COMPARATIVE ANALYSIS OF DIFFERENT PI/PID CONTROL STRUCTURES FOR TWO-MASS SYSTEM

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Abstract – **In the paper the analytical design procedure of a speed control system with PI and PID controllers and different additional feedbacks for a drive with an elastic joint is shown. The comparative analysis based on the location of closed-loop system poles is presented. The analytical equations, which ensure required damping coefficient of the drive system, are given. Moreover, the performances of the two-mass drive system with PI speed controller designed using the pole placement method was compared to the performances of the drive system with linear PI and fuzzy-logic PI controllers, both designed using genetic algorithm for the control index optimization. The dynamic behaviour of considered control structures with different speed controllers have been examined using computer simulations and experimental tests.**

Index terms – **Electrical drives, elastic joint, additional feedback, PI controller, fuzzy control**

I. INTRODUCTION

In some industrial applications the mechanical part of the system has very low resonant frequency, because of a long shaft between the motor and the load machine. So, especially in the drive systems with high performances speed and torque regulation, the motor speed is different from the load speed during transients. This speed difference means that the shaft is undertaking large torsional torque which influences it in a negative way. Additionally, speed oscillations cause decrease in the quality of the rolling material and can influence the stability of the control system. Except for rolling mill drives [8], [9] a similar problems appears in servodrives [1], [3], [4], [6], [10], [12], [14], space network antennas [5], robot arm [15] or cage host drive.

Several control structures have been developed for suppression of torsional vibrations. Most popular are structures with PI speed controller and different additional feedbacks [3], [4], [6], [8], [9]-[11]. However, there is a lack of analytical formulas for controller parameters adjustment as well as a comparative analysis with other control structures seems to be interesting.

Moreover, in the last few years fuzzy logic control (FL) has appeared a great field of interest in many technical applications, also in electrical drives [7], [10], [13]. FL controllers are specially designated to control problems of nonlinear, non-stationary or ill-defined

systems. But recently the fuzzy-logic techniques are also used for linear or quasi-linear systems.

The main goal of this paper is to develop systematic analysis and design guidelines for the speed control of two-mass system with PI/PID speed controller supported by different additional feedbacks as well as comparison of dynamical properties of such structures. Additionally the application of soft computing (SC) technique was discussed. The difference in dynamic performances between classical and SC approach was shown.

II. THE MATHEMATICAL MODEL OF THE DRIVE SYSTEM

In the paper a commonly used model of the drive system with the resilient coupling is considered. The system is described by the following state equations (in per unit system), with nonlinear friction neglected:

$$\frac{d}{dt}\begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ m_s(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{T_1} \\ 0 & 0 & \frac{1}{T_2} \\ \frac{1}{T_c} & \frac{-1}{T_c} & 0 \end{bmatrix}\begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ m_s(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{T_1} \\ 0 \\ 0 \end{bmatrix}[m_e] + \begin{bmatrix} 0 \\ \frac{-1}{T_{m2}} \\ 0 \end{bmatrix}[m_o] \quad (1)$$

where: ω_1- motor speed, ω_2- load speed, m_e– motor torque, m_s– shaft (torsional) torque, m_o– disturbance torque, T_1 – mechanical time constant of the motor, T_2– mechanical time constant of the load machine, T_c– stiffness time constant. Parameters of the analysed system are following: T_1=230ms, T_2=230ms, T_c=2.6ms.

The electromagnetic torque of the motor is used as a control input of the system and the angular speed of the motor is taken as the output value. Hence, results of this work can be applied to any kind of the electrical motor with high performance electromagnetic torque control.

