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An algorithm for tuning a fuzzy controller in a drive control system of a permanent magnet synchronous motor

***Abstract**. The article presents a model of a permanent magnet synchronous motor and the PWM inverter. The use of the angular speed fuzzy controller in the control system drive was proposed. The general procedure for tuning the fuzzy controller with using the nonlinear programming method was formulated. The simulation tests of the drive model for various load torques have been carried out. The results of simulation tests are presented as time curves of the stator phase currents, the angular speed and the electromechanical moment.*

***Streszczenie.** W artykule przedstawiono model silnika synchronicznego z magnesami trwałymi oraz przekształtnika PWM. Zaproponowano zastosowanie regulatora rozmytego prędkości kątowej w układzie sterowania napędu. Sformułowano ogólną procedurę strojenia regulatora rozmytego z zastosowaniem metody programowania nieliniowego. Przeprowadzono badania symulacyjne modelu napędu dla zmiennych wartości momentu obciążenia. Rezultaty badań zaprezentowano w postaci przebiegów czasowych prądów fazowych stojana, prędkości kątowej oraz momentu elektromechanicznego. (**Algorytm strojenia regulatora rozmytego w układzie sterowania napędu z silnikiem synchronicznym z magnesami trwałymi**).*

Keywords: fuzzy controller, permanent magnet synchronous motor, nonlinear programming method.
Słowa kluczowe: regulator rozmyty, silnik synchroniczny z magnesami trwałymi, metoda programowania nieliniowego.

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Introduction

Permanent magnet synchronous motors (PMSM) are becoming increasingly widely applied in various industry branches and in transport. This is due to their simple mechanical structure, high reliability, a favourable rate of torque to the rotor's moment of inertia, high energy efficiency and capability of sustained operation with high loads and small rotational speed. A higher energy efficiency as compared to that of induction motors results mainly from a different construction of the rotor [1, 9].

Owing to the advantages of permanent magnet motors presented above, they are frequently applied in high-efficiency electric drives with analogue broad-range adjustment of angular speed. The most popular applications include drives of electric vehicles, lifts, conveyor belts, and drives of various devices used in aircraft and ships [4]. PMSMs are powered from semiconductor converters, whose control algorithms include the angle between the rotor and the stator. The angle has therefore to be measured with maximal accuracy by means of an encoder [9]. It is also necessary to take into account the electromagnetic interference [6, 7].

A mathematical model of the PMSM

A permanent magnet synchronous motor can be described in a rotating coordinate system (d,q) by means of the following set of differential equations [1, 2, 5] :

$$u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega\psi_q \tag{1}$$

$$u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega\psi_d \tag{2}$$

where: u_d, u_q – components of the stator voltage vector, i_d, i_q – components of the stator current vector, ψ_d, ψ_q – components of the motor flux, R_s – phase stator resistance, ω – angular speed of the rotor.

The components of the magnetic flux in the coordinate system (d,q) are defined as

$$\psi_d = L_d i_d + \lambda_m \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

where: λ_m – magnetic flux generated by the permanent magnets of the rotor, L_d, L_q – components of the inductance.

The electromagnetic torque of the motor is

$$T_e = \frac{3}{2}\left(\psi_d i_q - \psi_q i_d\right) \tag{5}$$

Taking all the above into consideration, the motion equation can be represented as

$$J\frac{d\omega}{dt} = T_e - T_L = \frac{3}{2}\left(\psi_d i_q - \psi_q i_d\right) - T_L \tag{6}$$

where: J – moment of inertia, T_e – electromagnetic torque, T_L – external load torque.

The drive control system

In the model developed, the PMSM stator circuits are powered by a three-phase voltage inverter with a modulated pulse width. The drive control system consists of conventional stator current controllers for the particular phases and a fuzzy angular speed controller. The drive simulation model is presented in Fig. 1.

