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OPTIMIZING THE OPERATION OF DC MOTORS IN ELECTRIC DRIVE SYSTEMS

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Abstract: *The article presents the possibility of optimizing the operation of the DC motors by the rejection of the perturbations in different operating regimes. The torque estimator based control system using an Internal Model Control (IMC) structure it is presented in block diagrams and also the conditions the IMC system stability. In the end, the indicial step for a DC motor equipped with the presented torque controller is given. The simulated operation of the system is compared with the experimental results.*

Key words: *control system, IMC system, torque controller, torque estimator.*

1. Introduction

The direct current motor electrical drives are used frequently in industrial applications. Electric drives with DC motors are commonly used in industry and their operation is affected by disturbing couples. Accurate control of the torque when reaching an object requires the detection of transient torque by several sensors, which are also affected by unknown disturbances (such as temperature variation); for example, in the case of a robot, fast and accurate motion control requires compensating torques and parametric variations. The disturbance compensation method does not require knowledge of the nature and magnitude of the disturbances and allows calculation of load variations caused by the unknown object, friction and torque ripple [1].

The method of perturbation compensation allows the compensation of all perturbation torques that disturb direct current motor operation. The estimated perturbation torque includes load variation, torque ripple, friction forces, interaction forces and reactive forces due to the contact with the object. This method implies neither the knowledge of perturbations type nor their magnitude.

2. IMC Controller Based on Torque Estimator

The Internal Model Control (IMC) structure is an alternative to the classic negative reaction structure. Most commonly, these models are used as models with undetermined parameters for identification and/or adaptive control. The Fig. 1a shows

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the IMC system in general case and simplified in Fig. 1b where P is the fixed part, P_m - the transfer function of the transducer (P and P_m are not known exactly, but only their models, $\tilde{P}$ and $\tilde{P}_m$ at nominal values), P_d - the transfer function (evaluates the effect of the disturbance d' on the process output size, y), n - the measurement noise and Q is the regulator that determines the value of the command size, u. In the simplified block scheme, d represents the effect of the disturbance on the system output; when the output of the system is known (P_m = 1, n = 0), the reaction signal has the following form:

$$\tilde{d}(s) = (P - \tilde{P})u(s) + d(s). \tag{1}$$

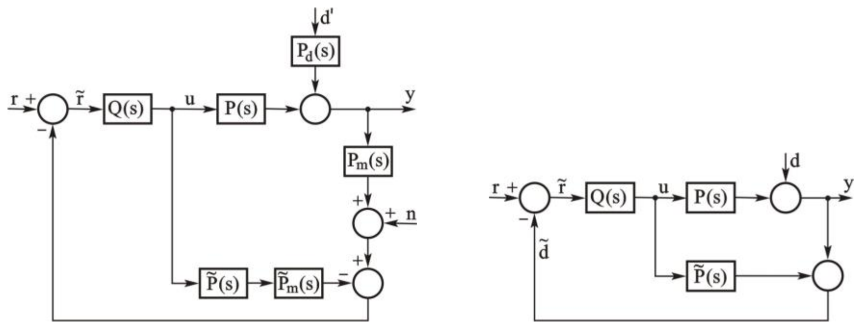


Fig. 1. *IMC system: a) general configuration; b) simplified configuration.*

If the model $\tilde{y}$ is accurate and the system does not cause disturbances (d = 0), the output of the model and the output of the process are equal ($P = \tilde{P}$) and the reaction signal is null.

The system operates in an open loop when there are no uncertainties or no unknown inputs (d); for open-loop stable processes, the negative reaction is imposed either by the existence of uncertainties over the model or by the disturbance. The reaction signal in the case of an imperfect model materializes the influence of the disturbance and the errors due to the modeling. Since the response signal includes the influence of disturbances, the IMC controller can ensure that these influences are canceled.

The fixed part model provides information on the dynamic mode of the process and can be described by a system of partial differential equations, or it can only be highlighted by the amplification factor and the duration of the transient regime. The behavior of the fixed part may change over time, without this event materializing in patterns. For this reason, the controller should not be affected as far as possible by modeling errors (model uncertainties), so it must be robust [2,3].