III. PI/PID SPEED CONTROL STRUCTURES FOR TWO-MASS SYSTEM

A. The control structures description

A typical electrical drive system is composed of a power converter-fed motor coupled to a mechanical system, a microprocessor-based system controller, current speed and/or positions sensors used as feedback signals (Fig 1). Typically, cascade control structure

containing two major control loops is used. The inner control loop performs a motor torque regulation and consists of the power converter, electromagnetic part of the motor, current sensor and respective current or torque controller. Therefore, this control loop is designed to provide sufficiently fast torque control, so it can be approximated by an equivalent first order term. If this control is ensured, the driven machine could be AC or DC motor, with no difference in the outer control loop. This outer loop consists of the mechanical part of the motor, speed sensor, speed controller, and is cascaded to the inner loop. It provides speed control according to the reference value
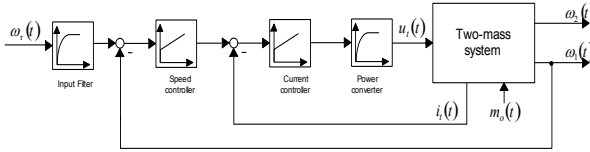

Fig. 1. The classical control structure

Parameters of the speed controller are usually set with the use of the classical symmetrical criterion. Then, however, the control system cannot effectively suppress torsional vibrations, and the drive transients are not satisfactory [6]. There are two major methods to improve the system characteristics. The first of them, based on alternative tuning methods of PI controller, was presented in [14]. Still, this method is only effective for inertia ratio (T_2/T_1) of a two-mass system bigger than two. For small inertia ratio vibrations suppression is still not appropriate. The second method is based on a modification of classical control structure using the additional feedback from the selected mechanical state variable inserted to the structure. This ensures the effective damping of torsional vibrations for the whole range of inertia ratio.

In the paper the modified control structures with additional feedback from, i.e. torsional torque (k_1) [6], derivative of torsional torque (k_2) [9], difference between motor and load speed (k_3) and load speed (k_4) [4], [6], [10], [13] are considered. The schematic diagram of the control structures (the optimised torque control loop is omitted) is presented in Fig 2.
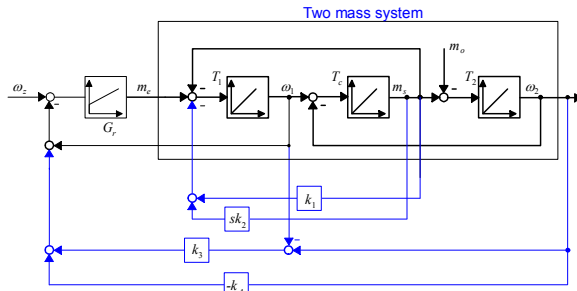

Fig. 2. Schematic diagram of the control structure with possible additional feedbacks

B. PI/PID controllers design

The classical system with PI controller (without additional feedback and parameters of the controller adjusted to achieve double poles location) has the damping coefficient ξ and the resonant frequency ω_0 dependent on mechanical parameters of the system. In order to obtain any assumed damping coefficient ξ_{ass}, the additional feedback is needed. According to Fig.2, it could be a feedback from: torsional torque (k_1), derivative of torsional torque (k_2) (two pairs of the controller parameters ensuring assumed damping coefficient are possible), difference between motor and load speed (k_3) and load speed (k_4).

The classical PID controller without additional feedback can also be used to damp torsional vibrations effectively. The properties of the classical system with PID controller were analysed and compared to properties of the systems with PI controller and additional feedbacks.

The parameters of control structure were obtained with the used of load speed transfer function:

$$G_{p\omega_2}(s) = \frac{\Delta\omega_2(s)}{\Delta\omega_r(s)} = \frac{G_r}{s^3 T_1 T_2 T_c + s^2 T_2 T_c G_r(1+k_3) + s\left(T_1 + T_2\left(1+k_1+sk_2\right)\right) + G_r(1-k_4)} \quad (2)$$

where:

$$G_r = sK_d + K_p + \frac{K_I}{s} \quad (3)$$

is the transfer function of the speed controller:

Table 1. Mathematical formulas used for parameters setting of PI/PID speed controllers of two-mass drive system

