Robust control of the PMSM drive with changeable inertia using TSK-type fuzzy controller

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In the work the application of the fuzzy TSK-type controller for the speed control of the nonlinear, nonstationary PMSM drive is considered. The parameters of the fuzzy controller are selected using genetic algorithm. The designed controller is robust against variation of inertia of the drive. The comparative study concerning proposed and classical control structure is considered. The theoretical consideration are verify by simulation tests. The obtained results show the superior performance of the proposed system.

KEYWORDS: electrical drive control, fuzzy speed control, TSK fuzzy controller, PMSM drive

1. Introduction

The modern high-performance drive systems are required to present very precise speed and position control. The designed control structure should shorten the transient time of the responses, minimize the responses overshoot and damp possible vibrations of the electromechanical states. The PMSM motors due to their small inertia, heavy duty torque, favorable power-to-weight ratio, compact size, precise control are popular in modern drive systems [2]-[6]. The PMSM motors are commonly applied in such application such as CNC machines, manipulators, industrial robots and electrical vehicles [7]-[8]. The important issues in the practical implementation of the PMSM drives is its robustness to the different disturbances such as: load torque, changes of its parameters or variation of the inertia of the load machine. In direct drive system (without mechanical gearbox) the changes of the inertia of the load machine affects the drive performances much more than in traditional drive. The evidence of the above-mentioned factors makes the control of the PMSM especially demanding task [7]. In order to ensure the correct transients of the drive the application of the advance control strategy e.g. adaptive, robust or fuzzy control is necessary [7], [13]-[14].

The general concept of the adaptive control relay on the tuning of the controller parameter(s) to the current operation point of the controlled plant. The adaptive methodology can be divided into two main frameworks: direct and indirect concepts. The indirect concept depends on the application of the additional block, in which the parameters of the plant are estimated in specific time interval. Next, on the basis on the calculated parameters the controller parameters are computed. The direct adaptive framework doesn't possess the estimation block. The controller parameters are adjusted directly using specify previously low on the basis on the actual plant input and/or output. The gain-scheduling methodology can be regarded as the simple direct adaptive scheme [15]. This algorithm changes the parameters of the controller according to the value of the selected variable(s) e.g. speed, current etc. The main advantages of the gain-scheduling method is its simplicity. As its drawbacks the rapid changes of the controller's parameters can be regarded because it can lead to the oscillation of the controlled states. This can affect the control structure performance, reduce the system reliability or even in some specific situation can break down entire drive system. The application of the fuzzy logic is an alternative methodology which can eliminate the drawback of the classical gain-scheduling concept. The possibilities of soft switches between specific working's regions ensure the proper work of the system with fuzzy controller.

The main of the work is an application of the robust TSK-type fuzzy controller to the control structure with PMSM drive. The paper is divided into fife section. After introduction the mathematical model of the drive system and the control structure is described. Then the applied fuzzy controller is descried in details. Next the simulation results concerning the properties of the control structure with classical and fuzzy controllers are presented. The short conclusions summarized the paper.

2. Mathematical model of the system and control structure

The considered two-mass drive system is driven by a PMSM machine whose mathematical model can be described in the reference frame using the following differential equations:

$$V_d = r_s i_d + L_d \frac{di_d}{dt} - \omega_e \tilde{L}_q i_q, \tag{1}$$

$$V_q = r_s i_q + \tilde{L}_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_m k_e, \tag{2}$$

$$m_e = \frac{3}{2} p\left[\left(L_d - \tilde{L}_q\right) i_d i_q + \tilde{k}_t i_q\right] \tag{3}$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(m_e - m_L\right), \tag{4}$$

where: r_s - denotes the stator resistance, L_d - inductances in d axis and $\tilde{L}_q$ - nonlinear stator inductances in q axis, V_d, V_q, i_d, i_q - are the voltages and currents in d and q axis respectively, ω_e - electrical pulsation, ω_m – angular speed of the rotor, p – is the number of pole, m_e, m_L – electromagnetic and load torques, J – inertia of the drive, $\tilde{k}_t$ - nonlinear relationship between torque and current in q axis.

