Combined Optimal Control System for excavator electric drive

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Abstract. The article presents a synthesis of the combined optimal control algorithms of the AC drive rotation mechanism of the excavator. Synthesis of algorithms consists in the regulation of external coordinates - based on the theory of optimal systems and correction of the internal coordinates electric drive using the method "technical optimum". The research shows the advantage of optimal combined control systems for the electric rotary drive over classical systems of subordinate regulation. The paper presents a method for selecting the optimality criterion of coefficients to find the intersection of the range of permissible values of the coordinates of the control object. There is possibility of system settings by choosing the optimality criterion coefficients, which allows one to select the required characteristics of the drive: the dynamic moment (M) and the time of the transient process (t_{pp}). Due to the use of combined optimal control systems, it was possible to significantly reduce the maximum value of the dynamic moment (M) and at the same time - reduce the transient time (t_{pp}).

1. Introduction

Using a broad spectrum of automatic control systems is due to the complexity of control objects of mining industry and the requirement for high performance and control quality. To a large extent, the performance of single bucket excavators is determined by the time of the turning movements. The rotation drive for the excavator, which operates in constant starting and braking modes, is a complex multi-mass electromechanical system and has a high moment of inertia, which must be reliably limited from the existing loads to acceptable values. The introduction of an optimized controlled electric drive of excavators allows solving important tasks - increasing operational reliability and increasing productivity.

Currently, one promising trend improving the quality of regulation is the use of combined control. Additional opportunities for improving control processes provide the application of combined control of the object's operation, consisting in the regulation of external coordinates based on the theory of optimal systems and the consequent correction of the internal coordinates of the electric drive, while the internal coordinate regulators are calculated using the "technical optimum" technique.

In the combined optimal control systems (COCS), it is possible to change the feedback coefficients (the coefficients of the optimality criterion), in contrast to the systems of subordinate regulation. This property of COCS allows us to find the best solution to the problem, that is, to reduce the shocks of the dynamic moments and the time of the transient process, using the positive properties of the systems of subordinate regulation and optimal control systems.

This article presents a synthesis and research of combined optimal control algorithms of the AC drive excavator rotation mechanism.

2. Materials and methods

There are a large number of algorithmic languages in which the solution of a task can be executed. The choice of the programming language depends on many conditions. Often a crucial role is rendered by the convenience of programming, existence of the checked mathematical methods, and simplicity of the representation of the modeling results. MATLAB package has such features containing in the structure of the instrument of visual modeling - SIMULINK.

The initial data for the research and simulation specifications are used in the induction motor of 110 kW and 5AM280s4e mark to simulate the electrical drive. To simulate the mechanical part of the rotary platform drive, the catalog data of the ECG-8I excavator were used.

For the synthesis of control algorithms, the authors used the methods of optimal control of Letov-Kalman, successive correction of Kessler, combined optimal control for solving problems of synthesis of control systems by the electric drive that are used based on the work of V P Kochetkov.

3. Synthesis of combined optimal control algorithms

The basis for the synthesis of AC electric drives with a vector control principle is the mathematical description of an asynchronous motor presented with a current source [1]:

$$\begin{cases} k_R r_R i_{sx} = \dfrac{1}{T_R}\psi_{Rx} + p\cdot\psi_{Rx} - (\omega_1 - p_p\omega)\psi_{Ry}, \\ 0 = \dfrac{1}{T_R}\psi_{Ry} + p\cdot\psi_{Ry} + (\omega_1 - p_p\omega)\psi_{Rx}, \\ M = 1.5 p_p k_R(\psi_{Rx} i_{sy} - \psi_{Ry} i_{sx}), \\ J_\Sigma p\omega = M - M_c. \end{cases} \tag{1}$$

where $k_R = x_m / x_R$; $T_R = x_R / r_R$; x_m, x_R, r_R – coefficients in relative units; p – complex operator; p_p – number of pole pairs of the motor; ψ_{Rx}, ψ_{Ry} – flux linkage axes «x» and «y»; i_{sx}, i_{sy} – stator current along axes «x» and «y»; M, M_c – electromagnetic and static moments; ω, ω_1 – angular rotational speed of the rotor and magnetic field, respectively; J_Σ – total moment of inertia.

The mathematical description of the mechanical part of a two-mass system consists of a system of three first-order differential equations and represents a model of the mechanical part of the control object.