PI, without additional feedbacks
$K_p = 2\sqrt{\dfrac{T_1}{T_c}}$, $K_I = \dfrac{T_1}{T_2 T_c}$
PI, feedback form torsional torque
$K_p = 2\sqrt{\dfrac{T_1(1+k_1)}{T_c}}$ $K_I = \dfrac{T_1}{T_2 T_c}$, $k_1 = \dfrac{\xi_{ass}^2 4T_1}{T_2} - 1$
PI, feedback from derivative of torsional torque
$x_{1,2} = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$, $a = T_2^2(T_1 + T_2)$, $\omega_0 = \sqrt{\dfrac{1}{T_2 T_c + x T_2}}$ $b = 2T_c T_2^2(T_1 + T_2) - \left(2 + 4\xi_{ass}^2\right)T_1 T_2^2 T_c$ $c = T_c^2 T_2^2(T_1 + T_2) + T_1 T_c^2 T_2^2 - \left(2 + 4\xi_{ass}^2\right)T_1 T_2^2 T_c^2$ $k_2 = xK_p$, $K_p = \dfrac{4\xi\omega_0 T_1 T_c}{T_c + x}$, $K_I = \omega_0^4 T_1 T_2 T_c$
PI, feedback form difference between motor and load speed
$\omega_0 = \sqrt{\dfrac{1}{(1+k_3)T_2 T_c}}$, $k_3 = \dfrac{\xi_{ass}^2 4T_1 - T_2}{T_1 + T_2}$ $K_I = \dfrac{T_1}{(1+k_3)^2 T_2 T_c}$, $K_p = \dfrac{4\xi\omega_0 T_1}{1+k_3}$
PI, feedback from load machine speed
$\omega_0 = \sqrt{\dfrac{1-k_4}{T_2 T_c}}$, $k_3 = 1 - \dfrac{T_1 + T_2}{T_1\left(4\xi_{ass}^2 + 1\right)}$, $K_I = \dfrac{T_1}{T_2 T_c}(1+k_4)$, $K_p = 4\xi\omega_0 T_1$,
PID without additional feedback

$$K_d = \frac{T_2}{4\xi_{ass}^2} - T_1 , \; K_p = 2\sqrt{\frac{T_1 + K_d}{T_c}} , \; K_I = \frac{T_1 + K_d}{T_2 T_c}$$

In the Table 1 mathematical formulas developed for PI and PID controllers' parameters, which enable any assumed damping coefficient of all considered control systems are presented.

In Fig 3. the closed-loop poles loci of all considered control systems are presented. These systems are of fourth order and presented poles are double. The damping coefficient in all systems with additional feedback was set to 0.7.
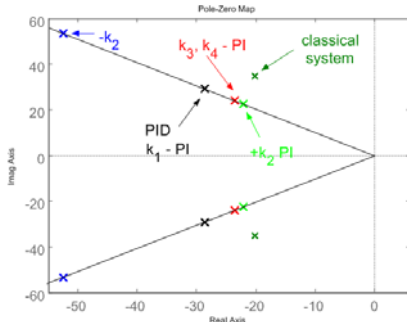

Fig. 3. Closed-loop poles loci for considered control structures of two-mass drive

The system with PI controller and additional feedback from derivative of torsional torque ($K_p=162$, $K_I=4357$, $-k_2=0,29$) has the highest value of the resonant frequency. However, this system is very sensitive to the noise level in the real system (because of big value of feedback coefficient). The next fastest control structures is the system with additional feedback form torsional torque ($K_p=26$, $K_I=384$, $k_1=0,96$) and the system with PID ($K_p=13$, $K_I=196$, $K_d=-0,11$) controller; the poles of both systems lie in the same place. The application of PID controller permits achieving assumed damping coefficient without additional feedback, which simplifies the implementation in the real system - measuring the additional variable could be difficult, so they should be estimated. The systems with additional feedback from difference between the load and the motor speed ($K_p=15$, $K_I=196$, $k_3=0,48$) or feedback from the load speed ($K_p=21$, $K_I=256$, $k_4=0,32$) have the same dynamic characteristics. The slowest is the system with additional feedback from derivative of torsional torque ($K_p=12$, $K_I=136$, $+k_2=0,021$).
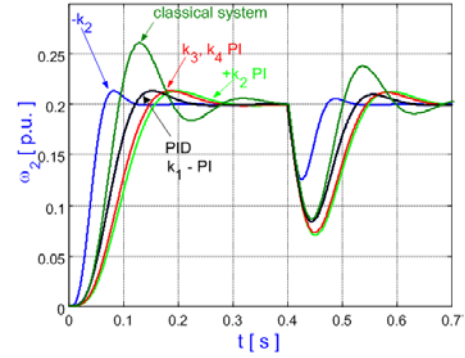