The considered non-linear model of PMSM drive describes the relationship of the forced electromagnetic torque in full-range of machine work. The inductance in q axis and resulting electromagnetic torque depend in non-linear way from the i_q current. In Fig. 1 the characteristic between the current in q axis and constant of the electromagnetic torque k_t(a) as well as the inductance in q axis and current in q axis are presented.

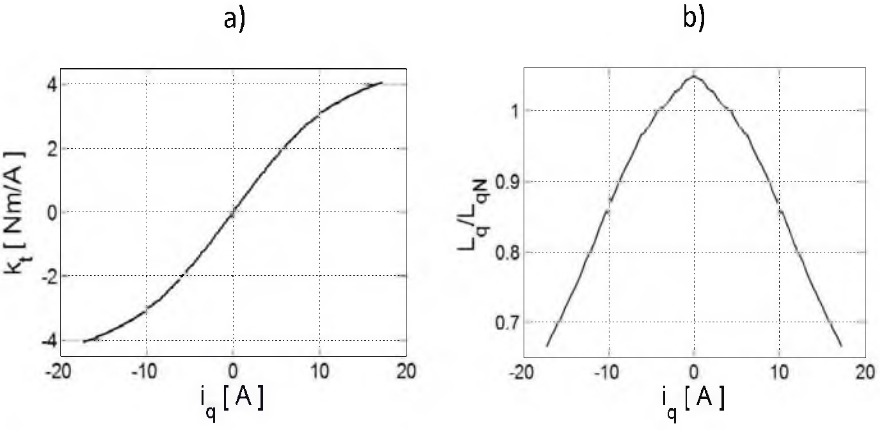

Fig. 1. Non-linear characteristic between the current in q axis and constant of the electromagnetic torque (a) as well as the inductance in q axis and current in q axis (b)

The proposed field-oriented vector control architecture for the dual-mass drive system is shown in Fig. 2.

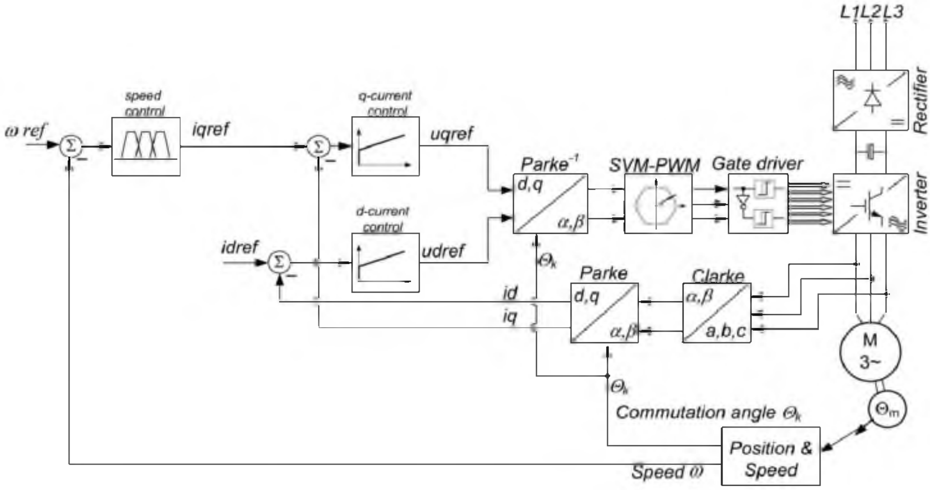

Fig. 2. Control structure

The control structure consists of two loops. The inner current control loop is responsible for motor torque regulation using the q-axis, current component and keeping the remaining d-axis component at zero. The corresponding d-q axis currents are obtained from the phase currents measurements using Clarke (a, b, c) → (α, β) and Park (α, β) → (d, q) transformation. Current control is realized using two proportional + integral (PI) controllers, one for each axis. The PI controllers are tuned to achieve maximum response speed without overshoot. Both current control loops are sampled at 10 kHz. At the output of the current control layer the d-q voltage reference vector is obtained and used further in the PWM process. The outer loop consists of the mechanical part of the motor/drive system, the TSK speed controller, and is responsible for speed and vibration control according to the reference value.

