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Direct torque control of an induction motor using the fuzzy controller

Abstract. *The paper presents a drive model with an induction motor fed by DTC converter. The application of the rotational speed fuzzy controller in the control system drive was proposed. The general rule base and the tuning procedure for the Mamdani fuzzy controller was presented. The simulation tests of the drive model were carried out during start-up, braking and reverse. The results of simulation tests are presented as time characteristics of the stator current, the rotor speed, the electromagnetic torque and the reference torque.*

Streszczenie. *W artykule przedstawiono model napędu z silnikiem indukcyjnym zasilanym przez przekształtnik DTC. W układzie sterowania napędu zaproponowano zastosowanie regulatora rozmytego prędkości obrotowej. Przedstawiono ogólną formułę bazy reguł oraz procedurę strojenia dla regulatora rozmytego typu Mamdaniego. Przeprowadzono badania symulacyjne modelu napędu podczas rozruchu, hamowania oraz rewersu. Rezultaty badań zaprezentowano w postaci przebiegów czasowych prądu stojana, prędkości wirnika, momentu elektromagnetycznego oraz momentu odniesienia.* ***(Zastosowanie regulatora rozmytego w układzie bezpośredniego sterowania momentem silnika indukcyjnego).***

Keywords: induction motor, direct torque control method, fuzzy logic controller.
Słowa kluczowe: silnik indukcyjny, metoda bezpośredniego sterowania momentem, regulator rozmyty.

Introduction

The direct torque control method (DTC) for AC drives has been proposed by Takahashi and Noguchi in 1986. The basic idea of this method is to use a non-linear estimators of the torque and flux, making it possible to eliminate the controllers of the stator currents. Semiconductor elements of the inverter are controlled in such a way as to ensure the simultaneous regulation the amplitude values of the stator flux and electromagnetic torque of the induction motor. Currently, the direct torque control method is popular because it provides excellent dynamic properties of drive systems. The use of fuzzy controllers allows the search for new possibilities to modify the method of adjustment torque and flux [1, 2, 5, 6].

The fuzzy control algorithms are increasingly used in the control of the drives, because they allow to take into account the phenomenon of nonlinearity and the characteristics of the measuring transducers [9, 10]. These algorithms also provide the improvement of quality indicators for the drive control system. This constitutes a certain advantage compared to the conventional solutions [7, 8, 12].

Direct torque control method

The components of the current and voltage of an induction motor stator described in a coordinate system (d-q) can be determined using the following relationships [3, 6]:

$$i_d = \sqrt{\frac{2}{3}}\, i_a \tag{1}$$

$$i_q = \frac{1}{\sqrt{2}}\left(i_b - i_c\right) \tag{2}$$

$$u_d = \sqrt{\frac{2}{3}}\, U_{DC}\left(S_1 - \frac{1}{2}\left(S_2 + S_3\right)\right) \tag{3}$$

$$u_q = \frac{1}{\sqrt{2}} U_{DC}\left(S_2 - S_3\right) \tag{4}$$

where: : i_d, i_q – components of the stator current, i_a, i_b, i_c – stator phase currents, u_d, u_q – components of the stator voltage, U_{DC} – the voltage in a DC intermediate circuit, S_1, S_2, S_3 – inverter control signals in the individual phases.

The components of the stator flux in a coordinate system (d-q) are defined by equations:

$$\underline{\psi}_d = \int_0^{\Delta t} (\underline{u}_d - R_s \underline{i}_d)dt \tag{5}$$

$$\underline{\psi}_q = \int_0^{\Delta t} (\underline{u}_q - R_s \underline{i}_q)dt \tag{6}$$

where: $\underline{\Psi}_d$, $\underline{\Psi}_q$, – vectors of flux components, R_s – resistance of the stator phase, t - time period for which the flux components are calculated.

