OF INDUCTION MOTORS

Abstract. A new method for the structural realization of the maximum toque per ampere strategy for the vector speed control system of an induction motor is proposed. This method differs from the typical system by the presence of an rotor flux linkage coupling loop and a reference-input unit. In presented system, reference forming for rotor flux linkage in moment-generating function. It allows to maintain nominal efficiency in a steady state, and also provides high quality of transients.

Keywords: electric drive, induction motor, vector control, maximum torque per Ampere, new structure realization, quality of transients, heat losses, efficiency.

Introduction. It is known that currently more than 50% of generated electric power is consumed by electric drives considerable part of which are vector controlled induction motors. One of the drawbacks of such systems is that efficiency decreases when the torque is varying and the flux is kept at the nominal level. Solution of this problem will result not only in power consumption efficiency increase and production cost reduction but also in an increase of time intervals between recharge cycles of autonomous power sources of electric vehicles.

In the systems of field-oriented vector control (FOC) of induction motor drive, initially, we magnetize the motor by supplying reference signal to the rotor flux linkage ψ_r or to the flux-forming component of the stator current i_{sd} and then we get down to regulation of mechanical references: torque, speed or state (position).

When electric drive works in intensive recurrent-short-time mode, the motor is not usually demagnetized during a pause, which results in additional heat loss in the stator windings in the process of maintaining the rotor flux linkage at the desired level. When the time of pause duration is sufficient, these losses can be reduced by demagnetization of induction motor at the beginning of the pause and by magnetization of it before starting a new cycle.

There are different ways to control the described effect. Among the known solutions there are systems for minimizing various types of losses in the motor and converter [1-3], as well as efficiency [4-6] and power factor [7-8] maximization systems. They use both rather simple algorithms and more complex ones with the use of loss models, optimum slip look-up tables [2], on-line search optimization techniques [3-5].

One of the simplest optimization methods is MTA (Maximum Torque per Ampere) strategy, the goal of which is to minimize the current amplitude for given load torque [9, 10]. In accordance with this strategy in the vector control system it is necessary to maintain the equality of the flux-forming i_{sd} and torque-forming i_{sq} components of the current, the magnitude of which is determined from the condition of providing the stall torque. To ensure the MTA criterion in speed control systems the speed control generates reference signal for motor torque, from which the reference signals to the orthogonal components of the stator current are determined. Thus power efficient control is provided. However, dynamics of transients during acceleration of the induction motor deteriorates substantially, because both current circuits and the speed loop start working simultaneously in such a system. In a typical vector control system the motor is magnetized when the motor is in static condition.

Flux linkage control process is carried out indirectly and has an exponential character, which is not optimal from the point of view of minimizing heat loss during magnetization and demagnetization. Within certain parameters and in certain operation modes, this can significantly affect the total losses in copper and steel [11].

The aim of this paper is to design the system, which would ensure the maintenance of the MTA mode without deterioration of the quality of the transients when the electromagnetic torque varies within the range from the moment of idling T_0 to the point $T_{\lim}$ at which the rotor flux linkage does not exceed its nominal value.

Materials and research results. To describe energy and transient processes in a vector-controlled induction motor, the following notation will be used: T – motor torque; T_L – load torque; I_s, U_s – stator (root m

ean square)-current and rms-voltage; i_s, u_s – stator peak current and peak voltage; ψ_r, –peak rotor flux linkage; R_r, R_s – rotor and stator resistance; L_r, L_s, L_m, – rotor, stator and mutual inductance; p – pole paars number; $\tau_r = L_r / R_r$ – rotor time constant; $k_T = 3pk_r/2$ – torque gain; $k_r = L_m / L_r$ – rotor magnetic linkage factor; J – inertia.

Mathematical description of the IM is fulfilled in the orthogonal coordinate system *dq*, oriented along the vector of the rotor flux linkage:

$$\begin{cases} u_{sd} + \dfrac{k_r}{T_r}\Psi_r + \omega_k \sigma L_s i_{sq} = i_{sd} R_{sr}\left(T_{sr}s+1\right), \\ u_{sq} - \omega_k \sigma L_s\, i_{sd} - p\omega k_r \Psi_r = i_{sq} R_{sr}\left(T_{sr}s+1\right), \\ L_m I_{sd} = \Psi_r\left(T_r s+1\right), \\ \omega_k = k_r R_r \dfrac{I_{sq}}{\Psi_r} + p\omega, \\ T = k_T \Psi_r i_{sq}, \\ T - T_L = J\omega s, \end{cases} \tag{1}$$

where ω_k is speed of the coordinate system**,**

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

Energy efficiency of any electric motor depends on the total losses, which can be divided into losses in windings (copper loss), losses in the magnetic circuit (iron loss), losses in the converter and mechanical losses. Copper loss is determinative for single-zone speed control, and losses in the stator prevail over losses in the rotor.