3. TSK-fuzzy speed controller

In classical control speed control structure of the PMSM drive usually the linear controllers are applied. They are described by linear control law. It is commonly known, that for the system with nonlinearity and parameter variation such controllers cannot ensure the superior performances of the system. Usually linear controller are tuned to the worst case, it means that in other operation points, the controlled plant is not working perfectly. In order to improve the plant performances in whole operation regions, different type of the controller can be applied. In this work the advanced TSK-type fuzzy controller is implemented to improve plant characteristics.

The structure of the considered controller is presented in Fig. 3. The trapezoidal-shape are implanted as the input membership functions. They are described by the following formulas:

$$f_i(x;a,b,c,d)=\left\{\begin{array}{ll} 0, & x\le a_i \\ \dfrac{x-a_i}{b_i-a_i}, & a_i\le x\le b_i \\ 1, & b_i\le x\le c_i \\ \dfrac{d_i-x}{d_i-c_i}, & c_i\le x\le d_i \\ 0, & d_i\le x \end{array}\right\} \tag{5}$$

where : i = NB (negative big), NS (negative small), ZE (zero), PS (positive small), PB (positive big). The used membership functions are presented in Fig. 4.

The input variables are as follows: speed error $e(k)$ and its derivative $\Delta e(k)$. The designed rule based is shown in Fig. 5.

The initial parameters of the controller's coefficients evident in Table 1 are as follows: $k_1 = 1$, $b_{ij} = 1$, ($i = 1, 2, 3; j = 0, 1$). The scaling coefficients k_2 and k_3 are selected as: $k_2 = K_p$ $k_3 = K_I$ where K_p and K_I are the parameters of the linear PI controller. In such situation the fuzzy controller has the some characteristic as the classical linear controller. After the initial test the coefficients b_{ij} are optimized using genetic algorithm. The following cost functions are applied:

$$I = I_1 \cdot I_2, \tag{5}$$

$$I_1 = \int e_1^2 t^2 dt, \tag{6}$$

$$I_2 = \int e_2^2 t^2 dt, \tag{7}$$

where: e_1 – the regulation error for the nominal inertia of the drive system $J = J_N$ and nominal value of the load torque m_{LN}, e_2 – regulation error for the system with double value of the inertia $J = 2J_N$ and nominal value of the load torque, t - time.

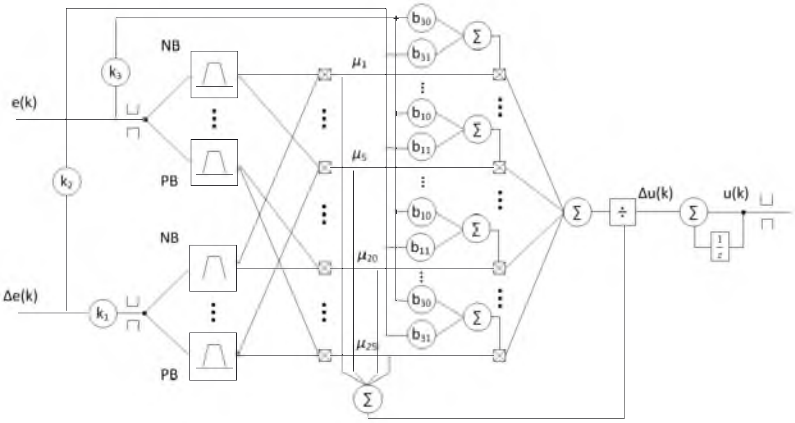

Fig. 3. Structure of the TSK-fuzzy speed controller

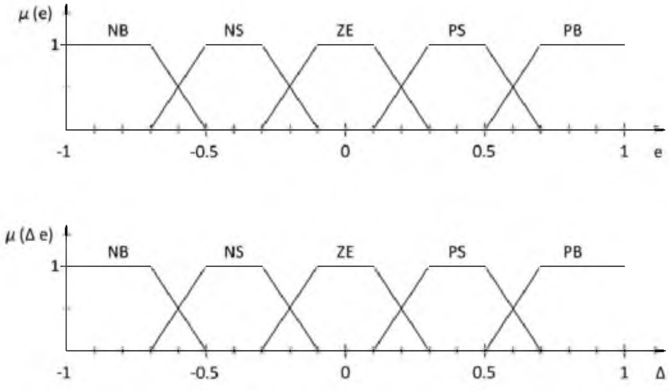

Fig. 4. The input membership functions of the speed and its derivative $e(k)$ i $\Delta e(k)$

