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DTC METHOD ANALYSIS IN APPLICATION OF PRESSURE AND FLOW CONTROL IN HYDRAULIC SYSTEM

Problems with controlling the torque of induction motor, considering the use of this drive in order to control the hydraulic drive power unit parameters (with constant displacement pump). In analyzed system, a Direct Torque Control method (DTC) and fuzzy PI type controller were used. Inverter-fed drive system with 2,2 kW ac motor was subjected to laboratory tests.

ANALIZA METODY DTC W ZASTOSOWANIU DO STEROWANIA CIŚNIENIEM I PRZEPŁYWEM UKŁADU HYDRAULICZNEGO

Analizowano problemy sterowania momentem silnika indukcyjnego, uwzględniając zastosowanie tego napędu do sterowania parametrami hydraulicznej stacji zasilającej z pompą o stałej wydajności geometrycznej. W analizowanym układzie zastosowano bezpośrednią metodę sterowania momentem (Direct Torque Control) oraz rozmyty regulator typu PI. Badania laboratoryjne dokonano w układzie napędowym z silnikiem o mocy 2,2 kW, zasilanym z falownika napięcia.

1. INTRODUCTION

Controlling the torque or force of hydraulic system requires using a control element enabling to change working liquid pressure. This element is usually the pressure reducing or overflow valve. Throttling control systems is characterized by low efficiency what limits its range of application to low power applications. Particularly low efficiency is a feature of systems with serial location of throttling element. In all these cases the energy loss occurs, which decreases the exploitation cost of hydraulic system.

There are unique correlations (nearly proportional) between the force of actuator piston rod or the torque of hydraulic motor shaft and the pressure. These relations can be used for the appropriate control of electric motor torque driving the constant displacement pump. Evolution of electric motors, electronic power converters, controlling methods and

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microprocessor systems enables the effective and energy-saving control of the operation parameters of hydraulic systems [5, 6].

Torque (pressure) control is mostly often carried out in two cases:

- working load, and also pressure of the hydraulic system actuator is a function (linear or non-linear) of motor angular velocity,
- working load (pressure) of the hydraulic system actuator is a linear or non-linear function of pressure (it is not motor angular velocity dependent).

In the first case (i.e. traction vehicle drive) there is a working medium flow and torque (pressure) change can take place in the torque control system (open-loop or closed-loop). Whereas in the second case (i.e. press drive), working medium flow can be slight with a considerable torque value, what can result in adverse working conditions of electric motor (high torque or pressure value with low motor angular velocity). Then, torque or pressure control can be carried out in simultaneous velocity and torque regulation system.

Velocity control of hydraulic actuator requires equipping system with a valve enabling constant change of actuator working liquid flow rate (throttling control system) or variable displacement pump (volumetric control system). There are unique correlations (nearly proportional) between the speed of piston rod or hydraulic motor shaft and the flow rate. In volumetric control systems, pumps with variable displacement are used. Change of efficiency can be made through a change of geometric pump volume, or through a change of its rotational speed.

Usually, induction motors are used as the drive in hydraulic pumps. They have good operating and control properties. New structures of induction motors achieve efficiency of about 90÷93% and mass to power ratio of 0.7÷1.5 kg/kW [1]. High popularity of three-phase inductive motors is also caused by structural and technological progress in the field of semiconductor power elements.

The Direct Torque Control (DTC) method of induction motor drive system with fuzzy controller was analyzed in the elaboration.

2. DIRECT TORQUE CONTROL METHOD

In Direct Torque Control method, a principle of forming the actual torque value through the adequate orientation of stator flux vector $\boldsymbol{\varphi}_s$ in relation to rotor flux vector $\boldsymbol{\varphi}_r$ [2, 3, 4]. From PWM modulation, the stator voltage vector is of six non-zero values (active vectors) and two zero values (zero vectors). Change of the sequence of active vectors causes the change of stator flux vector position, which end draws a hexagon-shaped trajectory. Whereas zero vectors do not change their trajectory shape but they cause the flux vector retention. Since the rotor flux vector moves constantly over the circular trajectory with synchronic velocity (angle γchange can be achieved by adequately changing the sequence of active and zero vectors). Changes of flux vector $\boldsymbol{\varphi}_s$ position in co-ordinate system connected with the stator, was divided into 6 sectors (fig. 1) and each of them was given a number from N=1 to N=6. Each sector includes angular range according to the following dependence