Let us take the single-circuit structure of the regulation of the flux linkage of a rotor (Figure 1). Using the procedure for calculating the system for the technical optimum, let us determine the transfer function of the rotor flux-linkage regulator along the "x" axis, equating the desired and real transfer functions of the open loop of the flux linkage.

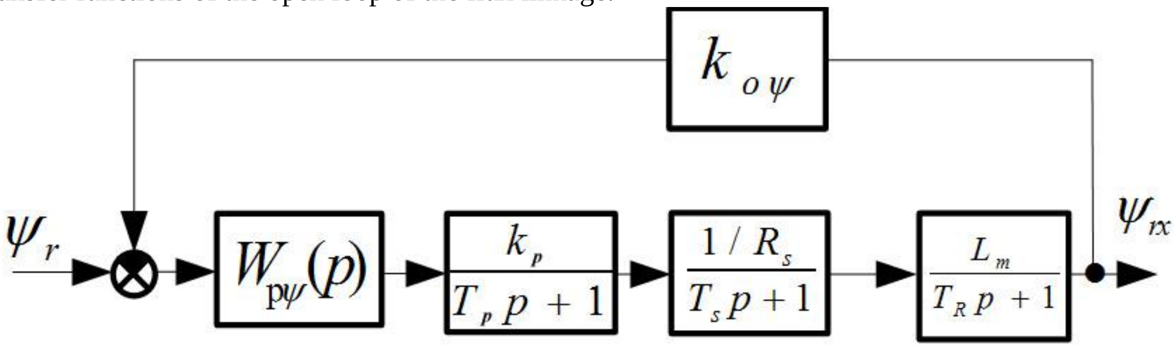

Figure 1. A structural diagram of a single-loop system for the regulated regulation of rotor flux-linkage.

The received transfer function of the flux linkage regulator along the "x" axis has the form:

$$W_{\text{p}\psi}(p)=\frac{(T_s p+1)(T_R p+1)}{2T_\mu \dfrac{k_\text{п}}{R_s} L_m k_{o\psi}\, p}=\frac{T_s+T_R}{T_{\text{i}1}}+\frac{1}{T_{\text{i}1}p}+\frac{T_s T_R}{T_{\text{i}1}}p, \tag{2}$$

where $T_{\text{i}1}=2T_\mu \dfrac{k_\text{п}}{R_s} L_m k_{o\psi}$, $\dfrac{T_s+T_R}{T_\text{i}}$ — proportional; $\dfrac{1}{T_\text{i} p}$ - integral, $\dfrac{T_s T_R}{T_i}p$ — differential parts of the flux regulator.

Thereby to obtain the PID controller, to synthesize the control system, let us consider the electromechanical system as single mass. The authors are neglecting uncompensated time constants in dual-system slave current control and flux linkage in the stator channel "x". The mathematical description of systems of external coordinates is represented in relative units, where the variables are multiplied and divided into their base values:

$$\begin{cases}\dfrac{di^*_{sy}}{dt}=-\dfrac{1}{T_S}i^*_{sy}-\dfrac{k_R}{L'_S}\omega_1^*+\dfrac{1}{L'_S}u^*_{sy},\\ \dfrac{d\omega_1^*}{dt}=\dfrac{3p_\text{п}k_R}{2J_\Sigma}i^*_{sy}\end{cases} \tag{3}$$

Let us multiply and divide all the variables of system (3) by their base values. It is possible to obtain a mathematical description of the control object containing the stator current along the "y" axis, the motor speed and the control action in relative units ($i^*_{sy}=i_{sy}/I_{sб}, \omega^*=\omega/\omega_б, u^*_y=u$) in the following form:

$$\begin{cases}\dfrac{di^*_{sy}}{dt}=-\dfrac{1}{T_S}i^*_{sy}-\dfrac{k_R}{L'_S}\omega_1^*+\dfrac{1}{L'_S}u^*_{sy},\\ \dfrac{d\omega_1^*}{dt}=\dfrac{3p_\text{п}k_R}{2J_\Sigma}i^*_{sy}\end{cases} \tag{4}$$

Let us introduce notations into the system (4):

$$i^*_{sy}=x_1,\ \omega^*=x_2,\ a_{11}=1/T_s,\ a_{12}=k_R\omega_б/L'_S I_б,\ b_k=u_б/L'_S I_б,\ a_{21}=3p_\text{п}k_R I_б/2J_\Sigma\omega_б k_{o\psi_x}.$$

Then, in a formalized form, system (4) is described by a system of equations:

$$\begin{cases}\dot{x}_1=-a_{11}x_1-a_{12}x_2+b_\kappa u_y\\ \dot{x}_2=a^0{}_{21}x_1\end{cases} \tag{5}$$

Let us consider the control object in the form of a single-mass electromechanical system described by the system of equations (5).