The stator flux ψ_s and the electromagnetic torque T_e can be estimated using the following relationship:

$$\psi_s = \sqrt{\psi_d^2 + \psi_q^2} \tag{7}$$

$$T_e = p\left(\psi_d i_q - \psi_q i_d\right) \tag{8}$$

The fuzzy controller of the drive control system

The Mamdani fuzzy controller, used in the control system of the AC drive is characterized by the general base of the rules [4, 11:]:

$$\begin{aligned}
&R^{(1)} : IF\,(x_1\ is\ LX_1^{(1)})\,AND\ \ (x_2\ is\ LX_2^{(1)})\ ...\\
&\qquad AND\ (x_n\ is\ LX_n^{(1)})\ THEN\ \ (u\ is\ LU^{(1)})\\
&R^{(2)} : IF\,(x_1\ is\ LX_1^{(2)})\,AND\ \ (x_2\ is\ LX_2^{(2)})\ ...\\
&\qquad AND\ (x_n\ is\ LX_n^{(2)})\ THEN\ \ (u\ is\ LU^{(2)})\\
&\qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&R^{(k)} : IF\,(x_1\ is\ LX_1^{(k)})\,AND\ (x_2\ is\ LX_2^{(k)})...\\
&\qquad AND\ (x_n\ is\ LX_n^{(k)})\ THEN\,(u\ is\ LU^{(k)})
\end{aligned} \tag{9}$$

where: x_1, x_2,...,x_n – input linguistic variables, $LX_1^{(1)}$, $LX_2^{(1)}$,..., $LX_n^{(1)}$; $LX_1^{(2)}$, $LX_2^{(2)}$,..., $LX_n^{(2)}$; $LX_1^{(k)}$, $LX_2^{(k)}$,..., $LX_n^{(k)}$ – linguistic values of input variables, u - output linguistic variable, $LU^{(1)}$, $LU^{(2)}$,..., $LU^{(k)}$ - linguistic values of output variable, k - number of rules.

The fuzzy controller has been designed using Fuzzy Logic Toolbox of the Matlab/Simulink package. The linguistic input data and the linguistic output data include the triangular membership functions. The rule base of the fuzzy controller was initially defined by means of the standard Mac Vicar-Whelan table, which was subsequently modified taking into account the input and output parameters of the membership functions.

The scalar value of the controller output signal for the discrete case is obtained from the following formula [11]:

$$u_N = \frac{\sum_{i=1}^{m} u_i \cdot \mu_U(u_i)}{\sum_{i=1}^{m} \mu_U(u_i)} = \frac{\sum_{i=1}^{m} u_i \cdot \max_k \mu_{CLU(k)}(u_i)}{\sum_{i=1}^{m} \max_k \mu_{CLU(k)}(u_i)} \tag{10}$$

where: u_N –the normalized output linguistic variable, μ_U - the membership function of output fuzzy set, $\mu_{CLU(k)}$ - the compressed membership function for each k-th rule

The simulation model of the drive with the fuzzy controller was presented in Fig. 1.