$$(2N-3)\,\pi/6 < \gamma(N) \le (2N-1)\,\pi/6 \tag{1}$$

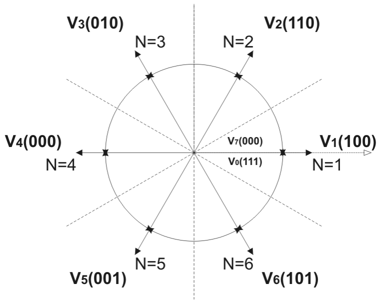

Fig. 1. Stator voltage plain and N stator flux vector φ_s *position sectors*

Inverter drive block diagram with direct flux and torque control is shown in fig. 2. Reference stator flux ϕ_z and torque M_z values are compared with measured values ϕ and M. In the system of flux regulation, the two level controller with a hysteresis width of H_ϕ, whereas in motor torque regulation loop – the three level controller with a hysteresis width of H_M .

Output states of flux controller are defined as follows [1, 2]:

$$u_\phi = 1 \quad \text{dla} \quad e_\phi > H_\phi \tag{2}$$

$$u_\phi = 0 \quad \text{dla} \quad e_\phi < -H_\phi \tag{3}$$

Analogically, for torque controller

$$u_M = 1 \quad \text{dla} \quad e_M > H_M \tag{4}$$

$$u_M = 0 \quad \text{dla} \quad e_M = 0 \tag{5}$$

$$u_M = -1 \quad \text{dla} \quad e_M < -H_M \tag{6}$$

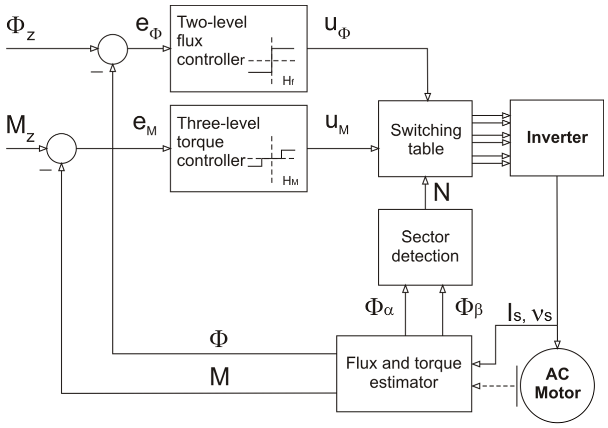

Fig. 2. Block diagram of direct motor torque and flux control system

Choice of voltage vector is made according to output signals of controllers and flux vector position. According to principles described above, the stator voltage vector $\boldsymbol{v}_S$ code chart was developed (table 1).

Tab. 1. Stator voltage vector code chart

$\boldsymbol{u_\phi}$,	$\boldsymbol{u_M}$ ***N***	***N*=1**	***N*=2**	***N*=3**	***N*=4**	***N*=5**	***N*=6**
$\boldsymbol{u_\phi}$**=1**	$\boldsymbol{u_M}$**=1**	$\mathbf{v}_2$(110)	$\mathbf{v}_3$(010)	$\mathbf{v}_4$(011)	$\mathbf{v}_5$(001)	$\mathbf{v}_6$(101)	$\mathbf{v}_1$(100)
	$\boldsymbol{u_M}$**=0**	$\mathbf{v}_7$(111)	$\mathbf{v}_0$(000)	$\mathbf{v}_7$(111)	$\mathbf{v}_0$(000)	$\mathbf{v}_7$(111)	$\mathbf{v}_0$(000)
	$\boldsymbol{u_M}$**=–1**	$\mathbf{v}_6$(101)	$\mathbf{v}_1$(100)	$\mathbf{v}_2$(110)	$\mathbf{v}_3$(010)	$\mathbf{v}_4$(011)	$\mathbf{v}_5$(001)
$\boldsymbol{u_\phi}$**=0**	$\boldsymbol{u_M}$**=1**	$\mathbf{v}_3$(010)	$\mathbf{v}_4$(011)	$\mathbf{v}_5$(001)	$\mathbf{v}_6$(101)	$\mathbf{v}_1$(100)	$\mathbf{v}_2$(110)
	$\boldsymbol{u_M}$**=0**	$\mathbf{v}_0$(000)	$\mathbf{v}_7$(111)	$\mathbf{v}_0$(000)	$\mathbf{v}_7$(111)	$\mathbf{v}_0$(000)	$\mathbf{v}_7$(111)
	$\boldsymbol{u_M}$**=–1**	$\mathbf{v}_5$(001)	$\mathbf{v}_6$(101)	$\mathbf{v}_1$(100)	$\mathbf{v}_2$(110)	$\mathbf{v}_3$(010)	$\mathbf{v}_4$(011)