It was adopt as exogenous signals r, u_1 and u_2 and as output signals y and $\tilde{y}$. Considering that there are no model errors $P = \tilde{P}$, it result the following relation:

$$\begin{bmatrix} y(s) \\ u(s) \\ \tilde{y}(s) \end{bmatrix} = \begin{bmatrix} P(s)Q(s) & (1-P(s)Q(s)) & P(s) \\ Q(s) & -P(s)Q(s) & 0 \\ P(s)Q(s) & -P^2(s)Q(s) & P(s) \end{bmatrix} \cdot \begin{bmatrix} r(s) \\ u_1(s) \\ u_2(s) \end{bmatrix}. \qquad (2)$$

The IMC system is internally stable if the fixed part *P* and the controller Q are stables $(y(s) = P(s)Q(s)r(s))$, Fig. 2. The open loop IMC system is stable only if there are no uncertainties on the model [4,5]. Making the unstable open loop systems stable request a feedback which makes the use of the IMC unfeasible structure.

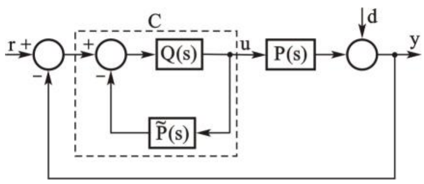


Fig. 2. *Equivalent feedback system block diagram.*

Considering that P and $\tilde{P}$ are grouped in a single block *C*, and that signals *u* and *y* are not affected, it can obtain the transfer function:

$$Q(s) = \frac{C(s)}{1+\tilde{P}(s)C(s)}. \qquad (3)$$

If fixed part *P* is stable and $P = \tilde{P}$, the IMC system is internally stable if transfer function *Q* is stable.

If the model of the fixed part is stable, the design of the controller in order to satisfy the desired closed loop performances is greatly simplified and is also characterized by robustness [6,7]. If the IMC controller is stable, the introduction of a regulator makes the closed loop system stable. When implementing the controller based on an IMC structure, the stability in the closed loop circuit is maintained even at the appearance of limitations and non-linearity.

The command signal $U_r(s) = Q_r(s)r(s)$ is sourced through a compensator designed to ensure the desired dynamic performances for the system. The perturbation is added to the command signal.

The influence of the input signals on the error is described by the following relation:

$$e(s) = \frac{1-\tilde{P}(s)Q_d(s)}{1+Q_d(s)(P(s)-\tilde{P}(s))}d(s) - \left(1 - \frac{P(s)Q_r(s)}{1+Q_d(s)(P(s)-\tilde{P}(s))}\right)r(s), \qquad (4)$$

which, if the model is an exact representation of the controlled system ($P(s) = \tilde{P}(s)$), becomes:

$$e(s) = (1 - P(s)Q_d(s))d(s) - (1 - P(s)Q_r(s))r(s). \quad (5)$$

With a suitable design, $Q_d(s)$ can be used to ensure the perturbation rejection and $Q_r(s)$ to ensure the satisfaction of the imposed performances for the system.

3. Implementation of an IMC Based Torque Estimator

The perturbation torques that influence the operation of a DC motor can be grouped [1] in the following equations:

$$M_r = M_{frc} + M_{int} + M_{ext} + D\omega, \quad (6)$$

$$Js\omega = M - M_r, \quad (7)$$

where M_r-resistant torque, M-motor torque (K_t torque coefficient), M_{frc}-dry friction torque, M_{int}-interactive torque including Coriolis, centrifugal and gravitational torques, M_{ext}-reaction torque when system touches the object, J- total inertia moment reduced to the motor shaft and D-viscosity coefficient.

The variations of inertia and torque coefficient can be emphasized in the following equations:

$$J = J_n + (J - J_n) = J_n + \Delta J, \quad (8)$$

$$K_t = K_{tn} + (K_t - K_{tn}) = K_{tn} - \Delta K_t, \quad (9)$$

where J_n is the total inertia moment reduced to the motor shaft and K_{tn} is the rated torque coefficient.

Based on (6) and (8) has been achieved the (10) which emphasizes the perturbation due to parameter variations.

$$J_n s\omega = K_{tn} I - (M_r + \Delta J s\omega - \Delta K_t I). \quad (10)$$

The perturbation torque can have irregular variations and includes the variation of inertia, friction torque, interactive torque, reactive torque and motor torque ripple:

$$M_p = M_r + \Delta J s\omega - \Delta K_t I = M_{int} + M_{ext} + M_{frc} + (J - J_n)s\omega + (K_{tn} - K_t)I. \quad (11)$$

Direct estimation of acceleration is not easy, therefore we prefer an estimator based on rotation speed. For the block diagram in Fig. 3 corresponding to relation (11), result the following equations:

