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INDIRECT FIELD-ORIENTED TORQUE CONTROL OF INDUCTION MOTORS WITH MAXIMUM TORQUE PER AMPERE RATIO

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The paper reports new theoretical and experimental results in vector control of induction motors. A novel indirect field-oriented torque tracking controller is designed for current fed induction machine, which guarantees maximal torque per Ampere ratio during steady state. The proposed controller assures quite fast dynamics in the torque response. Results of simulation and experimental tests illustrate important features of the control proposed.

Keywords: induction motor, field-oriented control, maximum torque per Ampere ratio.

НЕПРЯМЕ ПОЛЕОРІЄНТОВАНЕ КЕРУВАННЯ МОМЕНТОМ АСИНХРОННИХ ДВИГУНІВ З МАКСИМІЗАЦІЄЮ СПІВВІДНОШЕННЯ МОМЕНТ-СТРУМ

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В даній статті представлено нові теоретичні та експериментальні результати в галузі векторного керування асинхронними двигунами. Розроблено новий алгоритм непрямого струмового векторного керування моментом асинхронного двигуна, який гарантує максимальне співвідношення момент-струм в усталених режимах роботи. Запропонований алгоритм забезпечує достатньо високі динамічні показники регулювання моменту, що підтверджено результатами математичного моделювання та експериментальних досліджень.

Ключові слова: асинхронний двигун, поле-орієнтоване керування, максимум співвідношення момент-струм.

НЕПРЯМОЕ ПОЛЕОРИЕНТОВАННОЕ УПРАВЛЕНИЕ МОМЕНТОМ АСИНХРОННЫХ ДВИГАТЕЛЕЙ С МАКСИМИЗАЦИЕЙ СООТНОШЕНИЯ МОМЕНТ-ТОК

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В этой статье представлены новые теоретические и экспериментальные результаты в области векторного управления асинхронными двигателями. Разработан новый алгоритм непрямого токового векторного управления моментом асинхронного двигателя, который гарантирует максимум соотношения момент-ток в установившихся режимах работы. Предложенный алгоритм обеспечивает достаточно высокие показатели качества регулирования момента, что подтверждено результатами математического моделирования и экспериментальными исследованиями.

Ключевые слова: асинхронный двигатель, поле-ориентированное управление, максимум соотношения момент-ток.

1. Introduction. Modern electrical drives based on induction motors (IM) are the most spread electromechanical systems. From the control point of view, they represent a complex multivariable non-linear problem and they constitute an important area of application for non-linear control theory. On the other hand to solve the IM control problem achieving at the same time fast dynamics, high energy efficiency, robustness with respect of IM parameters variation and simple implementation is an important practical task. Over the recent years a several non-linear control strategies has been proposed to solve torque (speed) and flux tracking (regulation) problem [1]. Among them based on feedback linearization [2], output feedback [3], concept of system decomposition into electromechanical-electromagnetic subsystems [4]-[6], passivity based control [7], adaptive output feedback [8], [9].

All solutions [2]-[9] provide torque-flux decoupling in order to apply energy saving or other flux regulation strategies [10], [11], [12], [13], with no degradation of the mechanical variables control performance. Controllers [12], [13] are based on standard structure of field-oriented control and allow to form flux reference level in such manner, that maximum torque per Ampere ratio is achieved during torque regulation. Important to note that this condition is closed to minimum active losses one.

Different strategy is proposed in [14], where non-holonomic structure of IM is exploited to solve the same control problem. Observer based controller [14] is implemented in rotor oriented reference frame, it uses oscillatory properties of rotor circuit. The authors show that under suitable switching logic singularity free asymptotic torque regulation is achieved under condition of maximal torque per Ampere ratio. Controller provides relatively fast response and satisfactory robustness properties. Nevertheless control algorithm is quite complex and represents torque peaking during transients.

The aim of this paper is to solve torque tracking control problem preserving maximum torque per Ampere property during steady state.

2. Problem Statement

2.1 IM model. The equivalent two-phase model of symmetrical current-fed IM, under standard assumptions, is represented in an arbitrary rotating reference frame (d-q) as [10]

$$\begin{aligned}
&\dot{\omega} = J^{-1}(T - T_L), T = \frac{3}{2}\frac{L_m}{L_2}\left(\psi_d i_q - \psi_q i_d\right),\\
&\dot{\psi}_d = -\alpha\psi_d + (\omega_0 - \omega)\psi_q + \alpha L_m i_d,\\
&\dot{\psi}_q = -\alpha\psi_d - (\omega_0 - \omega)\psi_q + \alpha L_m i_q,\\
&\dot{\varepsilon} = \omega_0,
\end{aligned} \qquad (1)$$

where ω is the rotor speed; $\left(i_d, i_q\right)^T, \left(\psi_d, \psi_q\right)^T$ - denotes components of the stator current and rotor flux vectors, T_L is the load torque, ε_0 - is the angular position of the $(d-q)$ reference frame with respect to fixed stator reference frame. Positive constants in (1) are defined as follows: J is the rotor inertia; $\alpha = {R_2}/{L_2}$, R_2, L_2 - rotor resistance and inductance; L_m is the magnetizing inductance. One pole pair is assumed without loss of generality.