Table 1. Rule base

$\Delta e(k)$ / $e(k)$	NB	NS	ZE	PS	PB
NB	b_{30} b_{31}	b_{30} b_{31}	b_{30} b_{31}	b_{30} b_{31}	b_{10} b_{11}
NS	b_{30} b_{31}	b_{30} b_{31}	b_{20} b_{21}	b_{10} b_{11}	b_{30} b_{31}
ZE	b_{30} b_{31}	b_{20} b_{21}	b_{10} b_{11}	b_{20} b_{21}	b_{30} b_{31}
PS	b_{30} b_{31}	b_{10} b_{11}	b_{20} b_{21}	b_{30} b_{31}	b_{30} b_{31}
PB	b_{10} b_{11}	b_{30} b_{31}	b_{30} b_{31}	b_{30} b_{31}	b_{30} b_{31}

The TSK-type fuzzy controller is often treated as the quasi-linear controller. It can be represented by series connection on n- separate PI-type linear controllers as shown in Fig. 5.

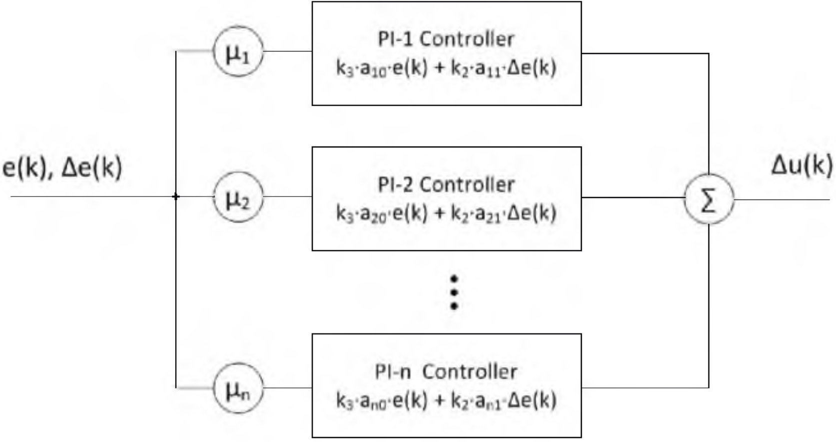

Fig. 5. Representation of the TSK-type linear controller as series connection of the linear PI controller

In this case the value of the controller's output is described by the following formula:

$$\Delta u(k) = \widetilde{K}_P \Delta e(k) + \widetilde{K}_I e(k), \tag{8}$$

where:

$$\widetilde{K}_p = k_2 \sum_{i=1}^{n} \mu_i a_{i1}, \tag{9}$$

$$\widetilde{K}_I = k_3 \sum_{i=1}^{n} \mu_i a_{i0}, \tag{10}$$

μ_i – degree of fulfillment i – premises. The control surface of the considered controller can be represented in the plane in the way shown in Fig. 6. Because the input membership function are selected as trapezoidal, this surface possess specific futures. In the presented plane three types of the sector can be distinguish:

- the areas which depends only on one rule;
- the areas which depend on two rules;
- the areas which depend on four rules.

Due to the selected, trapezoidal-type, membership functions there are sectors in the control surface which depends only on one rule. Because the premises in such areas are fulfilled totally, the consequence part of the specific rule depend only on the input vector of the system multiply by the linear coefficients b_{ij}. So, each such sector can be interpreted as the one specific linear PI controller. The gray color indicates the sector in the plane in which more than one rule is activated. This areas can be treated as the soft switching part between two (or four) separate rules.