It is known [11] that without taking into account iron saturation effect, the minimum stator current for a given tourqe is provided when

$$\psi_{rMTA} = \sqrt{\frac{2TL_r}{3p}} = \sqrt{\frac{TL_m}{k_T}}. \tag{3}$$

Meanwhile *d*- and *q*- components of stator current are equal:

$$i_{sdMTA} = i_{sqMTA} = \sqrt{\frac{T}{k_T L_m}}, \tag{4}$$

this also leads to minimization of electric loss in stator winding:

In this case, the *d*- and *q*-components of the stator current turn out to be equal to each other:

$$\Delta P_{sCu} = 3R_s I_s^2 = \frac{3}{2}(i_{sd}^2 + i_{sq}^2) \rightarrow \min. \tag{5}$$

Minimization of total losses in stator and rotor copper

$$\Delta P_{\Sigma Cu} = \frac{3}{2}\left[R_s i_s^2 + R_r i_r^2\right] = \frac{3}{2}\left[R_s(i_{sd}^2 + i_{sq}^2) + R_r(i_{rd}^2 + i_{rq}^2)\right] \rightarrow \min \tag{6}$$

is achieved by

$$\psi_{r\,opt} = \sqrt{\frac{2TL_r}{3p}\lambda}, \tag{7}$$

where

$$\lambda = \sqrt{\frac{R_{sr}}{R_s}} = \sqrt{1 + \frac{k_r^2 R_r}{R_s}}; \tag{8}$$

$$i_{sdopt} = \sqrt{\frac{T}{k_T}\lambda}, \quad i_{sqopt} = \sqrt{\frac{T}{k_T \lambda}}, \quad \frac{i_{sdopt}}{i_{sqopt}} = \lambda. \tag{9}$$

Nominal rotor flux linkage $\psi_{r\,n}$ is the value that in the nominal operation mode of the motor provides maximum efficiency, and, therefore, minimum total losses. The rotor flux linkage reaches this value when the open loop drive induction motor is operating in the nominal operation mode. Normally, when $0 < \psi_r < \psi_{r\,n}$ the motor operates almost on the linear range of the magnetization curve, and values (3) and (8) shift the induction motor to saturation mode.

To prevent this, it is necessary to limit the rotor flux linkage at the nominal value level. Limiting value of the torque, at which the linkage reaches the limiting level can be determined by the formula (3):

$$\psi_{rMTA}(T_n) = \sqrt{\frac{T_n L_m}{k_T}}, \qquad \psi_{rMTA}(T_{\lim}) = \sqrt{\frac{T_{\lim} L_m}{k_T}} = \psi_{rn}, \tag{10}$$

wherefrom

$$T_{\lim} = \frac{k_T}{L_m}\psi_{r\,n}^2 = T_n\left(\frac{\psi_{r\,n}}{\psi_{r\,MMA}(T_n)}\right)^2. \tag{11}$$

Simplified block diagram of the induction motor IFOC system in rotating coordinate frame *dq*, which implements the strategy of MTA, is shown in Fig.1.

