ISSN 1068-3712, Russian Electrical Engineering, 2018, Vol. 89, No. 4, pp. 234–239. © Allerton Press, Inc., 2018.
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The Main Stages of Development of an Electric Drive of a Cold Rolling Mill

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Received March 19, 2018

Abstract—This article discusses selection of variables of electrical power equipment and variables of adjusting feedbacks of a control system of heavy-duty equipment using sequential partial optimization. The stages of the proposed procedure as well as its evaluation are exemplified by electric drive of cold rolling mill. It has been demonstrated that the best effect is achieved at the second stage due to application of elongated motor; herewith, it is possible to decrease inertia by about two times and the total transient time by about 25–30%. Practical design methods of electrical-power equipment of high precision drives can be supplemented by certain stages. This is very important for equipment operating in wide range of loads on the working shaft (more than four to five rated values) and/or that contains elements with mechanical compliance in control channel. By means of appropriate selection of the reduction ratio, it is possible to decrease significantly the influence of resonant maximums, which is necessary if the mechanical part is to meet requirements for quality of adjustment of a sequential correcting device of a conventional subordinate process-control circuit of a metallurgical electric device. The proposed procedure can be successfully applied also in systems with conventional variables for mechanisms operating with frequent starts/brakes. For instance, getting rid of ratios of rotor length to its diameter that are conventional for an asynchronous motor in some cases permits losses to be approximately halved.

Keywords: cold rolling mills, sequential partial optimization, response time
DOI: 10.3103/S1068371218040028

Fabrication of thin and extrathin pipes with a minimum thickness difference is greatly demanded by the nuclear, automotive, and helicopter industries. It is possible to fabricate pipes with extrathin walls and high-quality surfaces using cold rolling mills. In this case, the billet cross section is reduced by 75–85% and the pipe strength is significantly higher than in the case of hot rolling.

This problem cannot be solved by retiring and replacing old equipment. For instance, the response time of control circuits upon high variation of deviation signals at controller inputs cannot be increased by simply increasing the installed-motor capacity, since in this case the permitted acceleration (MH/J) sometimes can decrease and the existing compliances in the control channel in the pipe-supply mechanism can be made up for only by an appropriate complex approach to selection of electric power equipment (a drive system) and mechanical power equipment (a mechanical reducer).

In electric drives of supply mechanisms of cold rolling mills, the precision properties of positioning system can be improved by increasing the response time of the system. Simplified dependence of positioning precision of working body on response time and overcontrol has been discussed elsewhere [1]. The existing system based on a synchronous variable-frequency electric drive provides the following quality parameters evaluate by experimental oscillograms of transient processes (Fig. 1, curves *1–3*): the ultimate response time in the control circuit of the supply-mechanism position did not exceed 0.3 s with a linear-motion precision of 0.1 mm.

The maximum response time can be provided by subsequent partial optimization. The number of segments was selected on the basis of statistical analysis of oscillograms of transient processes at an existing cold rolling mill. Analysis of histograms of transient processes of electric drive (Fig. 1b) demonstrated that five segments are most significant. Hence, the overall time interval of working-body positioning (from 0 to 0.35 s) was approximately subdivided into these segments:

(1) the segment of armature-current increase (Fig. 1a, curve *1*), from zero to 0.125 s;

(2) the acceleration segment, from 0.125 to 0.2 s, when controllers of position and speed were saturated;