A fuzzy controller of the type Sugeno applied in the angular speed control circuit has the following rule base [8]:

$$\begin{aligned}
&R^{(1)}: IF\ (x_1\ is\ LX_1^{(1)})\ AND \dots\\
&\qquad AND\ (x_n\ is\ LX_n^{(1)})\\
&\qquad THEN\ \ u_1 = f_1(x_1, x_2, \dots, x_n)\\
&\dots\dots\dots\dots\dots\dots\dots\dots\\
&R^{(k)}: IF\ (x_1\ is\ LX_1^{(k)})\ AND \dots\\
&\qquad AND\ (x_n\ is\ LX_n^{(k)})\\
&\qquad THEN\ \ u_k = f_k(x_1, x_2, \dots, x_n)
\end{aligned} \tag{7}$$

where: $x_1,\dots,x_n$ – input linguistic variables, $LX_1^{(1)},\dots, LX_n^{(k)}$ – linguistic values of input variables, $f_1(x_1,x_2,\dots,x_n),\dots, f_k(x_1,x_2,\dots,x_n)$ – functions of input linguistic variables; $u_1,\dots,u_k$ – linguistic variables of individual rules, k – number of rules.

A characteristic property of a Sugeno type controller is that the normalisation procedure is executed only with respect to the predecessors of rules. The successors are not normalised because they are overt function dependences, defined for the real domain [3, 10].

The fuzzy controller has been designed with the use of Fuzzy Logic Toolbox. The controller has two modules of input data $x_1=e$ and $x_2=ie$, and one module of output data u. The linguistic input data include triangular membership functions defining the error e and the error integral ie. The linguistic output data include standard linear functions.

The rule base of the fuzzy controller was defined by means of the standard Mac Vicar-Whelan table. The algorithm of the fuzzy controller tuning employs the sequential quadratic programming method.

This algorithm consists of the following steps:
- Selection of variables to be optimized,
- Division of the error input space,
- Division of the integral error input space,
- Determining the constraints referring to the time characteristics,
- Performing the calculations for the particular fragments of the input space by means of the nonlinear programming method,
- Preparing the matrix consisting of the amplification factors and of the doubling times obtained for the particular fragments of input spaces,
- Applying the results obtained in the form of the matrix for determining the parameters of the fuzzy controller.

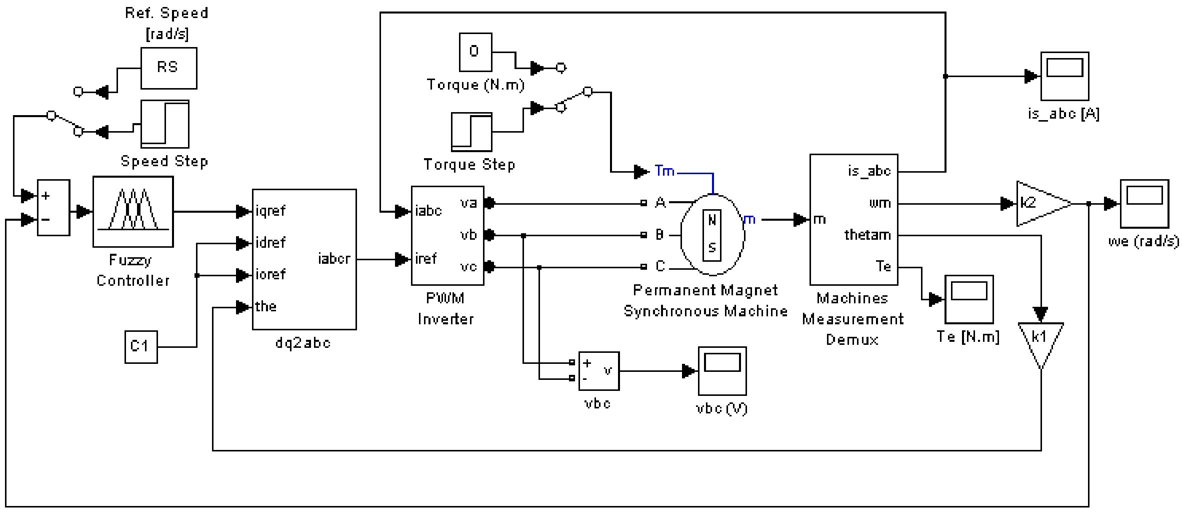

Fig.1. The simulation model of the drive with the permanent magnet synchronous motor