There is no direct motor stator current regulation in control system. Instead of the flux and torque measurement, an estimation of these values can be made. However, in this case the quality of regulation will depend on the accuracy of motor mathematical model identification and consideration of changes of its parameters.

Motor flux estimation can be made in various ways, i.e. by using the voltage or current model, observers, Kalman's filter or neural network. Motor electromagnetic torque can be determined from the following dependency

$$M = \frac{U\,I}{\omega} \tag{7}$$

where: U – rectifier output voltage, I – rectifier output current, ω – angular velocity.

3. MOTOR TORQUE AND ANGULAR VELOCITY CONTROL

Electric motor torque control can be carried out in a system shown in fig. 2. With the use of this system configuration also the values of hydraulic system can be controlled, such as: torque and rotational speed of hydraulic motor, force and displacement velocity of servo-motor piston rod, and in general case, the pressure or flow rate of hydraulic drive power unit (fig. 3).

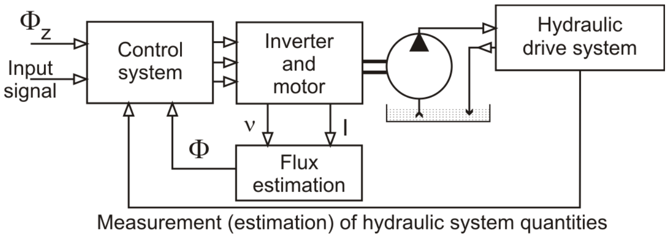

Fig. 3. Control system block diagram

In fig. 4 there are exemplary time responses of torque *M* (solid line) for set motor torque course M_z (dashed line). Controlling torque is practically inertialess, however it is characterized by some regulation error. Stator flux remains at constant level regardless of *M* torque value. Load torque M_O do not influence the electromagnetic motor torque value.

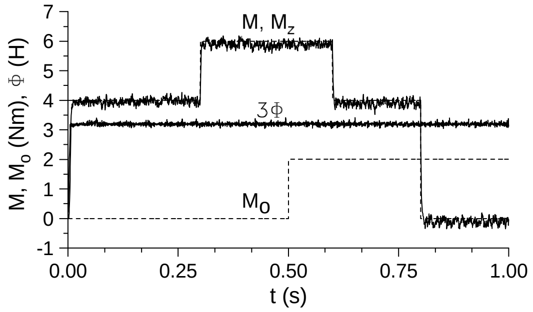

Fig. 4. Time responses of inverter drive controlled by DTC method (system from fig. 3)

In case of higher requirements regarding quality and accuracy of electric motor torque control or quantities of hydraulic station, a system equipped with regulator should be used, i.e. PI type (fig. 5). In further analysis, a PI fuzzy controller was assumed [5, 6, 7]. For fuzzy controller, the information of mathematical model is not required or this kind of information can possibly be formulated in fuzzy categories. So, there is no necessity of using the parametric identification process, hard in practical realization. Moreover, fuzzy control is also effective in case of complex, non-linear and multidimensional control systems.