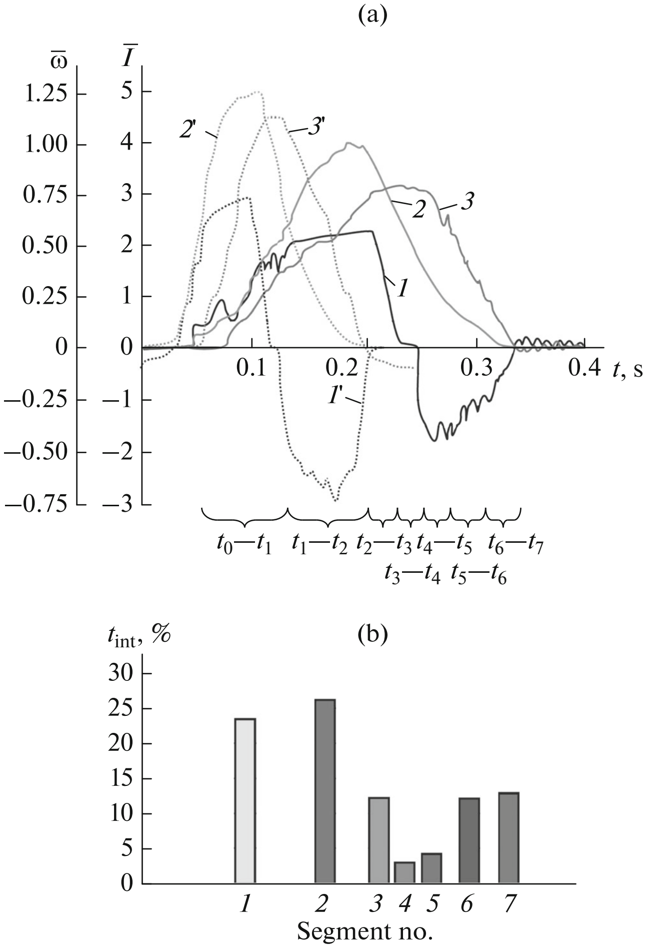

Fig. 1. Curves of transient processes of cold rolling mills: (a) (*1*) armature current, (*2*) preset speed, and (*3*) current speed; (b) histograms of electric-drive load in various segments.

(3) the segment of electric-drive operation at constant speed, from 0.2 to 0.25 s (Fig. 1a, curve *3*), when the speed controller operates in a linear mode;

(4) the segment of electric-drive operation in the generating mode, from 0.25 to 0.3 s; and

(5) the segment from 0.3 to 0.35 s, when the position controller leaves saturation.

For each selected segment, we should formulate a target that is not obligatorily described by conventional mathematical dependence in the form of an analytical expression as in a spreadsheet. Let us solve the problem that has been set out of optimization of multidimensional function as applied to a positioning electric drive assuming a single criterion for each segment: minimum calculated time.

In the first segment of motion, the signal of deviation between the preset position of the working body and the actual signal results in saturation of the controllers of position and speed. A stepwise preset signal is supplied to the position-control circuit. Due to the limited time response of the current-control circuit, the output signal does not vary instantly.

It was suggested that the torque-control circuit had the same time response as the current-control circuit. Figure 2 illustrates an approximation of the torque-control circuit by subsequent connection of units: pure delay with a time constant equal to the scan time, as well as an aperiodic unit of the first order approximately accounting for the inertia of the phase winding of the motor. The validity of such replacement was considered elsewhere [1].