Fig. 4. Comparison of the load speed responses of analysed systems with PI/PID controllers to speed reference and load torque changes

In Fig. 4 transients of the considered systems are presented. The shown responses confirm the conclusions obtained after the analysis of closed-loop poles locations.

IV. APPLICATION OF FUZZY LOGIC AND GENETIC ALGORITHMS IN THE CONTROL STRUCTURE OF TWO-MASS SYSTEM

The main aim of the research presented in this chapter has been the comparison of the dynamic characteristics of control structures with three types of speed controllers in the structure without additional feedbacks (as in Fig.1):

1 - classical PI controller with parameters obtained using analytical equations (according to the Table 1),
2 - classical PI controller with parameters obtained using genetic algorithms,
3 − fuzzy logic controller with parameters obtained by means of genetic algorithms.

Genetic algorithms (GA) were successfully applied for optimisation procedure of fuzzy logic controllers [1,2,10]. The application of GA to fuzzy controllers design, hold a great deal of promise in overcoming two major problems in fuzzy controllers adjustment: time design and optimally design.

Because one of the main goals of this paper was the comparison of the dynamic behaviour of the two-mass drive system with the classical PI and FL speed controllers, both controllers were designed using the same control index and the same optimization procedure (GA).

The following control index was taken into account:

$$K_I = \min \int_0^\infty \left(|\omega_{ref} - \omega_L| t \right) dt ; \qquad (2)$$

Parameters of the proposed fuzzy controller are presented in Fig. 5.

a)

b)   c)

Fig. 5. Parameters of fuzzy logic controller: a – general structure
b - membership functions, c - rule base
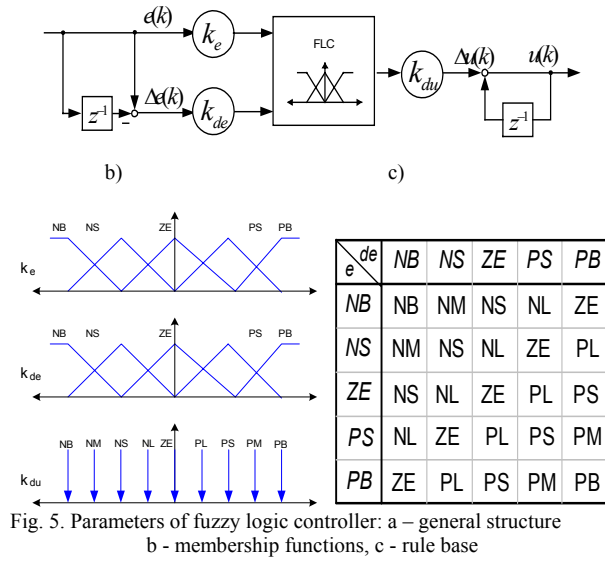
The considered controller has 25 rules, which are symmetric to the main diagonal in order to ensure the same system performance in both speed directions. The number of membership functions is five for controller's input and nine for controller's output. The input functions usually have a triangular shape. To make real implementation easier the output has singletons function.