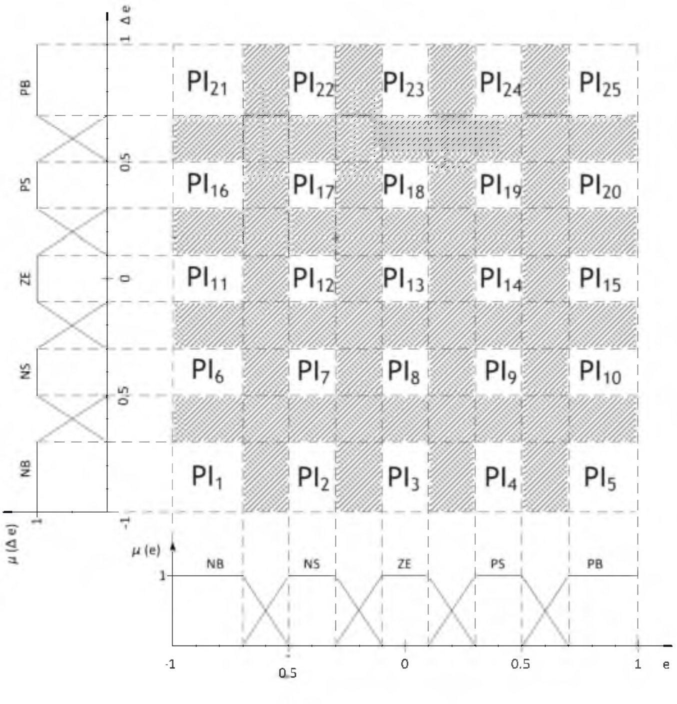

Fig. 6. The hypothetical control surface of the TSK-type fuzzy controller

In order to simplify the optimization process, the coefficient evident in the Table 1, where replaced in shorten list of the gains in the following form:

$$b_{10} = \{a_{50}, a_{90}, a_{130,} a_{170,} a_{210,}\},$$

$$b_{20} = \{a_{80}, a_{120}, a_{140}, a_{180}, \},$$

$$b_{30} = \{a_{10}, ..., a_{40}, a_{60}, a_{70}, a_{110}, a_{150}, a_{160}, a_{190}, a_{200}, a_{220}, ..., a_{250}, \},$$

$$b_{11} = \{a_{51}, a_{91}, a_{131}, a_{171}, a_{211}, \},$$

$$b_{21} = \{a_{81}, a_{121}, a_{141}, a_{181}, \},$$

$$b_{31} = \{a_{11}, ..., a_{41}, a_{61}, a_{71}, a_{111}, a_{151}, a_{161}, a_{191}, a_{201}, a_{221}, ..., a_{251}, \}.$$

This allows to fasten the optimization procedure. However, the non-linear characteristic of the TSK-type fuzzy controller is still guaranteed.

4. Results

The study are done using Matlab-Simulink software. Different level of the system speed, changeable load torque, and variation of the load inertia are considered in the research. In order to judge the obtained results fair, also the classical control structure is considered.

The system transients for the control structure using classical as well as the fuzzy speed controllers for nominal and double values of the inertia (J_N , $2J_N$) are presented in Fig. 7. The reference speed is set to the following value n_{ref} = 1000 rpm. The nominal load torque (m_{LN} = 1,09 Nm) is switched on and off in t_1=50 ms and t_2=100 ms respectively.

