CONTROL OPTIMIZATION OF ELECTROMECHANICAL SYSTEMS BY FRACTIONAL-INTEGRAL CONTROLLERS

Ob'єктом дослідження в роботі є електромеханічні системи, характерною особливістю яких є наявність суттєвої степенної залежності в математичному описі. Через це виникають проблеми при виборі структури та параметрів регуляторів. Зокрема, в двигуні постійного струму з послідовним збудженням, вентильно-реактивному двигуні та електромагнітних гальмах може відбуватися насичення магнітної системи в статичних і динамічних режимах. Заставований в роботі апарат дробово-інтегрального числення дозволяє такі нелінійні об'єкти описати з високою точністю лінійними передавальними функціями дробового порядку. Так, при апроксимації якірного ланцюга двигуна постійного струму передавальною функцією дробового порядку отримано найменшу середньоквадратичну похибку. Комбінація звичайного PID-регулятора з дробовими інтегральними складовими порядку 0,35 та 1,35 забезпечує найкращу якість перехідного процесу – струм досягає заданого значення максимально швидко без перерегулювання. По-друге, вентильно-реактивний двигун, в моделі якого необхідно враховувати степенної залежності, при опиці переходних процесів швидкості при струмі напруги апроксимовано аперіодичною функцією порядку 0,7. За сімейства досліджених регуляторів традиційний PI-регулятор з додатковими дробовими інтегральними складовими порядку 0,7 та 1,7 забезпечив астатизм контуру швидкості порядку 1,7 та найменше перерегулювання. По-третє, електромагнітна гальма ведучих коліс автомобіля, що використовуються для налаштування двигуна внутрішнього згоряння, також після тестування найбільш точно описані передавальною функцією дробового порядку. За допомогою PIDDγ-регулятора, що забезпечує астатизм замкненого контуру порядку 1,63, досягнуто стабілізації швидкості обертання двигуна без протифазних коливань і точне відпрацювання трикутної тахограми. Таким чином, завдяки апарату дробово-інтегрального числення забезпечується більш точна ідентифікація параметрів об'єкта, математичний опис зводиться до лінійних передавальних функцій дробового порядку. В замкнених системах можна забезпечити астатизм дробового порядку 1,3–1,7 та досягти кращої якості перехідних процесів, ніж при використанні класичних методів.

Ключові слова: дробово-інтегральне числення, дробові інтегрально-диференційні регулятори, замкнuta система управління, електромеханічна система.

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The aim of this research is to study the possibility of using the apparatus of fractional integral calculus in electromechanics to optimize transient and steady-state processes. DC motor with series excitation, switched reluctance motor and an induction brake are considered as objects of research.

2. Methods of research

The study of each of the listed objects was carried out according to the generally accepted methodology. Based on the testing of objects by supplying standard signals, identification of model parameters was carried out with the subsequent synthesis of optimal controllers and verification of closed systems. However, at the identification stage, in addition to the generally accepted ones, models are considered that include fractional differential equations. This choice is due to the fact that the apparatus of fractional integral numbering is based on power functions, and in the considered electromechanical objects the magnetization...
curve is also close to the power function. It is precisely this which suggests that controllers with integral and differential components of non-integer order can provide the best dynamic and static indicators of systems.

3. Research results and discussion

Transients significantly differ from solutions of differential equations of the first or second order in DC motor with series excitation at a current in the armature circuit above the rated value [8].

The smallest standard error is provided when using the following mathematical model:

\[
W_{m} = \frac{K}{a_{2}s^{2} + a_{1}s + 1}, \tag{1}
\]

where for the studied motor with a power of 450 W received \( K = 0.193 \) – gain coefficient; \( \mu = 0.35 \) – indicator of the fractional differential equation; \( a_{2} = 0.0062 \), \( a_{1} = 0.127 \) – parameters equivalent to the time constants in degrees \( 1 + \mu \) and \( \mu \), respectively.