The comparison of transient responses of three considered systems is shown in Fig. 6. The first system with PI controller and parameters obtained using analytical equations ($K_p=18$, $K_I=384$) has a large overshoot and long settling time which depends on mechanical parameters of the system. The second examined system with PI controller optimised by GA ($K_p=20$, $K_I=306$) has a much smaller overshoot and settling time. It provides much better dynamic characteristics than the first one. The third considered system with FL controller ($k_e=1$, $k_{de}=0,01$, $k_{du}=2500$) and parameters adjusted using GA has the best dynamic properties. It has the shortest rising and settling time and the smallest overshoot.
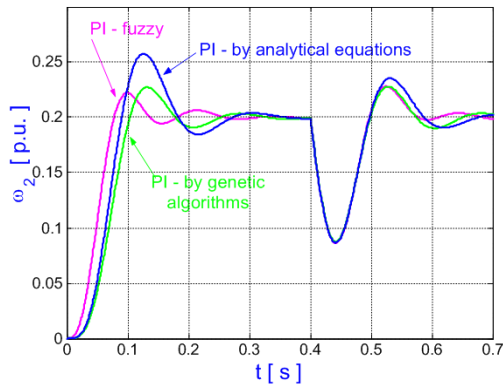

Fig. 6. Comparison of the load speed responses of the PI and FL controllers to speed reference and load torque changes

The above speed transients for the control structures with different types of PI controllers confirm that the application of genetic algorithms and fuzzy logic theory can improve the dynamic properties and effectively suppress oscillations of the two-mass drive system.

V. EXPERIMENTAL RESULTS

All simulation tests have been verified in the experimental set-up presented in Fig. 7. The real system is composed of a DC motor driven by a four-quadrant chopper. The motor is coupled to a load machine by an elastic shaft (a steel shaft of 5mm diameter and 600mm length). The moment of inertia can be varied by a flywheel, where the inertia ratio of motor to load varies from 0.125 to 8. The load machine is also a DC motor. Two motors have the nominal rating of 500W each. Speed and position of DC motors are measured by incremental encoders (5000 pulses per rotation). The mechanical system has a natural frequency approximately 9.5 Hz, time constants T_1, T_2 and T_c of the real system as the same as given in chapter 2. The control algorithms are implemented in DSP using the dSPACE software.
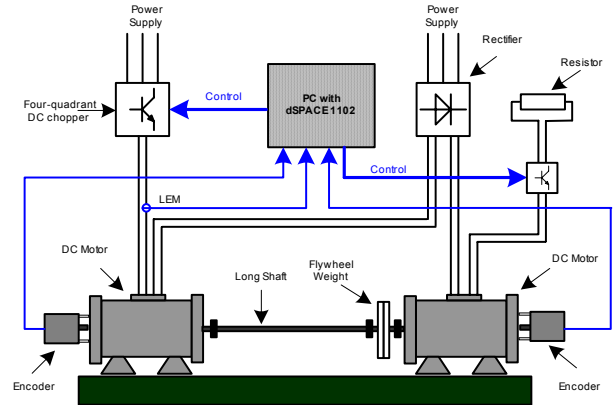

Fig. 7. The schematic diagram of experimental set-up

The information about the torsional torque (in some structures) was obtained using a simple estimator [5], which block diagram is presented in Fig 8.
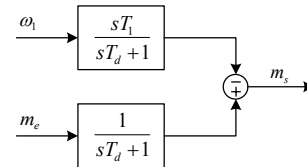

Fig.8. The block diagram of a torsional torque estimator

The T_d time constant should be as small as possible and depends on the noise level in the real system (it was set to the value of 3ms in experimental drive).

Transients of the motor and load speed are presented in Fig.9. To avoid limitation of electromagnetic torque, the speed reference value was set to 20% of nominal speed.

The first considered control structure was the system with PI controller without additional feedback. As shown in Fig 9a, the load speed of the system has a large overshoot and settling time.

Next, transients of the system with additional feedback from torsional torque (k_1) are presented in Fig. 9b. Torsional vibrations were successfully damped. The system with additional feedback from derivative of torsional torque was also tested. Because of a quite big noise level in the real system, the structure with bigger resonant frequency ($-k_2$) was not examined. In Fig. 9c the load and motor speed transients for the slower system ($+k_2$) are presented.