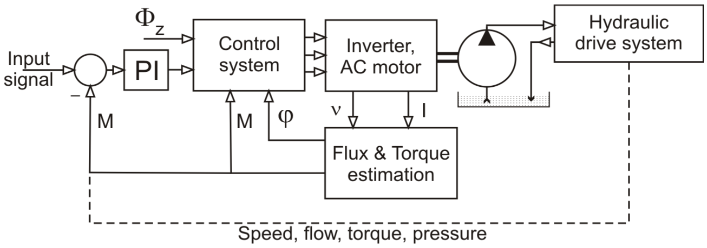

Fig. 5. Control system block diagram

In case of fuzzy controller, input signals are: regulation error *e* and speed of changes *de* of this error. Error *e* of torque *M* regulation for given value of M_z

$$e(k) = M_z(k) - M(k) \tag{8}$$

and speed of changes *de* of this error

$$de(k) = e(k) - e(k-1) \tag{9}$$

are regulator input signals. Input variables e and de and regulator output variable u are expressed by the following sets of linguistic expressions

$$\begin{aligned}&\{e(k)\} = \{\mathrm{NL, NM, NS, Z, PS, PM, PL}\}\\&\{de(k)\} = \{\mathrm{NL, NM, NS, Z, PS, PM, PL}\}\\&\{u(k)\} = \{\mathrm{NVL, NL, NM, NS, NVS, Z, PVS, PS, PM, PL, PVL}\}\end{aligned} \tag{10}$$

where N stands for „negative”, P – for „positive”, L – for „large”, M – for „medium”, S – for „small”, Z – for „zero” and V – for „very”. The variables e and de were expressed in relative units

$$e'(k)=e(k)/K_e\ ,\quad de'(k) = de(k)/K_{de}\ ,\quad u'(k) = u(k)/K_u \tag{11}$$

where K_e, K_{de} and K_u are experimentally determined coefficients of the controller.

Membership functions of fuzzy sets $\{e'\}$, $\{de'\}$ and $\{u'\}$, which correspond to the above linguistic expresions are represented in Fig. 6. Parameters K_e and K_{de} was selected in a way that values of variables e' and de' were included in an interval [-1, 1].

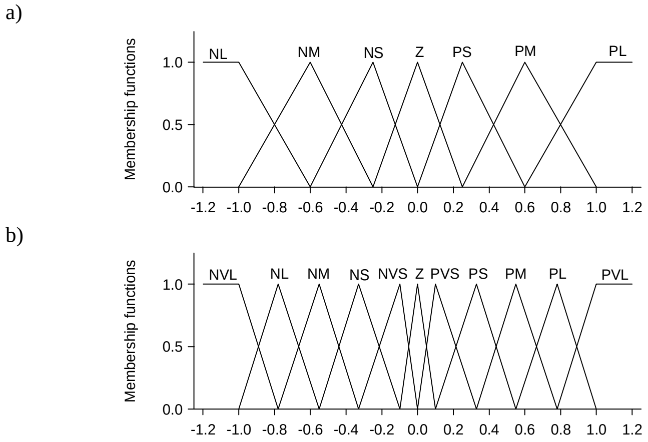

Fig. 6. Membership functions of fuzzy controller for: a) error e' and error change de', b) output signal u'

Set of fuzzy rules of controller is listed in table 2.

Tab. 2. Fuzzy rules for PI controller

de' **e’**	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	NVL	NVL	NVL	NL	NM	NS	Z
NM	NVL	NVL	NL	NM	NS	Z	PS
NS	NVL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PVL
PM	NS	Z	PS	PM	PL	PVL	PVL
PL	Z	PS	PM	PL	PVL	PVL	PVL

Procedure of control signal $u'(k)$ calculation is divided into the following stages:

1. Sampling od $e(t)$ and $de(t)$ signals
2. Determination of $e(k)$ error and $de(k)$ error change and their relative values $e'(k)$ and $de'(k)$ according to equations (11).
3. Calculation of membership function μ_{e_i} $(e'(k))$ and μ_{de_i} $(de'(k))$ of output variables e' and de' for i-th fuzzy control rule, i=1, 2, ..., N; N – number of control rules (in analyzed example $N=7^2=49$).
4. Calculation of minimum value