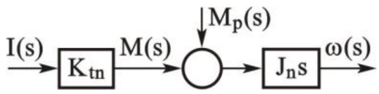


Fig. 3. *Equivalent DC motor block diagram.*

$$x = \begin{bmatrix} M_p \\ \omega \end{bmatrix}, \quad y = \omega, \quad u = I, \quad \dot{x} = \begin{bmatrix} 0 & 0 \\ -\dfrac{1}{J_n} & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \dfrac{K_{tn}}{J_n} \end{bmatrix} u, \quad J = \begin{bmatrix} 0 & 1 \end{bmatrix} x. \tag{12}$$

The perturbation torque is not controllable but is observable thus it possible to develop a minimal order estimator, Fig. 4.

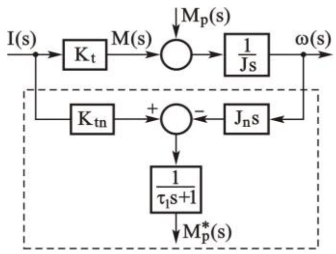


Fig. 4. *Torque estimator block diagram.*

With this estimator we can obtain an acceleration controller using the feedback of the perturbation torque, Fig. 5.

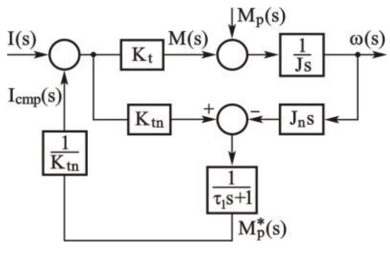


Fig. 5. *Acceleration controller block diagram.*

If in (10) it take into consideration that:

$$I_{cmp}(s) = \frac{1}{K_{tn}} \frac{G_f(s)}{1 - G_f(s)} (K_{tn} I - s\omega J_n), \tag{13}$$

result that:

$$s\omega J_n = K_{tn} I(s) + K_t I_{cmp}(s) - M_p(s), \tag{14}$$

with equivalent expression:

$$s\omega J_n = K_{tn} I(s) - \frac{1-G_f(s)}{1-\left(1-\frac{K_t}{K_{tn}}\right)G_f(s)} M_p(s), \tag{15}$$

where the function:

$$G_p(s) = \frac{1-G_f(s)}{1-\left(1-\frac{K_t}{K_{tn}}\right)G_f(s)}, \tag{16}$$

emphasizes the system robustness to perturbation torque.
The rejection of the perturbation are from $\lim_{s\to 0} G_f(s) = 0$ results also that $\lim_{s\to 0} G_p(s) = 0$.
Filter $G_f(s) = \frac{1}{\tau_1 s + 1}$ has been introduced into the controller structure under the physical feasibility condition and may be substituted by a block of shape $G_f(s) = \frac{sJ^* R^*}{K_t^*}$, whose position in the controller block diagram is indicated in Fig. 6, where, *R* is the rotor resistance, *L* the rotor inductance, K_{ee} the amplification factor of the controlled rectifier and *u* the applied voltage. This control algorithm can be numerically implemented approximating the rotation speed derivative with the derivative calculated on a sampling period. A good approximation is obtained if the sampling period is lower than the time constants of the motor.

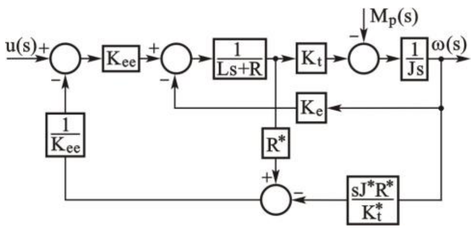
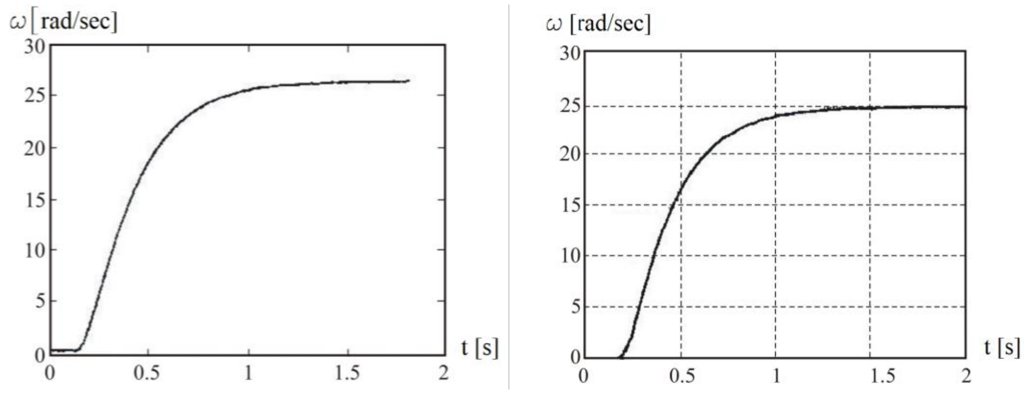