Then, transients of the system with additional feedback from difference between motor and load speed (k_3) and form load speed (k_4) are presented in Fig. 9d and Fig. 9e, respectively. In Fig. 9f the motor and load speed traces of the system with PID controller are shown.

Next, transients of the systems with classical PI and PI fuzzy logic speed controllers, tuned by genetic algorithm, without additional feedbacks are presented. The load speed (in the case of both systems) has a small overshot; as in simulations. The system with fuzzy-logic controller has slightly bigger overshoot, which could be minimised but then the rising time (which is the shortest of all systems) will increase.
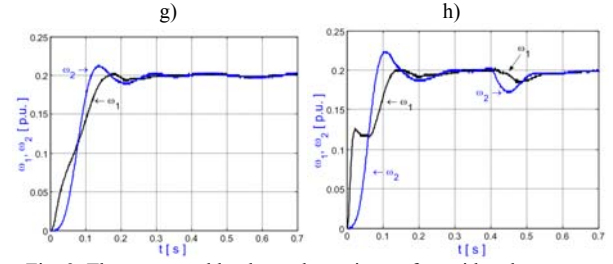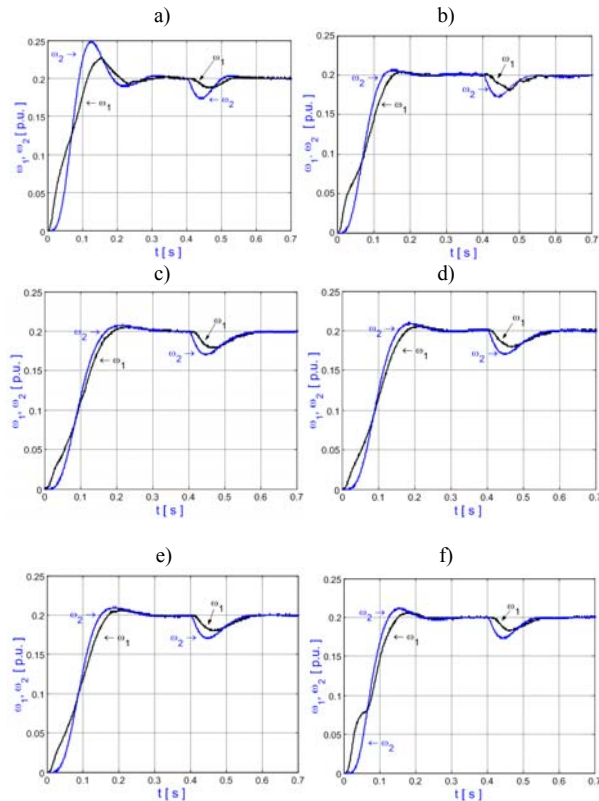

Fig. 9. The motor and load speed transients of considered systems: a – PI, no additional feedback, b – PI, feedback from torsional torque, c – PI, feedback from derivative of torsional torque, d - PI, feedback from difference between motor and load speed, e - PI, feedback from load speed f – PID, no additional feedback g – PI tuned using GA, no additional feedback, h - PI-FL tuned using GA, no additional feedback

VI. CONCLUSION

In the paper an analysis of different PI/PID control structures for the drive system with elastic joint was done. The analytical formulas for PI and PID controllers' parameters, which enable any assumed damping coefficient of all considered control systems were developed and dynamic characteristics were compared. In order to provide the assumed damping coefficient in the systems with PI controller the insertion of additional feedback is needed. The PID controller without additional feedback is an interesting alternative. Still, it requires a good speed sensor. The system with additional feedback from derivative of torsional torque has the best dynamic property ($-k_2$), but it requires a low noise level in real application. Next, the control structure with additional feedback from torsional torque has the best characteristics. The implementation of this structure in real system is quite easy. The system with PID controller has the same properties. Besides, the application of the genetic algorithm for PI and fuzzy logic controllers was considered. It was shown that both methods could be successfully applied in control of the two-mass system.

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