$$a_i = min[\mu_{e_i}(e'(k)),\ \mu_{de_i}(de'(k))] \tag{12}$$

5. Calculation of membership function of input signal u' from the following dependency

$$\mu(u') = max\{min[\alpha_i,\ \mu_{u_i}(u')]\} \qquad 1,...,N \tag{13}$$

6. Calculation of regulator output signal $u'(k)$ by defuzzification , i.e. using the centre of gravity method.
7. Determination of control signal $u(k)$ for PI type regulator from the following dependence

$$u(k) = u(k-1) + K_u u(k)\ , \qquad k = 0,\ 1,\ 2,\ ... \tag{14}$$

On-line velocity or position control according to the presented procedure is possible if a fast microcontroller and digital signal processor have been used. Another solution is a tabulation of the signal value u'. Range of changes of input variables e' and de' was divided into L intervals, and each interval was assigned with indexes, respectively j and l (j, l=1, 2, ... , L). Next, this table was saved in controller memory (computer). Input signal values u' for the combination of values of indexes j and l – which describes sets of values of deviation e' and speed of deviation changes de' – were listed in table 3 (L=10 assumed). In laboratory tests L=50 was used.

Tab. 3. Output signal values u'

j \ l	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	-0.86	-0.86	-0.76	-0.72	-0.56	-0.30	-0.18	-0.06	0.00	0.06
2	-0.86	-0.88	-0.76	-0.64	-0.38	-0.16	-0.12	0.00	0.08	0.12
3	-0.76	-0.76	-0.66	-0.58	-0.30	-0.10	0.00	0.12	0.18	0.22
4	-0.72	-0.64	-0.58	-0.32	-0.12	0.00	0.10	0.16	0.30	0.32
5	-0.56	-0.38	-0.30	-0.12	0.00	0.12	0.30	0.38	0.56	0.62
6	-0.30	-0.16	-0.10	0.00	0.12	0.32	0.58	0.64	0.74	0.90
7	-0.18	-0.12	0.00	0.10	0.30	0.58	0.68	0.78	0.76	0.88
8	-0.06	0.00	0.12	0.16	0.38	0.64	0.78	0.88	0.86	0.88
9	0.00	0.08	0.18	0.30	0.56	0.74	0.76	0.86	0.86	0.86
10	0.06	0.12	0.22	0.32	0.62	0.90	0.88	0.88	0.88	0.90

Then, a regulator equation, for previously determined values of indexes *j* and *l*, has the following form

$$u(k) = u(k-1) + K_u u(j,l) \tag{15}$$

In the design of a fuzzy PI controller, experimental selection of the values of coefficients K_e, K_{de} and K_u is of essential importance. They decide about the character of the velocity transient process, including system stability.

Torque control systems with fuzzy regulators are not much sensitive to changes of resistance and inertia moment of motor, but they show higher sensitivity – and after exceeding particular boundary values of changes, even a strong sensitivity – to the motor induction variations. Considering the fact that among the motor parameters, biggest changes of values are in case of resistances (temperature variations of windings), the mentioned properties of this regulator should be considered as positive.

Figure 6 illustrates an example of step response of torque *M* and stator flux amplitude ϕ of regulation system with fuzzy controller (fig. 7). Input of tested system was given the steps of M_z torque values. In this case, practically there should be no regulation error.

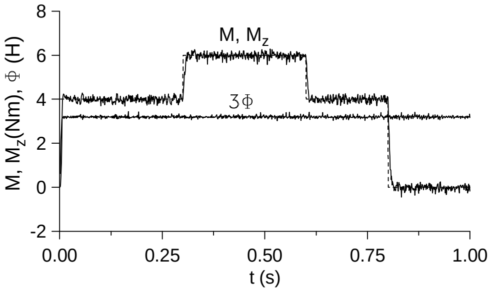

Fig. 7. Time responses of inverter drive to step variations of M_Z torque

In fig. 8, there are time responses of motor torque for M_z = 5 Nm, and the motor was loaded by stepping values of loading torque M_o. Analyzed system does not show any sensitivity to variations of loading moment values.