In this paper, the authors consider the problem of an analytically constructed optimal regulator. The optimality criterion is selected as minimization of the quadratic deviations of coordinates and feedback control and, accordingly, this system is optimal in the transitional process [2, 3]:

$$J=\frac{1}{2}\int_0^\infty\left(x_1^2+x_2^2+u^2\right)dt, \tag{6}$$

This article synthesizes the structure of an analytically constructed optimal regulator, which is placed in a direct control channel. Let us use the computational procedure of the maximum principle of L. S. Pontryagin [4].

It is possible to compose the Hamiltonian:

$$H=-\frac{1}{2}(x_1^2+x_2^2+u^2)+\psi_1(-a_{11}x_1-a_{12}x_2+b_k u)+\psi_2 a^0_{21}x_1. \tag{7}$$

Equating the derivative of the Hamiltonian control function to zero, let us obtain the optimal control:

$$u^0 = b_k \psi_1. \tag{8}$$

Assuming that the optimal control is negative with respect to the driving force, equation (8) takes the form:

$$u^0 = -b_k \psi_1. \tag{9}$$

Let us take the partial derivatives of the Hamiltonian (7) and make up to the coordinates system of conjugated equations:

$$\begin{cases} \dfrac{d\psi_1}{dt} = -a_{11}\psi_1 + a_{21}^0\psi_2 - x_1, \\ \dfrac{d\psi_2}{dt} = -a_{12}\psi_1 - x_2. \end{cases} \tag{10}$$

On the basis of (9) and (10), it is possible to form the structure of an analytically constructed optimal regulator (ACOR) (Figure 2).

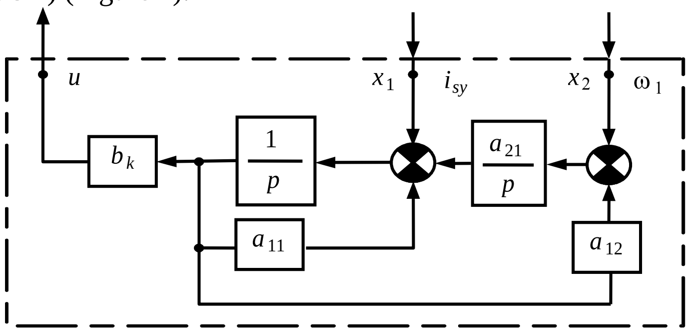

Figure 2. Structural scheme of ACOR in i_{sy} and ω_1

Let us place the ACOR not in the reverse circuit, but in the straight channel for regulating the speed of the motor, while improving the practical implementation of the control system, which is approaching in appearance to the systems of subordinate regulation. The structure of the motor speed control with ACOR in the forward channel can be represented as a two-loop subordinate control system with an internal circuit and an aperiodic stator current regulator along the «y» axis, as well as an external circuit with an integrated motor speed controller and internal feedback from the stator current regulator to the regulator motor speed.

COCS consists of an inner contour of the stator flux linkage "x" axis calculated by the method of the optimum technical and ACOR method in the direct channel for the stator current "y" axis and motor speed.

Thus, the combined optimal control system can be considered as a three-loop subordinate control system with an internal contour of the rotor flux coupling along the "x" axis and a PID controller and a two-loop system of subordinate regulation of external coordinates with a stator current loop along the "y" axis and an aperiodic regulator, and a speed loop with an integrated regulator, and there is an internal feedback from the current controller to the speed controller.

The graph (Figure 3) shows the results of simulation of the electric drive with sequential current correction and stator flux coupling along the "x" axis and optimal regulation of i_{sy} and ω_1. The dependence of the maximum moment rolls (M_{max}) and the time of the transient process (t_{pp}) on the stator current weight coefficient in the "y" channel (i_{sy}) and on the motor speed (ω_1) is observed.