General specification for torque controlled electrical drives indicates that two IM outputs, torque and rotor flux modules defined as

$$\begin{pmatrix} T \\ |\psi| \end{pmatrix} = \begin{bmatrix} \frac{3}{2}\frac{L_m}{L_2}\left(\psi_d i_q - \psi_q i_d\right) \\ \left(\psi_d^2 + \psi_q^2\right)^{\frac{1}{2}} \end{bmatrix} \qquad (2)$$

must be controlled using two-dimensional current vector $\boldsymbol{i} = \left(i_{1d}, i_{1q}\right)^T$ on the base of measured speed only.

2.2 Control Objectives. The specific problem of IM torque control under condition of maximum torque per Ampere ratio leads to non-holonomic restriction on controlled variables for the system (1). Let T^* is the torque reference, bounded function with known bounded derivative; assume, that motor parameters are known and constant. Under these assumptions, it is required to design an output feedback controller satisfying the following control objectives:

CO 1. Torque-flux tracking, i.e.

$$\lim_{t\to\infty}\tilde{T} = 0, \qquad \lim_{t\to\infty}\tilde{\psi} = 0, \qquad (3)$$

where torque and flux tracking errors are defined as $\tilde{T} = T - T^*, \tilde{\psi} = |\psi| - \psi^*$, with $\psi^* > 0$ - flux modulus reference defined later;

CO 2. Sleep frequency $\omega_2 = \omega_0 - \omega$ relation for torque per Ampere maximization

$$|\omega_2| = \alpha \pm \varepsilon(t), \text{ if } T^* \neq 0. \qquad (4)$$

where $|\varepsilon(t)| \ll \alpha$.

3. Controller design

Standard indirect field-oriented flux controller [10] is given by

$$\dot{\varepsilon}_0 = \omega_0 = \omega + \alpha L_m \frac{i_q}{\psi^*} \qquad (5)$$

$$i_d = \frac{1}{\alpha L_m}\left(\alpha\psi^* + \dot{\psi}^*\right), \qquad (6)$$

which guarantees that flux modulus tracking $\lim_{t\to\infty}\left(\psi_d - \psi^*\right) = 0$ and asymptotic field orientation $\lim_{t\to\infty}\psi_q = 0$ are globally achieved.

In order to satisfy the control objectives (4) we define in (5),(6) the following flux reference

$$\psi^* = \psi_0^* + L_m\left|i_q\right|, \qquad (7)$$

where $\psi_0^* > 0$ is the minimal flux level in order to avoid singularity in (5)

From torque error equation

$$\tilde{T} = \mu_1\left[\left(\psi_0^* + L_m\left|i_q\right|\right)i_q + \tilde{\psi}_d i_q - \tilde{\psi}_q i_d\right] - T^*, \mu_1 = \frac{3}{2}\frac{L_m}{L_2} \qquad (8)$$

solutions for torque current are given by the algebraic equation

$$\mu_1 L_m\left|i_q\right| i_q + \mu_1\psi_0^* i_q - T^* = 0 \qquad (9)$$

in the following form

$$\begin{aligned}
i_q &= (2\mu_1 L_m)^{-1}\left[-\mu_1\psi_0^* + \left(\left(\mu_1\psi_0^*\right)^2 + 4\mu_1 L_m T^*\right)^{\frac{1}{2}}\right], \text{if } T^* \geq 0\\
i_q &= (2\mu_1 L_m)^{-1}\left[\mu_1\psi_0^* - \left(\left(\mu_1\psi_0^*\right)^2 - 4\mu_1 L_m T^*\right)^{\frac{1}{2}}\right], \text{if } T^* < 0
\end{aligned} \qquad (10)$$

The error dynamics, generated by the controller (5),(6),(7),(10) is

$$\begin{aligned}
&\tilde{T} = \mu_1\left(\tilde{\psi}_d i_q - \tilde{\psi}_q i_d\right)\\
&\dot{\tilde{\psi}}_d = -\alpha\tilde{\psi}_d + \omega_2\tilde{\psi}_q\\
&\dot{\tilde{\psi}}_q = -\alpha\tilde{\psi}_q - \omega_2\tilde{\psi}_d
\end{aligned} \qquad (11)$$

Since equilibrium point $(\tilde{\psi}_d, \tilde{\psi}_q) = 0$ system (11) is globally exponentially stable it results that $\tilde{T}(t)$ goes exponentially to zero, satisfying condition (4) with ε dependent from ψ_0^*.