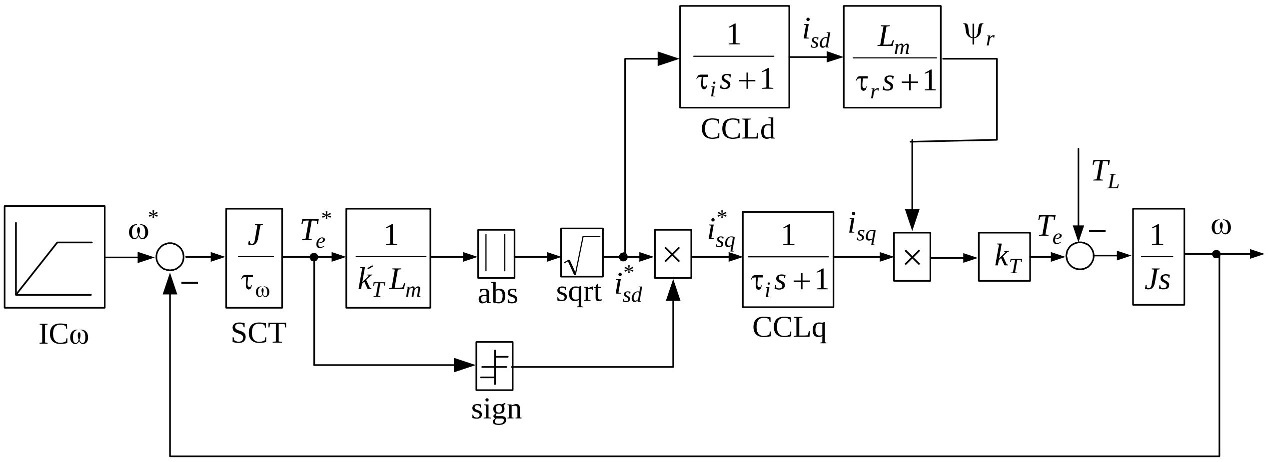

Figure 1 – Block diagram of the simplest typical induction motor vector control system

The figure shows: CCLd, CCLq – closed current loops for the stator *d*-and *q*-components, approximately represented by aperiodic links with a small time constant τ_i

$$W_{CCLd}(s)=W_{CCLq}(s)=\frac{i_s(s)}{i_s^*(s)}\approx\frac{1}{\tau_i(s)+1}; \tag{12}$$

SCT – proportional speed controller with transfer function, which generates reference signal for motor torque T_L^*

$$W_{SCT}(s)=K_{SCT}=\frac{J}{\tau_\omega}, \tag{13}$$

and converts it into reference signals into the orthogonal components of the stator currents i_{sd}^* and i_{sq}^* in accordance with (4), taking into account the fact that the sign of the *q*-component must coincide with the sign of the torque, and the *d*-component is always positive; ICω is the ramp-function generator.

Transients in this system are shown in Fig. 2.

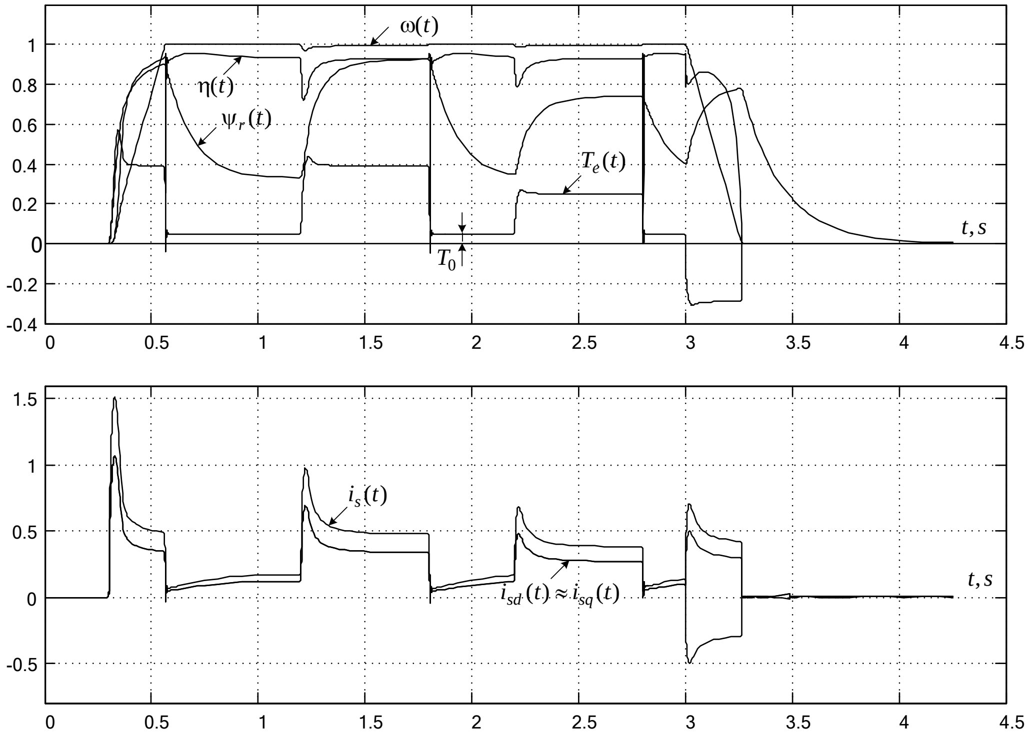

Figure 2 – Transients in typical induction motor vector control system

From Fig. 2 we can see that orthogonal components of stator currents in such a system coincide not only in steady-state regimes, but also in transients, providing the maximum possible ratio of the torque to the stator current. However, the quality of the transients deteriorates significantly in comparison with the typical vector control system: the speed decreases, the torque over-shoot increases, especially at the beginning of acceleration, the oscillation of transient process increases with the decay of the torque.