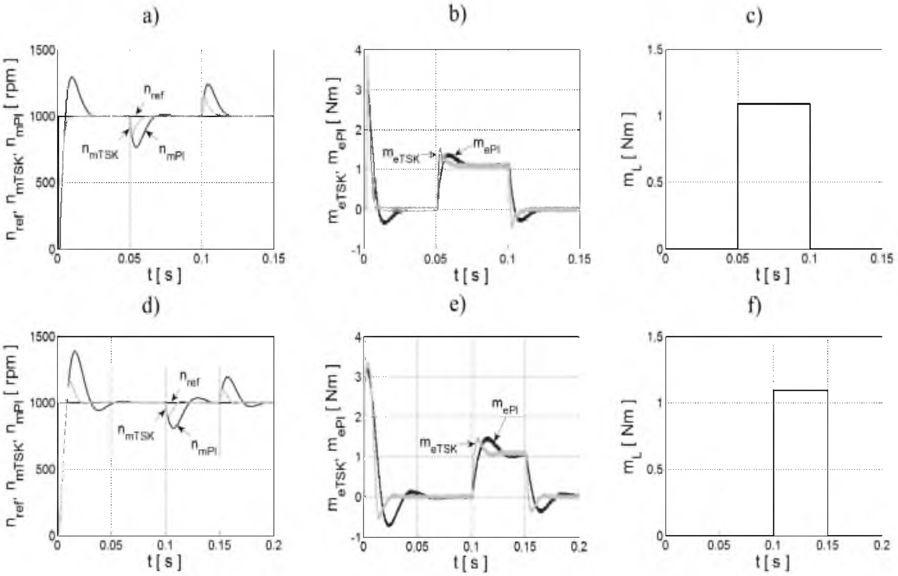

Fig. 7. Transients of the system speed (a,d), electromagnetic torque (b,e) and load torque (c,f) for the system with classical and fuzzy speed controllers for the nominal (a,b,c) and double value of the system inertia (d,e,f) and value of the reference speed n_{ref} = 1000 rpm

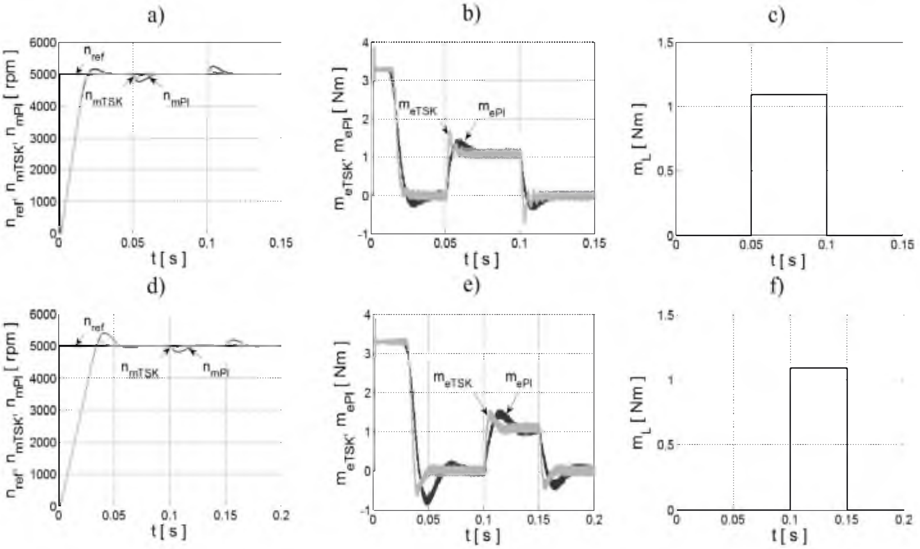

Fig. 8. Transients of the system speed (a,d), electromagnetic torque (b,e) and load torque (c,f) for the system with classical and fuzzy speed controllers for the nominal (a,b,c) and double value of the system inertia (d,e,f) and value of the reference speed n_{ref} = 5000 rpm

As can be observed in presented Fig. 7 both control structures are working correctly. However, in the control structure with classical controller a noticeable overshoot is evident. Also the application of the load torque affects the control system with PI controller in more visible way. The speed fluctuations in classical system have bigger magnitude. The system needs more time to reject they. Contrary to the system with linear controller the fuzzy controller works in more effective way. During the start-up the settling time is much shorter in such control structure. Also the changes of the load torque do not influence the speed in such visible way. The better dynamic of the fuzzy controller can be clearly seen into the electromagnetic torque transients. Due to the non-linear characteristic of the fuzzy controller it is regulated much more dynamically. Next the system with increased value of the inertia is tested. The transients of the system states are shown in Fig. 7d, e, f. Also in this case the fuzzy controller ensure much better performances of the system.

Then the study is repeated for the changed value of the reference speed n_{ref} = 5000 rpm. The obtained results are presented in Fig. 8. Firstly, the structure with nominal value of the inertia is considered (a, b, c). As in the previous case, the system with fuzzy controller posses better dynamic characteristic than the plant with linear PI controller. The changes of the system inertia worsen the performances of the classical structure with linear controller. Also the structure with the fuzzy controller is affected, but more slightly. The raising time in both system is much bigger than previously which results from the limitation of the electromagnetic torque (Fig. 8b, e).