The block diagram of the proposed controller is shown in Fig.1. In real implementation stator currents i_d and i_q, given by (6), (10) are used as reference currents for internal current loops.

4. Performance evaluation

Simulation and experimental tests have been performed using $0.75kW$ induction motor, whose rated data are reported in Table.

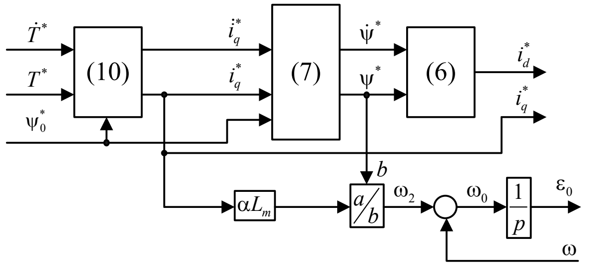

Fig.1. – Structure of the controller

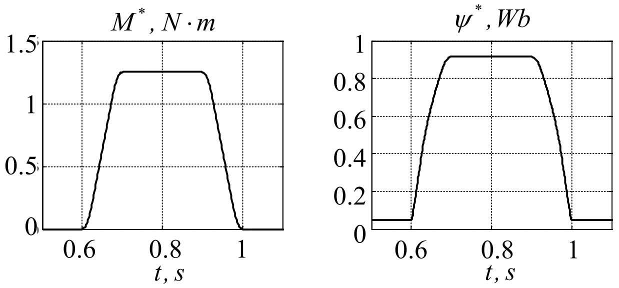

Fig.2. – Torque and flux reference trajectories.

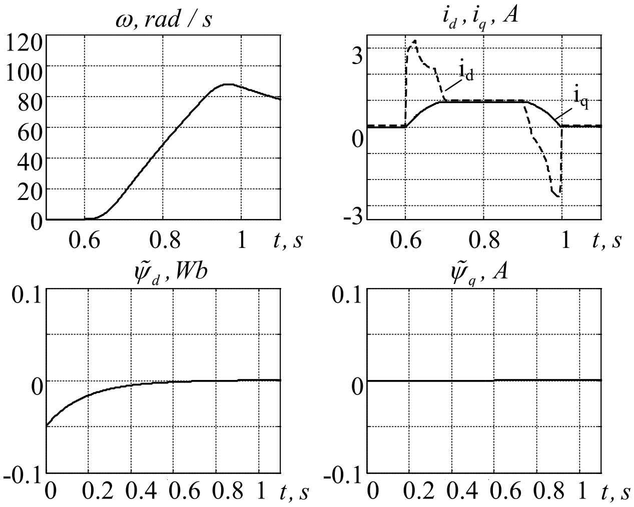

Fig.3. – Transients during torque tracking (simulation)

The first set of simulation and experimental results is reported in Fig.2-4 to demonstrate the tracking performance of the proposed controller. The following operating sequence is used:

1. During initial time interval $(0 \le t < 0.6s)$ the minimal flux level reference $(0.05Wb)$ is applied.
2. The unloaded motor is required to track torque trajectory, shown on Fig.2, starting at $t = 0.6s$ from zero initial value and reaching the steady value of $1.25Nm$ (50% from rated torque) with the first and second derivatives equal to $16.7\,{}^{Nm}\!/_{s}$ and $667\,{}^{Nm}\!/_{s^2}$ correspondingly.
3. After time interval of movement with constant torque, reference for torque is reduced to zero.

The experimental tests were carried out using rapid prototyping station [15], based on custom floating-point 32-bit digital signal processor board. Internal current loops with high gain PI current controllers have been implemented in synchronous reference frame. Sampling time during all tests has been set to $200\mu s$.