This disadvantage can be eliminated by forming non stator current components from the reference signal at the motor torque, and the reference signal for the rotor flux linkage ψ_{rMTA} from the calculated torque according to formula (3). In this case, the system is supplemented with the PI regulator of the rotor flux linkage FC(Field Controller) and reference-input unit of linkage ICψ, on which the signal, when the motor is stationary or at the speed which does not exceed certain small threshold value is formed according to formula (3). The speed controller in this circuit generates a reference signal not for the torque (moment), but for the q-component of the stator current according to the formula

$$W_{SCi}(s) = K_{SCi} = \frac{J}{k_T \tau_\omega \psi_r(t)}, \tag{14}$$

This approach allows, firstly, to separate the processes of initial magnetization and acceleration of the motor in time; secondly, to limit the reference to the rotor flux linkage easily, avoiding saturation of the machine; thirdly, to vary the law of linkage variation; and, fourthly, to adapt the speed controller gain factor to the flux linkage change.

A variant of such a system is shown in Fig. 3, and transient processes in it are shown in Fig. 4

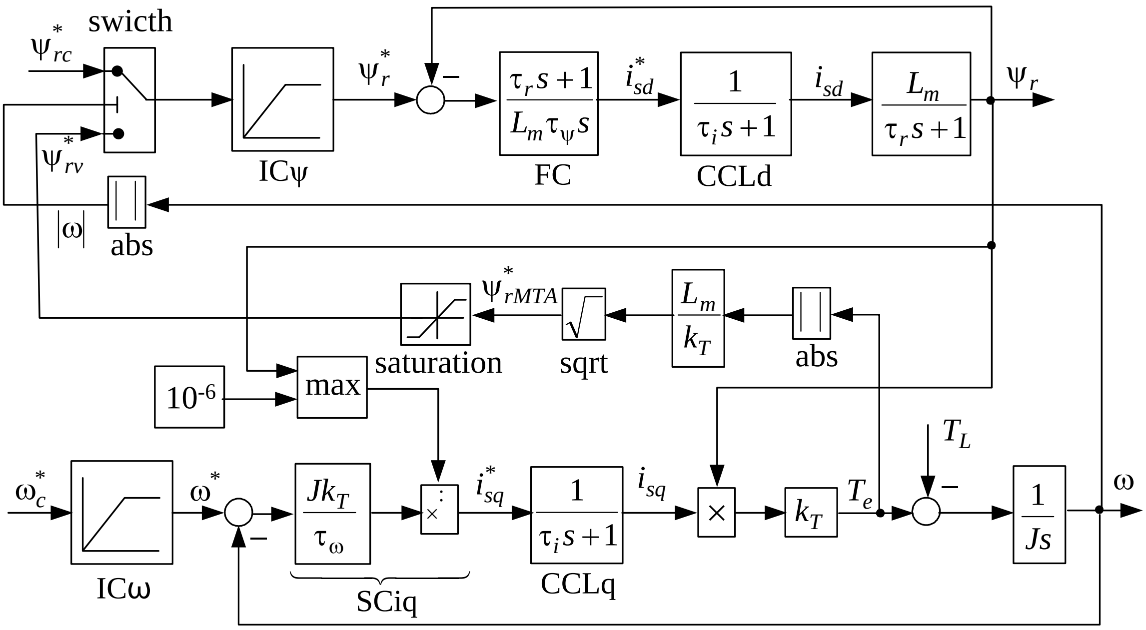

Figure 3 – Block diagram of induction motor vector control system implementing MTA strategy by means of reference forming for rotor flux linkage in moment-generating function

The maximum value of rotor flux linkage is limited by the saturation unit at the level ψ_{rn} in order to avoid entering the iron saturation regime. Linkage change is carried out according to linear law by the block ICψ.