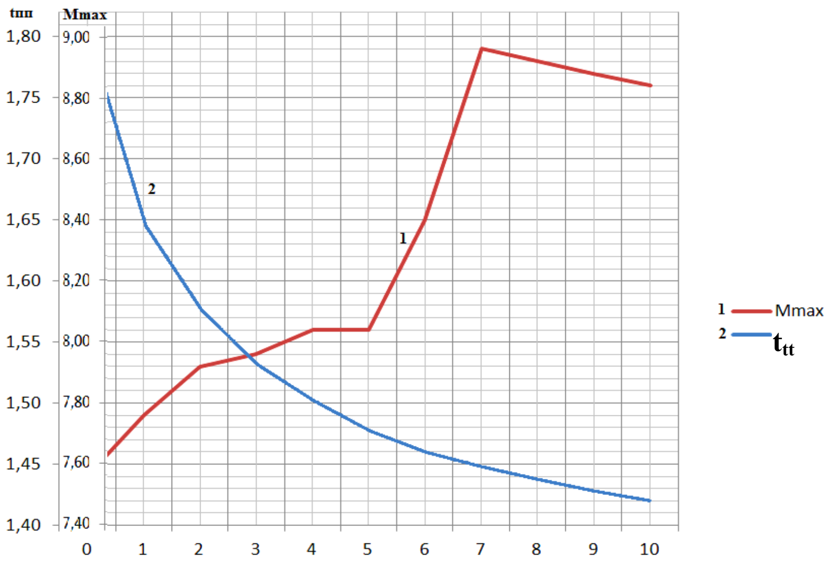

Figure 3. The graph of the dependence of the dynamic moment rolls (M_{max}) and the transient time (t_{tt}) on the motor speed ($K_{\omega 1}$).

As can be seen from the graph (Figure 3), with an increase in the weight coefficient of the motor speed, the maximum dynamic torque spikes decrease, but the transient time increases. By adjusting the value of the weighting factor for the motor speed, one can adjust the system in such a way that it meets the necessary requirements. Thus, it is possible to configure the system for the required parameters of transient processes. With different variations of the stator current weight in the "y" channel, a similar trend is observed.

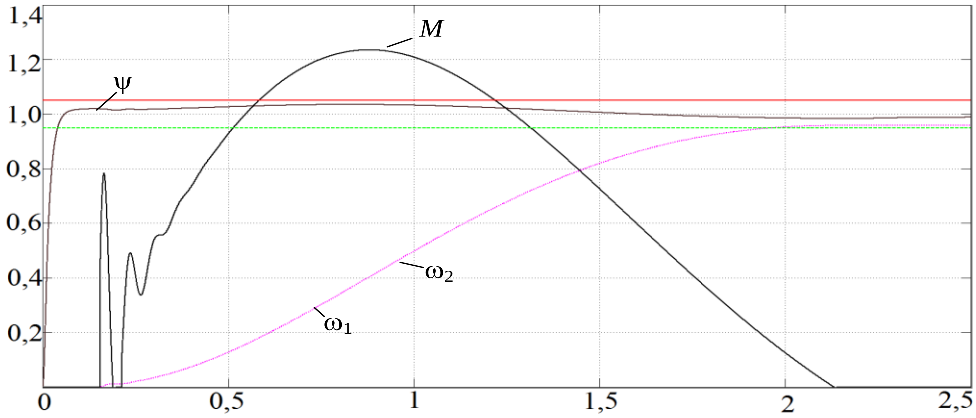

Figure 4. Transient processes of the electric drive with COCS with correction of flux linkage and optimal regulation of i_{sy} and ω_1.

The simulation results, obtained oscillograms (Figure 4) show that there is a significant decrease in the dynamic moment rolls (M) when the motor is started together with the decrease in the transient time (t_{tt}), affects the reliability and productivity of the excavator. An increase in the service life of the excavator, positively affects the increase in the volume of mining of rocks. Using a vector AC drive with COCS allows one to take advantage of asynchronous electric drives while improving the quality of system regulation.

4. Conclusion

The systems considered differ from the classical combined control systems combining control systems by deviation and disturbance. In general, the structure of the analytically constructed optimal regulator is determined by the transposed model of the control object. In the combined optimal control systems, in a particular case, the problem of determining the weight coefficients of the optimality criteria was solved. Due to the use of COCS, it was possible to significantly reduce the maximum value of the dynamic moment rolls (M) and at the same time to reduce the transient time (t_{tt}).

The result of the research showed the advantage of optimal combined electric drive control systems over classical systems of subordinate regulation. The ability to configure the system by choosing the weight coefficients of the criterion of optimality allows one to select the required characteristics of the electric drive: the torque of the dynamics (M) and the time of the transient process (t_{tt}).

The use of an AC drive with COCS has significant advantages over a DC electric drive despite the more complex practical implementation.

The field of application of the research results are mining facilities (excavators, dredges and other mechanisms), the working cycle of which is associated with severe operating conditions.

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