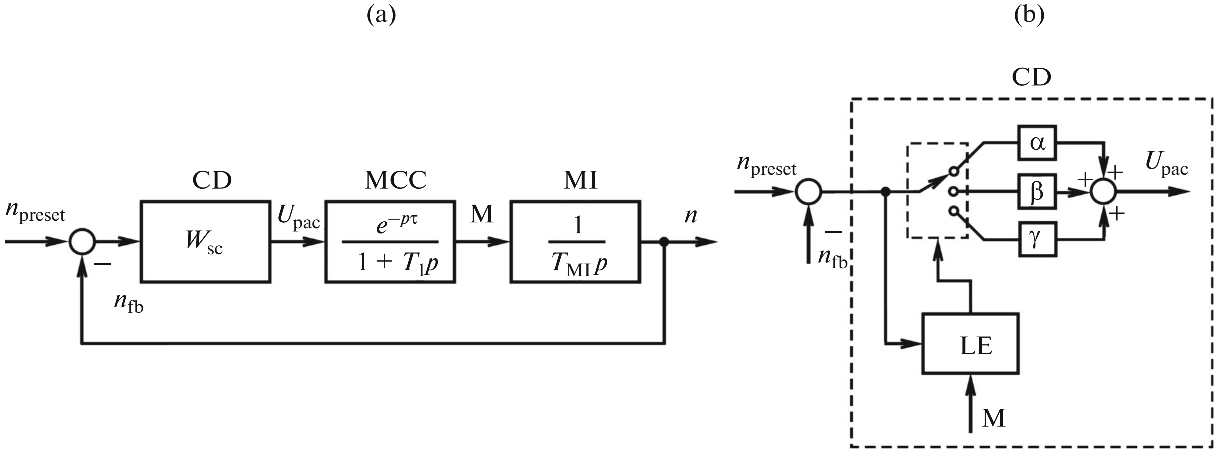

Fig. 2. Optimization of the first segment of motion: (a) schematic view of system; (b) speed controller with variable structure; CD, control device; MCC, electromagnetic-torque control circuit; MI, unit taking into account motor mechanical inertia; LE, logical element; n_{preset}, preset speed; n_{fb}, feedback signal for speed; U_{pac}, preset armature current; W_{sc}, transfer function of speed controller; T_M, motor mechanical consent; T_1, equivalent constant of torque-control circuit; and e^{-pt}, pure delay unit.

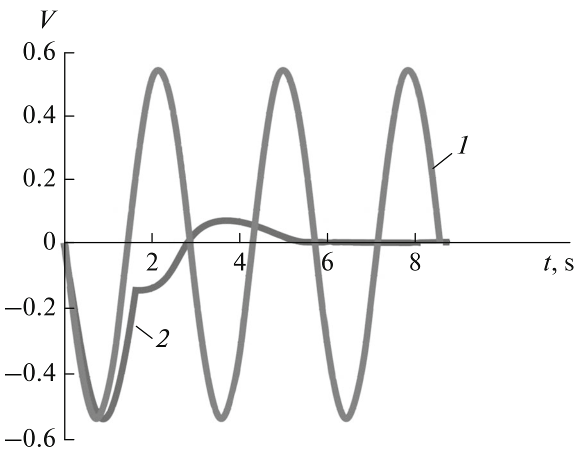

Fig. 3. Transient processes in a current-control circuit: (*1*) before correction; (*2*) with controller of variable structure.

It is known from the classical theory of automatic control that, in a system containing units of pure delay, integrating and aperiodically increasing the circuit transfer coefficient of the following correcting device leads to an unstable operation mode (Fig. 3, curve *1*).

This difficulty can be eliminated by selecting a controller with a variable structure. Figure 2b illustrates the structure of a controller with a transfer coefficient that depends on a linear combination of the error signal and its derivative (electromagnetic torque, in this specific case).

The CD controller has a variable structure: $\alpha > 0$ if the product of error signal and its derivative (M) is higher than zero and $\beta < 0$ when the product of error signal and its derivative is negative, equal to γ at the final stage of transient process.

Figure 3 (curve *2*) illustrates the pattern of the transient process of speed $v(n)$ in an electric drive caused by application of resistance torque. At the first segment ($0 < t < 1.8$ s), the speed controller had coefficient b; at the segment where $1.8 < t < 3$ s, the controller structure was toggled and the transient function was c; and, at the last segment ($t > 3$ s), the speed controller had transfer factor γ. Despite the oscillating pattern of the transient function, the system remained stable. In systems with variable structures, it is impossible to completely compensate the influence of a pure delay, unit but it is possible to expand the range of uniform frequency transmission. Measurements confirmed that the selected correction method increased the time response by about 1.5–2 times.

In the second segment of motion (Fig. 1a), the transient process in the current (torque) control circuit terminates and the electric drive approaches the segment of established dynamic acceleration. It is possible to increase the time response in this segment only by improving the weight and dimensions of the electromechanical converter. The maximum acceleration of the electric drive in this segment was evaluated from the mechanical time constant of the electric motor: the time during which the motor shaft varied its speed from zero to an ideal idle speed, provided that the shaft was influenced by an electromagnetic torque equal to the rated M_R.