The change rate of this signal is chosen in such a way that the magnetizing and demagnetizing losses of the motor are minimal [11]:

$$\frac{d\psi_r}{dt} = \frac{\psi_{r0}}{\sqrt{3}\lambda\tau_r}. \tag{15}$$

In the proposed system, the equality of the stator current components is ensured only in the sections where both the torque and the linkage remain unchanged. Despite this, the efficiency is maintained approximately at the level of the nominal value and has, as shown in the scheme of Fig. 1, dips only in the sections of a sudden increase in torque.

The total copper loss in the compared systems with the selected operation mode is approximately the same, however, the quality of the transients in the system in Fig. 2 is much better.

For comparison, Fig. 5 shows the graphs of the transients in a typical vector control system without changing the rotor flux linkage in the function of the torque.

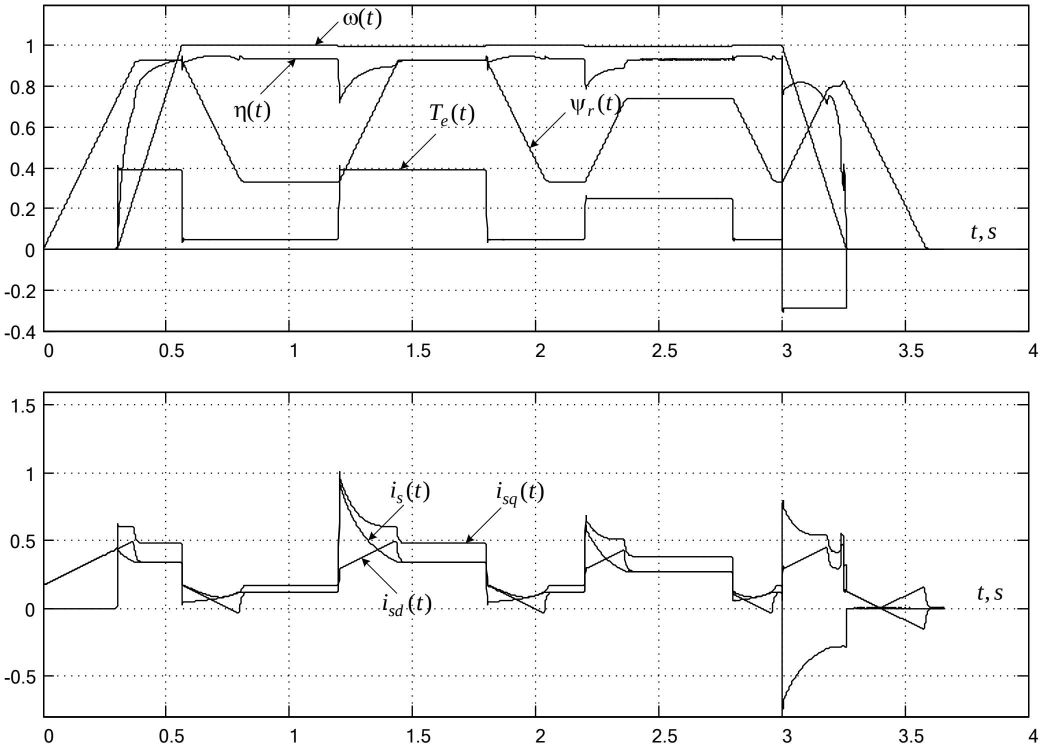

Figure 4 – Transient processes in MTA system

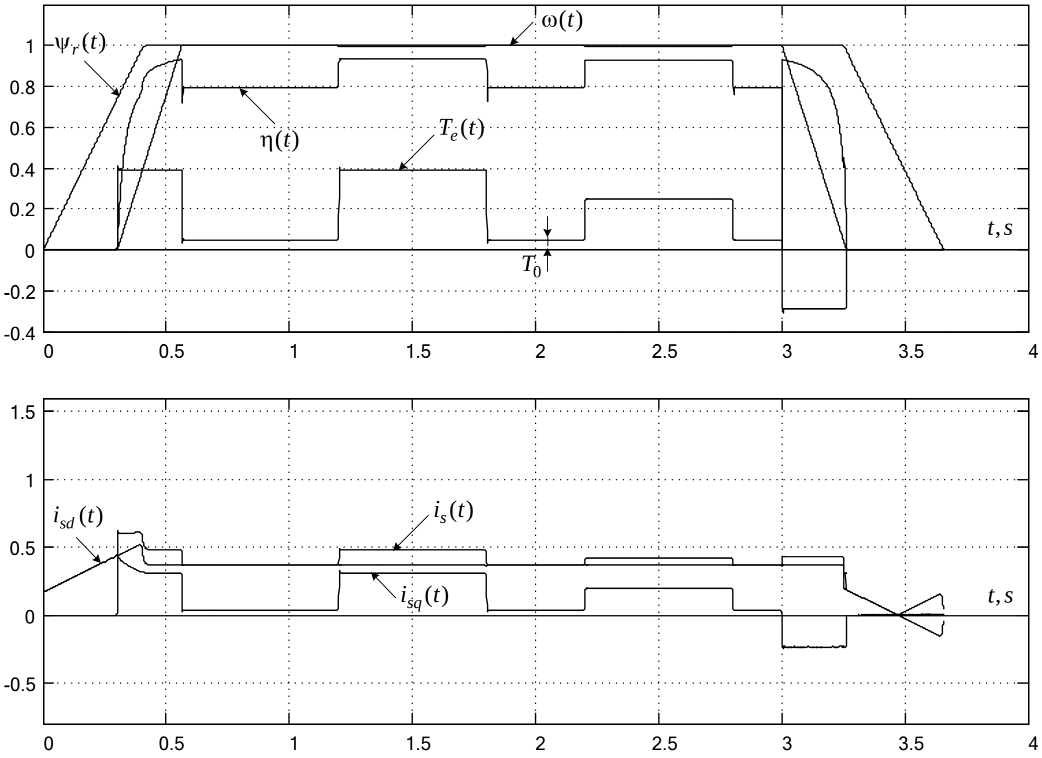

Figure 5 – Transients transients in a typical vector control system without changing the rotor flux linkage in the function of the torque

The graphs confirm the efficiency decrease while working with the torques $T < T_{\lim}$, although the total loss in the stator and rotor windings of the motor under consideration in this work cycle are even less than in the systems implementing MTA strategy. This is explained by the absence of magnetizing and demagnetizing losses of the motor when the torque changes.

Thus, the MTA strategy application can improve the energy efficiency of the drive only when working sections are sufficiently extended and have constant torque which does not exceed the level $T_{\lim}$.

Conclusions. A new method for the structural realization of the MTA strategy in a speed control system with vector control has been proposed for induction motor. This method differs from the typical system by the presence of an rotor flux linkage coupling loop and a reference-input unit which forms the linear law of linkage variation with the rate ensuring minimum magnetizing and demagnetizing losses. The reference-input unit can be controlled either by an independent source or