Results of the simulation experiments

The simulation experiments carried out for the drive with a permanent magnet synchronous motor included start-up for prescribed angular speeds and for various load torques. The basic parameters of PMSM: P_N=1,1kW, U_S=230V, n_N=3000rpm, T_N=3Nm.

With the results obtained as waveforms representing the variation of stator phase currents, angular speed, electromagnetic torque and quality indicators over time, it was possible to assess the drive control strategy adopted in the study.

The selected results in the form of time characteristics of the stator phase currents, angular speed, and electromechanical torque are presented in Fig. 2-7.

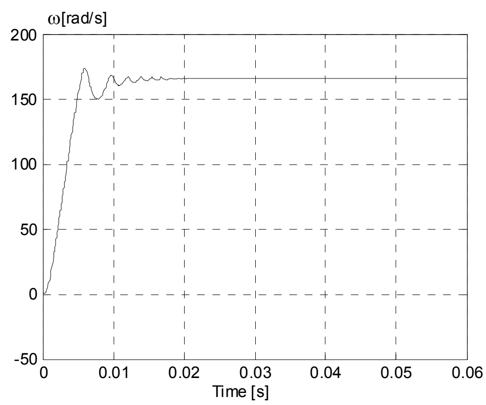

Fig.3. Time characteristics of the angular speed (T_O = 0 Nm)

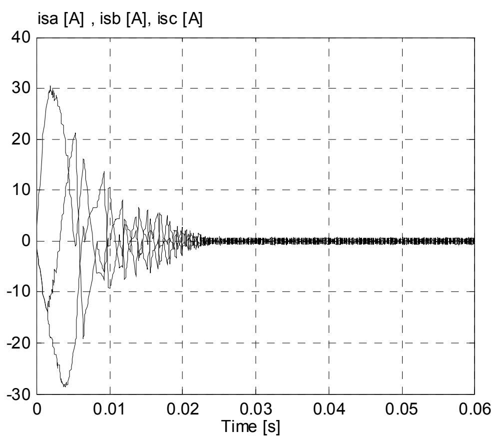

Fig.2. Time characteristics of the stator phase currents (T_O = 0 Nm)

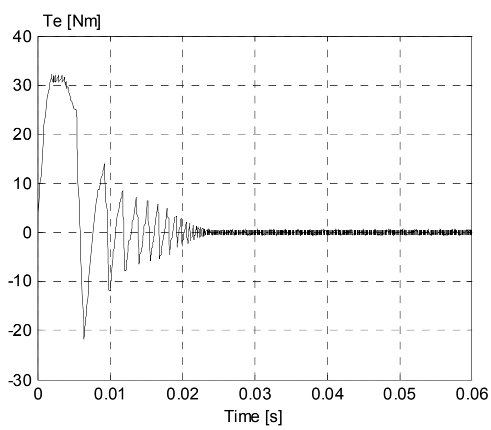

Fig.4. Time characteristics of the electromechanical torque (T_O = 0 Nm)