Fig. 6. *Block diagram of the system DC motor with acceleration controller.*

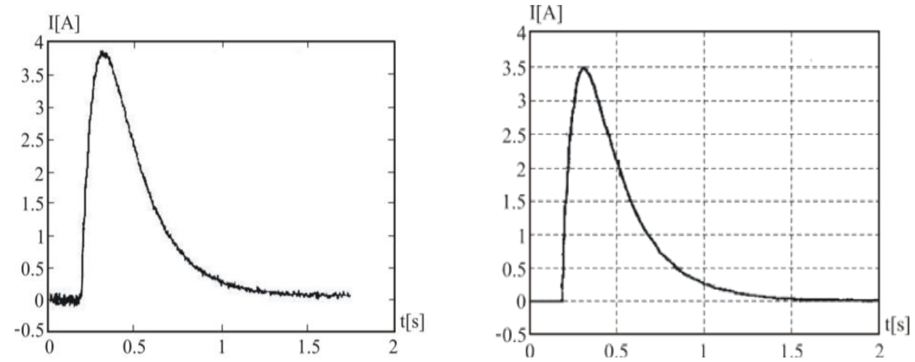
4. Experimental Results

It was used a DC motor with following characteristics: U_n = 110V, P_n = 0.25kW, I_n = 3.3A, ω_n = 1750rot/min, rotor resistance is 3.1Ω and rotor inductance is 0.16H controlled by a controller with torque estimator with block diagram in Fig. 6. Experimental results have been compared with simulated results obtained using the MATLAB software [8]. The experimental and simulated motor indicial responses when using the torque-based estimator are show below. It was observed a good concordance between experimental and simulated results emphasizing the rejection of perturbation torque in Fig. 7 for motor speed, in Fig. 8 for motor current and Fig. 9 for signal control.



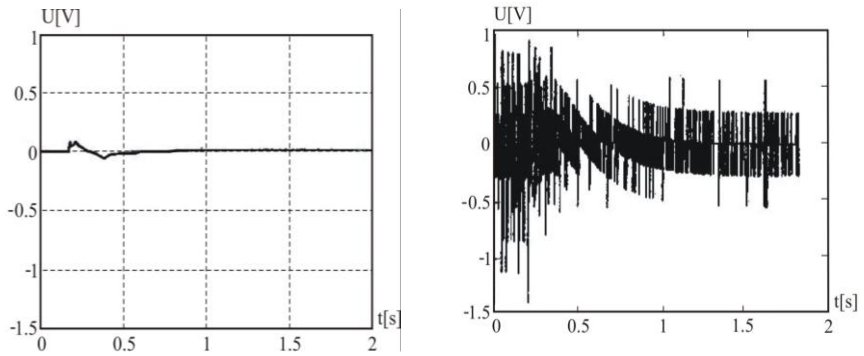
a) b)

Fig. 7. *Motor speed result for the indicial step of the motor with torque estimator: a)experimental; b)simulated.*



a) b)

Fig. 8. *Motor current result for the indicial step of the motor with torque estimator: a)experimental; b)simulated.*



a) b)

Fig. 9. *Signal control result for the indicial step of the motor with torque estimator: a)experimental; b)simulated.*

5. Conclusions

The control method presented in this paper ensures good performances of electric drives with DC motors which are commonly used in industry and are affected by disturbing torques; for example, in the case of a robot, fast and accurate motion control requires compensating torques and parametric variations. The control is robust but can be used only for low frequencies. The use of IMC structure for systems containing integrator elements (mechanical systems, vehicles, etc) needs that the unstable fixed part be supplemented with a local feedback loop. Then, the IMC structure is applied to the closed loop system thus obtained. The uncertainty of the model results from the fact that the controller design is based on a process model $\widetilde{P}$ which is an approximation of the real dynamics of the fixed part P. The imposed characteristics for the answer of the system and the rejection of perturbations can be obtained by introducing another controller block leading to an IMC system with two degrees of liberty.

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