by the as a function of the motor torque according to the formula (3). The reference magnitude for the flux linkage does not exceed the nominal value, which allows to avoid transition of the motor to saturation mode, but limits the magnitude of the torque at which the MTA criterion is met, at the level $T_{\lim}$ (we can see formula (11)). The speed control gain factor has been adapted to the flux linkage change by adding-on the flux-division unit to the PC.

Suggested system, along with maintaining the nominal efficiency when the torque is changed, provides high quality of transient processes.

The task of further research can be to search for the optimal control law for rotor flux linkage to minimize the total heat losses in the motor windings, taking into account the losses of the rotor flux linkage change.

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Надійшла до редколегії *Рецензент: С.М. Пересада*

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Структурна реалізація стратегії максимум моменту на ампер для систем векторного керування асинхронним двигуном. У роботі запропоновано новий спосіб структурної реалізації стратегії максимізації моменту на ампер в системі регулювання швидкості асинхронного двигуна з векторним керуванням, що відрізняється від типового наявністю контуру потокозчеплення ротора та задавального пристрою. У представленій системі зміна завдання на потокозчеплення виконується у функції моменту, а відпрацювання цього завдання здійснюється за лінійним законом з темпом, що забезпечує мінімізацію втрат у міді на намагнічування та розмагнічування двигуна. Такий підхід дозволяє в усталеному режимі підтримувати ККД на рівні номінального значення. Завдяки тому, що у синтезованій системі регулятор швидкості виробляє сигнал завдання не на момент двигуна, а на моментоутворюючу складову струму статора, в ній легко виконується лінеаризація контуру швидкості шляхом установки на виході регулятора швидкості блоку ділення на потокозчеплення, що забезпечує при його зміні підтримку високої якості перехідних процесів.

Електропривод, асинхронний двигун, векторне керування, максимум моменту на ампер, нова структурна реалізація, якість перехідних процесів, теплові втрати, ефективність.