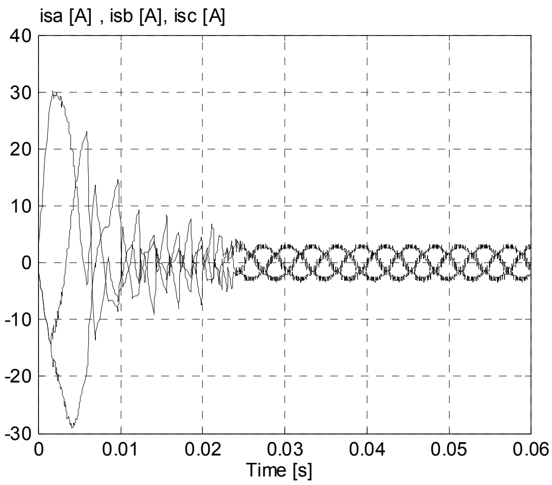

Fig.5. Time characteristics of the stator phase currents (T_O = 3 Nm)

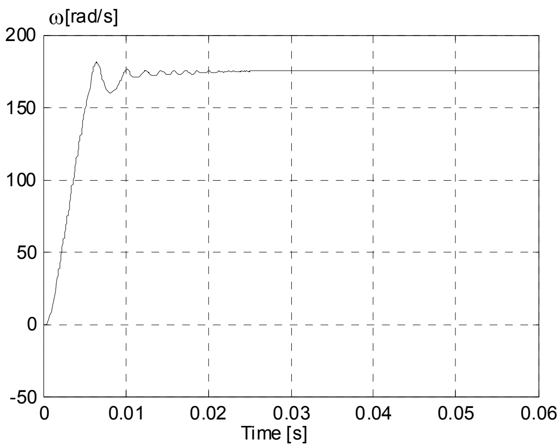

Fig.6. Time characteristics of the angular speed (T_O = 3 Nm)

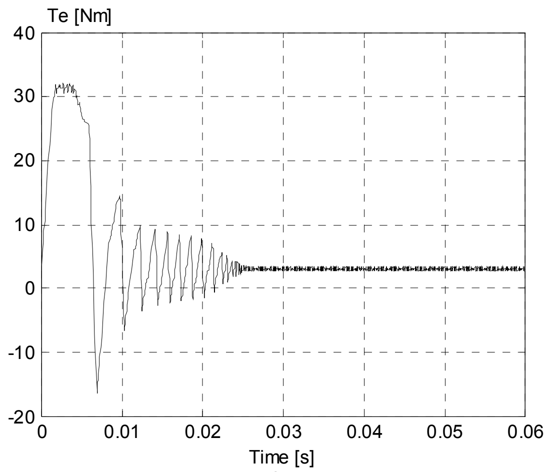

Fig.7. Time characteristics of the electromechanical torque (T_O = 3 Nm)

To verify the simulation experiments obtained, a system with a conventional controller has also been tested for identical prescribed parameters.

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

$$\mathrm{I}_{\Omega} = \int_0^{\infty} t \cdot \left| e_{\omega}(t) \right| dt = \int_0^{t_k} t \cdot \left| e_{\omega}(t) \right| dt = \int_0^{t_k} t \cdot \left| \omega_R - \omega(t) \right| dt \tag{8}$$

where: $\omega(t)$ - angular speed, ω_R - prescribed angular speed, $e_{\omega}(t)$ - angular speed error.

The comparison of the quality indicators can be seen in Table 1.

Table 1. Quality indicators for the AC drive model with the fuzzy control system and with the conventional control system

Parameters	Fuzzy control system		Conventional control system	
Load torque T_o *[Nm]*	Setting time t_r [s]	Integral quality indicator I_{Ω}	Setting time t_r [s]	Integral quality indicator I_{Ω}
0	0,018	2,31	0,018	2,33
1	0,019	2,38	0,019	2,41
2	0,021	2,45	0,022	2,48
3	0,023	2,52	0,024	2,56

Concluding remarks

The most important advantage of a Sugeno type fuzzy controller is that it offers a possibility of decomposing the complex control system, which can be analysed as a number of subsystems of lesser complexity. These subsystems can be linear in some cases, which significantly simplifies the process of constructing the rule base and tuning the controller. After decomposition, it is possible to identify the dynamics of the component subsystems. The decomposition itself is typically fuzzy, too, since the knowledge of a given system is necessarily limited.

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