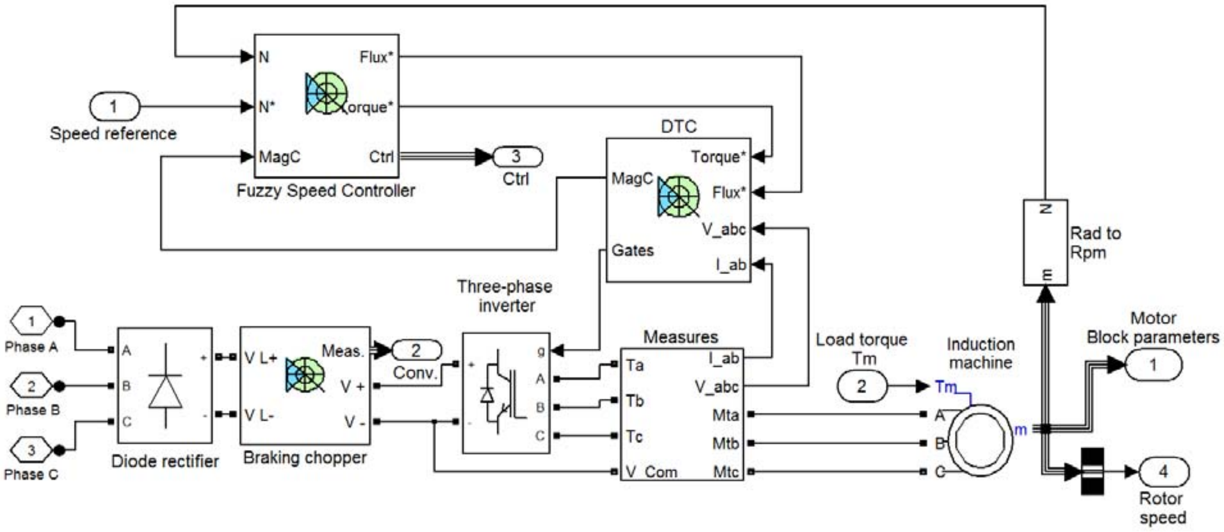

Fig. 1. The simulation model of the drive with the induction motor

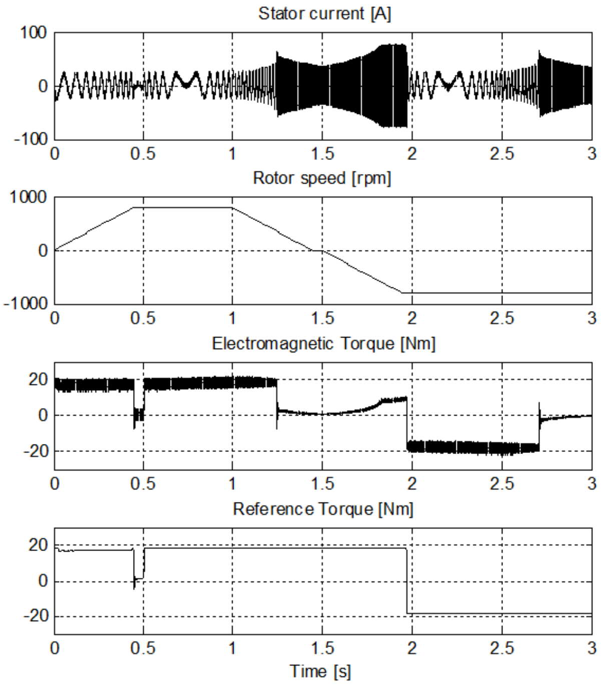

Fig. 2. Time characteristics of the stator current, the rotor speed, the electromagnetic torque and the reference torque during starting, braking and reverse of the drive

The results of simulation experiments

The simulation experiments of the drive with an induction motor fed by DTC inverter were performed at the start-up, the braking and the reverse.

The basic parameters of the induction motor: P_N=2,2kW, U_S=230V, f=50Hz, p=2, R_S=0,44 Ohm, R_R=0,82 Ohm, L_S=0,002H, , L_R=0,002H, M=0,07H, J=0,88 kg·m^2.

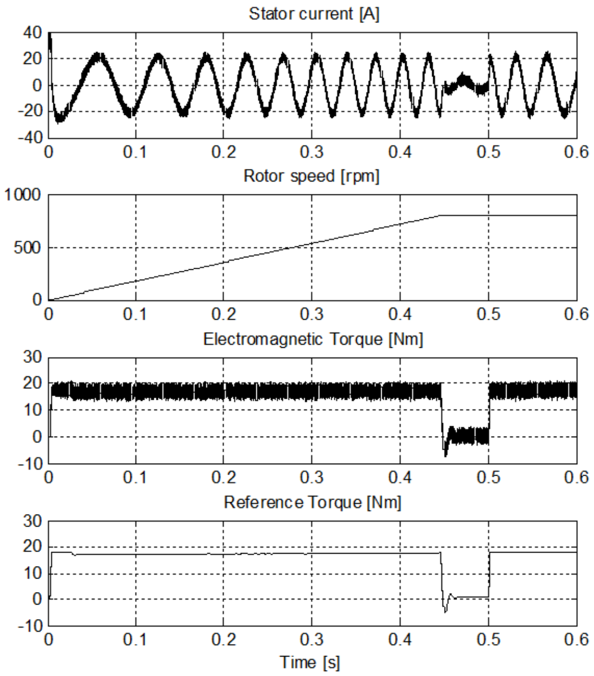

Fig. 3. Time characteristics of the stator current, the rotor speed, the electromagnetic torque and the reference torque during starting of the drive

The selected results in the form of time characteristics of the stator current, the rotor speed, the electromagnetic torque and the reference torque are presented in Fig. 2-4.