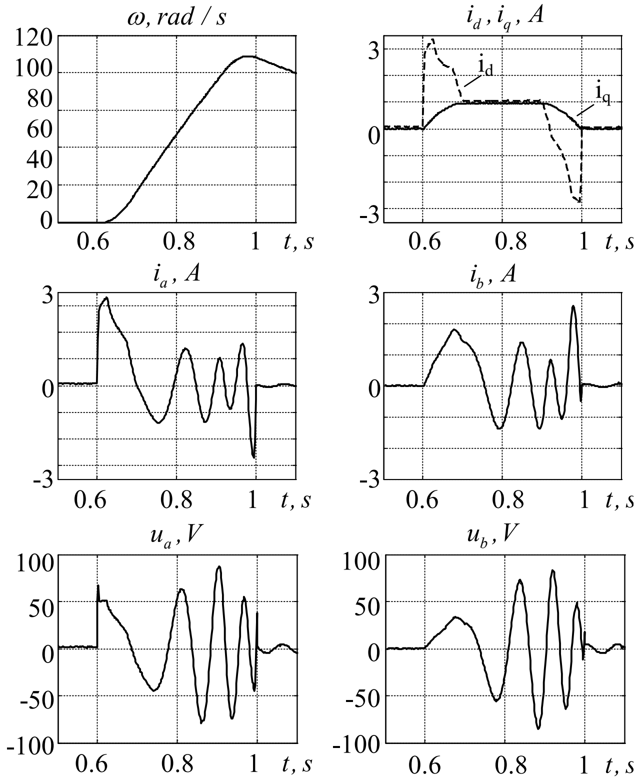

Fig.4. – Experimental speed and current transients during torque tracking

The transient obtained from the experimental test (Fig.4) corresponds with good accuracy to those of recorded from the simulations.

As it follows from the transients, Fig.3 and Fig.4 condition (4), which is equivalent to $i_d \cong i_q$ is satisfied during steady state and therefore maximal torque per Ampere ratio is achieved, when $\dot{T}^* = 0$. During transients dynamic behaviour of the flux current i_d directly depends from the torque reference profile, namely $\dot{T}^*$.

Fig.5 shows transients obtained with twice smaller $\dot{T}^*$. From the comparison of flux current trajectories, shown on Fig.4 and Fig.5, it follows that optimization problem should be solved, when torque tracking is considered, in order to find the achievable compromise between torque dynamics and stator current profile during transients.

5. Conclusions

In this paper a novel torque tracking under condition of maximal torque per Ampere ratio indirect field-oriented controller is designed. It guarantees global exponential torque tracking of the bounded torque reference trajectories, having bounded first derivatives. Steady state torque per Ampere ratio maximization is achieved when torque reference derivative is zero. Intensive comparison study of the proposed solution and already existing [12]-[14] is needed in order to define the specific fields of application for each of them.

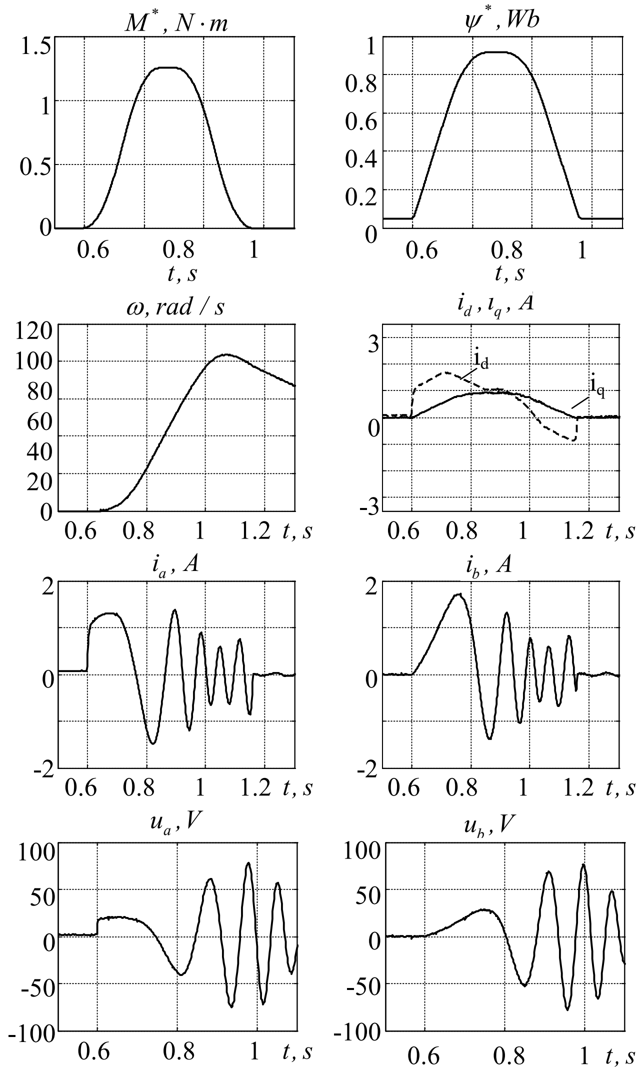

Fig.5. – Experimental speed and current transients during torque tracking

Table. IM rated data

Stator current (rms), *A*	1,7
Number of pole pairs	1
Stator resistance, *Ω*	11
Rotor resistance, *Ω*	5,3
Stator inductance, *H*	0,95
Rotor inductance, *H*	0,95
Magnetizing inductance, *H*	0,91
Total moment of inertia, $kg \cdot m^2$	0,0036

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