Accordingly, to ensure optimum tuning with a given integer or fractional orders of astatism, \( D_{1}P_{1}I\gamma I_{m} - , P_{1}I\gamma I_{m} - , P_{1}I\gamma I_{m} - \) controllers are required.

In the course of experimental studies, the best quality of the transient process was obtained with the \( P_{1}I\gamma I_{m} - \) controller (Fig. 1, a). In this case, the current reaches the reference as quickly as possible and without overshoot.

It turned out that such settings are effective even with reference signals half the maximum, as well as with stepwise change of reference (Fig. 1, b, c). It can be seen that the quality indicators of the system remain unchanged and correspond to the desired settings.

Another electric machine, in the description of which it is necessary to take into account power dependencies, is a switched reluctance motor. To identify a closed speed loop, a fractionally aperiodic transfer function of the following form was also chosen [9]:

\[
W_{m} = \frac{K}{a_{2}s^{3} + a_{1}s + 1}. \tag{2}
\]

The approximation results are illustrated in Fig. 2. As can be seen, at different applied voltages, the nature of the transition process changes, but the use of the fractional transfer function (2) provides the smallest deviation. And this also allows for the synthesis of controllers to abandon the complex motor model described by a system of nonlinear differential equations.

Accordingly, the adjustment of the closed loop is greatly simplified – the modular optimum provides the \( PI\gamma P\) controller, and the fractional order of astatism 1.7 is achieved using the \( PI\gamma P\) controller.

Fig. 3 shows the simulation results of transients in the speed control loop of a switched reluctance motor. In Fig. 3, a, the graphs of transients during the jump of the reference are shown, in Fig. 3, b – with a step change in the reference signal. In all cases, a system with a fractional order of astaticism has the best dynamic characteristics.

A similar approach was used for the synthesis of the electromagnetic retarders control system of the driving wheels of a car on a stand for tuning and measuring the power (torque) of an internal combustion engine (ICE) [10].

According to the experimental data obtained, the control object is approximated with an error of about 1% by the following transfer functions:

\[
W_{m1} = \frac{K}{(a_{1}+1)(a_{2}s + 1)}. \tag{3}
\]

\[
W_{m2}(s) = \frac{K}{a_{2}s^{3} + a_{1}s^{2} + 1}. \tag{4}
\]
Using the transfer function (3), the coefficients for the PID controller were found, and according to (4), two types of fractional-integral controllers were synthesized: DIP, which provides tuning to the modular optimum, and PIDIP, which allows obtaining the fractional astaticism order 1.63.

When conducting experimental studies, transient graphs were obtained with stabilization of the speed of the semi-axles of the car (Fig. 4, a). The PID controller provided the best performance (2.55 s), but with the greatest overshoot $\delta_1=27.6\%$. With the DIP controller, the overshoot was $\delta_2=16.3\%$, and the duration of the transient process was 4.42 s. The smallest overshoot was obtained with the PIDIP controller – $\delta_3=3.3\%$ for a duration of 3.8 s.

An important step in checking the results of engine settings is to measure the power and maximum torque when forming a triangular tachogram.

The results of such a test with the fastest (PID) and most accurate (PIDIP) controllers are shown in Fig. 4, b.

Both controllers provide stabilization of speed in the entire range of power measurement, but less overshoot and oscillation at the beginning of acceleration (the initial sections of transient processes with various controllers are compared in the upper left in Fig. 4, b). This allowed to make the final decision on choosing a control system block diagram in favor of the PIDIP controller.

4. Conclusions

Thus, the use of the fractional integral calculus for three types of nonlinear electromechanical objects, in the
description of which there are power functions, allowed us to obtain the following:

1. A more accurate identification of the parameters at which the smallest discrepancy between the calculated and experimental data is achieved when testing open systems.
2. A simplified mathematical description due to the use of fractional-order linear transfer functions in models.
3. The best dynamic and static indicators, especially when using fractional-integral controllers, providing a fractional (1.5–1.7) order of closed loop astaticism.

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