With respect to drive systems, an indicator is often applied which is calculated as an integral of the product of time and the absolute value of the control deviation. The indicator can be represented as [3]:

$$I_{ITAE}=\int_0^\infty t\cdot|e(t)|\,dt=\int_0^{t_k} t\cdot|e(t)|\,dt \tag{11}$$

where: $e(t)$ - the control deviation, t_k - is the time of ending the control process, t - is the time.

The integral quality indicator of the torque can be expressed in the following relation:

$$\begin{aligned} I_{Torq}&=\int_0^\infty t\cdot\left|e_{Torq}(t)\right|dt=\int_0^{t_k} t\cdot\left|e_{Torq}(t)\right|dt=\\ &=\int_0^{t_k} t\cdot\left|T_{ref}-T(t)\right|dt \end{aligned} \tag{12}$$

where: $T(t)$ – the torque in time function, T_{ref} – the reference torque, $e_{Torq}(t)$ - torque error.

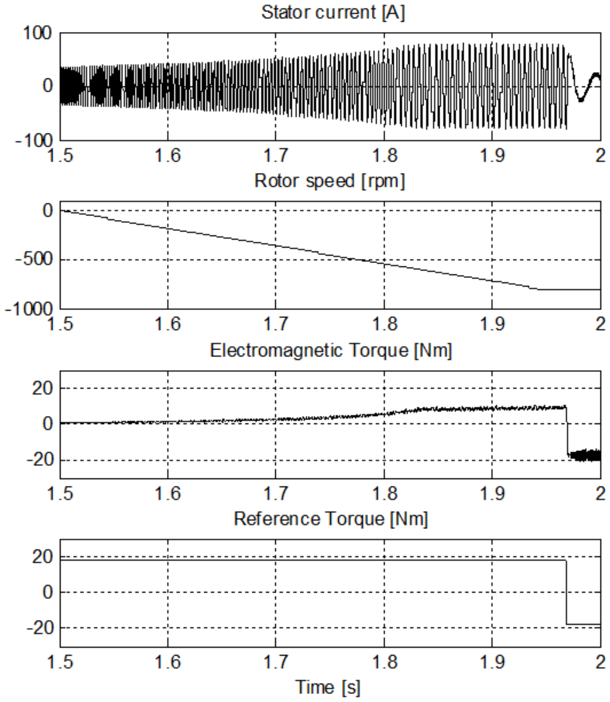

Fig. 4. Time characteristics of the stator current, the rotor speed, the electromagnetic torque and the reference torque during reverse of the drive

Table 1. Quality indicators for the DTC drive model with the fuzzy controller and the conventional controller

Parameters	Fuzzy control system	Conventional control system
Set speed ω *[rpm]*	Integral quality indicator I_{Torq}	Integral quality indicator I_{Torq}
200	0,043	0,044
400	0,061	0,063
600	0,097	0,101
800	0,136	0,141

Research results of drive models with the fuzzy controller and the conventional controller are compared. This comparison allowed to verify the proposed control strategy for direct drive torque control technique. Selected results of research in the form of integral quality indicators are presented in Table 1.

Conclusions

The time characteristics of the stator current, the rotor speed, the electromagnetic torque and calculated values of quality indicators prove the necessity of the use of fuzzy direct torque control system of the induction motor. The control space of the designed fuzzy logic controller consists of a number of segments which are not, in the general case, planes. The segments are multilinear spaces which can assume various locations and various degrees of convexity, which makes it possible to shape the time characteristics of the drive system.

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