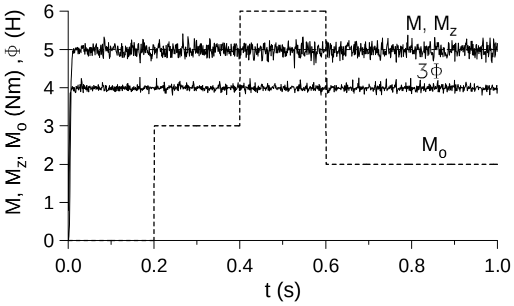

Fig. 8. Time responses of inverter drive loaded by variable value of loading moment M_o

In hydraulic system, proper running of pump often requires at least 600-800 rev/min. Also the electric motor achieves higher values of torque during revolutions close to the nominal value. So, the effective torque or pressure control in hydraulic system can be carried out in conditions in which there is an inflow of fluid. Then, the torque or pressure control can be carried out with a system shown in fig. 9. In this system, to achieve satisfactory quality of regulation it is only required use P type regulator. In this system, constant angular velocity ω_z of motor is kept and it also guarantees proper conditions of pump running.

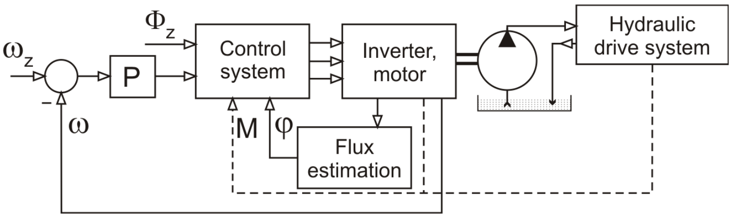

Fig. 9. Control system block diagram

Figures 10 show time responses of the system from fig. 9 with set angular velocity $\omega_z = 100$ rad/s and step function of motor level torque M_o, for the gain coefficient of P type regulator 11,2. Low value of regulator gain coefficient results in considerable change of motor angular velocity, which compensates given torque M_o. To achieve required dynamic and static features of the system, high regulator amplification value should be taken. No problems with system stability was found during tests.

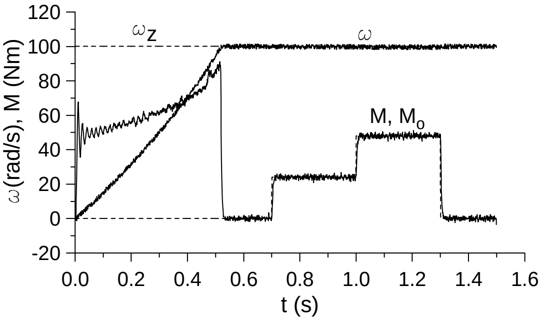

Fig. 10. Time responses of control system from fig. 9

On the basis of structure shown in fig. 2, fig. 3 and fig. 5, various control systems can be configured. And, if instead of torque *M*, the following features will be introduced: pressure, force, velocity or flow rate, the possibility of control and regulation of these values will be achieved. In fig. 11, the example of pump capacity *Q* control (index *z* – set value) in the system presented in fig. 5 was shown.

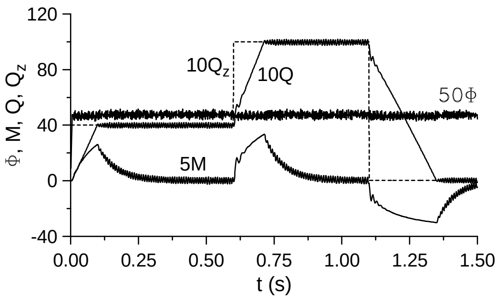

Fig. 11. Time responses of flow control system

4. SUMMARY

In the paper, a problem was presented of torque and flux control of inverter-fed induction motor. System was analyzed in terms of its application in hydraulic supply station drive. As a result of analysis made, it was concluded that application of DTC method provides practically inertialess control of motor torque. Using above method can effectively control of the hydraulic system quantities.

For the torque regulation of inverter drive, the PI type fuzzy regulator was proposed, which synthesis does not require formulation of mathematical model of drive system and its loading. Proposed method of regulator input signal tabulation does not add high amount of calculations in real time. Application of proposed control method requires current information applying to regulated system quantities. Analyzed control system is, in a slight degree, sensitive to changes of motor parameters and load. Proper selection of the value of gain coefficient K_u decides of the quality of torque transient states. Also, to some extent, the shape of the membership function and set value L influence the regulation quality.

5. REFERENCES

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