Finally, the system with changeable during work inertia is examined. The variation of the inertia is shown in Fig. 9d. As can be seen the inertia is changing from $t_1 = 0$ s to $t_2 = 40$ ms in a linear way. Then at t_3=200 ms, $t_4 = 400$ ms and $t_5 = 600$ ms is changing rapidly as presented in Fig. 9d. Also in this test the superior work of the fuzzy controller can be observed.

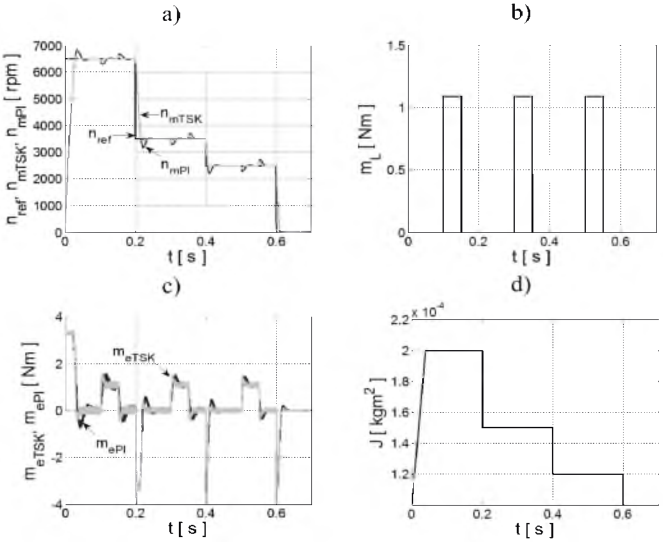

Fig. 9. Transients of the system speed (a), electromagnetic torque (c) and load torque (b) and inertia of the system (d) for the system with classical and fuzzy controllers

The parameters of the PMSM drive used in the study are placed in Table 2.

Table 2. Parameters of the PMSM drive

Parameter		**Value**	**Unit**
Nominal torque	M_N	1,09	Nm
Maximal torque	M_{max}	3,3	Nm
Nominal speed	n_N	7800	obr/min
Nominal current	I_N	2,2	A
Nominal power	P_N	893	W
Torque constant	k_T	0,501	Nm/A
Electromagnetic constant	k_e	0,435	V/rad/s
Stator resistance	R_s	3,35	Ω
Inductance in d axis	L_d	7,202	mH
Inductance in qaxis	L_q	7,233	mH
Inertia	J	0,0001	kgm^2

5. Conclusions

In the work issues related to the application of the fuzzy logic to the speed control of the non-linear, non-stationary PMSM drive are presented. The main point of the work has been to design the robust against the changes of the drive inertia control structure. The parameter of the fuzzy controller was finally tuned with the help of the genetic algorithm. On the basis on the following study the final remarks can be formulated:

- The application of the TSK type fuzzy controller is preferable in the PMSM drive. The fuzzy controller ensures the better transients of the system speed. The settling times and the overshoot are reduced compared to the classical linear controller. This situation is evident for the system with nominal and changed moment of inertia. The better dynamic of the system is visible also in the electromagnetic torque.
- The selection of the controller parameters is a crucial point of the design procedure. The initial parameters of the fuzzy controllers are set in a way which ensure the some responses of the linear and classical system are similar. Then only, the values evident in the consequence part of the rules are optimized. This is changing the control sectors of the fuzzy controller in a non-linear way.
- The application of the genetic algorithm allows to optimally design of the fuzzy controller's parameters for non-linear, non-stationary system according to the specify cost function.
- The application of the fuzzy TSK system for the control of different plants is especially suitable for the industry. The way of operating of the TSK-type fuzzy controller can be explained as a series connection of the linear commonly-know controllers. This approach is more likely to be suitable to industry engineers due to the fact that it referees to the commonly know PI controller's theory. So the parameters of each rules, describing selected area of the operating point, can be set and analyses using classical theory.
- The TSK controller can be regarded as the gain-scheduling methodology. However, contrary to it, the TSK system guarantee soft switches between selected regions. This avoid possible oscillation which can be generated in classical gain-scheduling scheme.

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