The Q factor (M_R/J) of electromechanical converter can be increased only by increase in the ratio of active part of the rotor magnetic drive to its diameter. Variation of this property for conventional electric machines can result in increased shaft deflection, as well as to deterioration of motor cooling. These issues are eliminated in reaction machines with a solid rotor that has no winding and is rigid in the radial direction. The cooling conditions in the motor are more favorable, since the rotor of an electric machine rotates synchronously with the field, has no windings and, hence, is not heated under ideal conditions. In fact, due to losses caused by commutations of stator phase currents, the machine rotor is heated, but the heating can be decreased by varying configuration of the stator slot or by scouring the rotor surface.

Figure 4 illustrates the dependences of the acceleration of electric drive (M_R/J) that is permitted in terms of heating on the rated motor toque and the rotor length as exemplified by an asynchronous motor and synchronous reaction machine. In both cases, an increase in the motor length improved the Q factor. However, in the asynchronous motor, the relative shaft deflection (not more than 10% of air gap) restricts the maximum values of its length and, hence, its acceleration.

In the third segment (Fig. 1), the position controller remained saturated and the speed controller shifted into the linear mode, restricting the maximum speed. In this segment, the optimum value of the maximum speed can be selected in different ways. In the 1930s, it was proposed to select the maximum motor speed on the basis of the minimum kinetic energy of an electromechanical system (motor and working body) [2]; the authors of [3] proposed a precision criterion of searching for an optimum value of the reducer transfer number on the basis of the minimum of the resonant maximum in a dual-mass system due to the increase or decrease of electromechanical feedback depending on the ratio of generalized variables of an electrical-engineering ensemble evaluated on the basis of cutoff frequencies ω_1, ω_2, and ω_3:

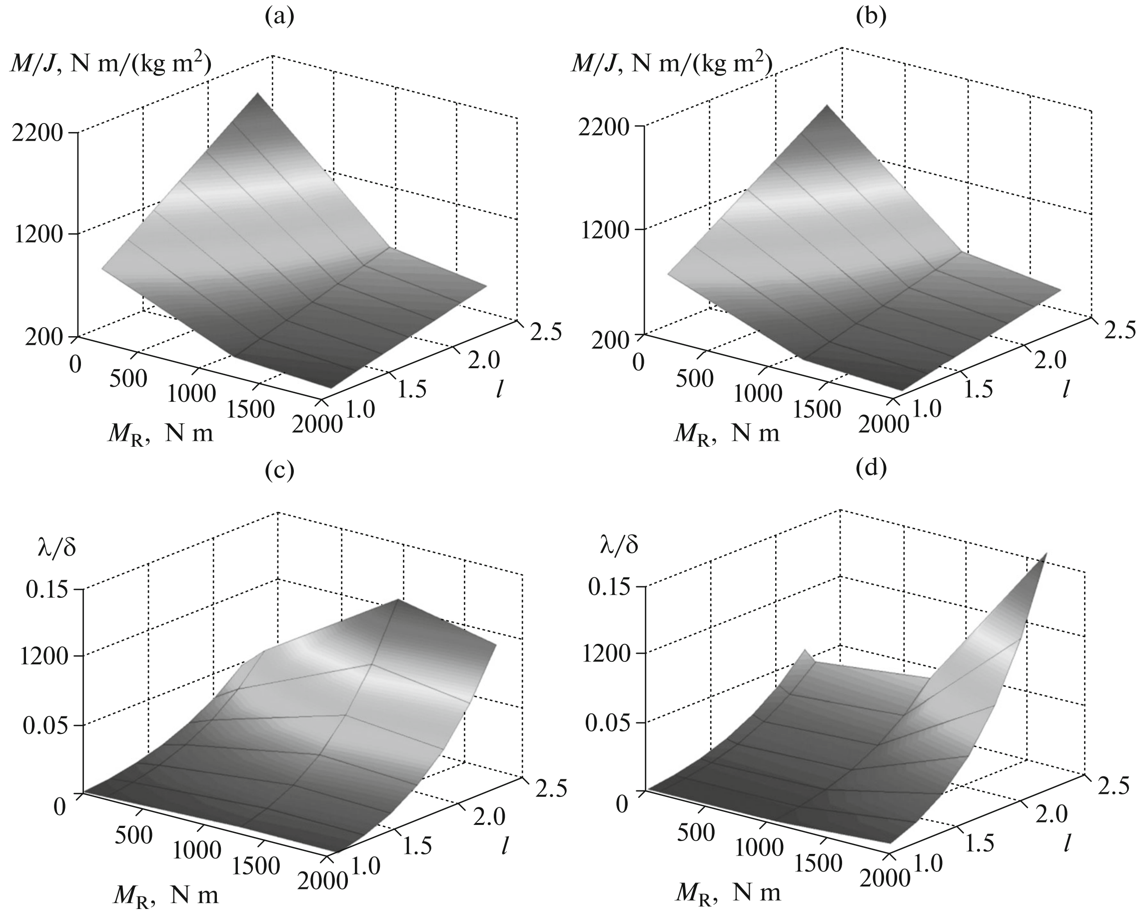

Fig. 4. Optimization of the second segment of motion: (a) M_R/J ratio in an asynchronous motor, (b) M_R/J ratio in a multiphase synchronous-reaction electric drive, (c) shaft deflection in an asynchronous motor, and (d) shaft deflection in a multiphase synchronous-reaction machine.

$$
\begin{gathered}
j_{\text{lim}} = \sqrt{\frac{J_{\text{wb}}}{k_{\text{cm}}k_{\text{sc}}k_{\text{mc}}}\frac{1}{T_{\text{eu}}}};\\
T_{\text{cm}} = \frac{J_{\text{wb}}}{k_{\text{cm}}k_{\text{sc}}k_{\text{mc}}j^2};\\
T_{\text{eu}} = \frac{J_{\text{wb}}}{C_1} = \frac{1}{\omega_2};\\
T_{\text{csc}} = \frac{J_{\text{m}}}{k_{\text{cm}}k_{\text{sc}}k_{\text{mc}}} = \frac{1}{\omega_1};\\
\omega_1 = \begin{cases} \dfrac{\omega_2^2}{\omega_1}, \text{ if } \omega_2 < \dfrac{1}{T_{\text{sc}}};\\ \dfrac{\omega_2^2}{\omega_1^2}, \text{ if } \omega_2 > \dfrac{1}{T_{\text{sc}}}; \end{cases}\\
\omega_1 = \frac{1}{T_{\text{cm}}},
\end{gathered}
\tag{1}
$$

where ω_1 is the cutoff frequency of the motor-speed controller, ω_2 is the frequency of a circuit permitting the existence of an elastic unit with torsional rigidity C_1, ω_3 is the frequency of circuit accounting for the existence of electromechanical influence of elastic oscillations on the operation of the speed-controller circuit, k_{cm} is the transfer factor of the torque-control circuit, J is the reducer transfer number, J_{wb} and J_{m} are the inertia torques of the working body and motor, and k_{sc} is the transfer coefficient of the speed controller.

Equation (1) determines the boundary value of the reducer transfer number. At the stage of selection of the electromechanical converter, an algorithm can be recommended that has the main stages illustrated in Fig. 5. If current value of the reducer transfer number is lower than the boundary value, that is, cutoff frequency ω_1 is highest and in circuit *3* (ω_3) it is lowest, then the reducer transfer number is calculated on the basis of minimum kinetic energy. Otherwise, it would be more convenient to select reasonable variables of power equipment using the procedure in [1].

During operation of the positioning electric drive on the fifth segment (Fig. 1), all the sequential adjusting devices (controllers of speed and position) were in the linear mode. In this case, when selecting the opti-

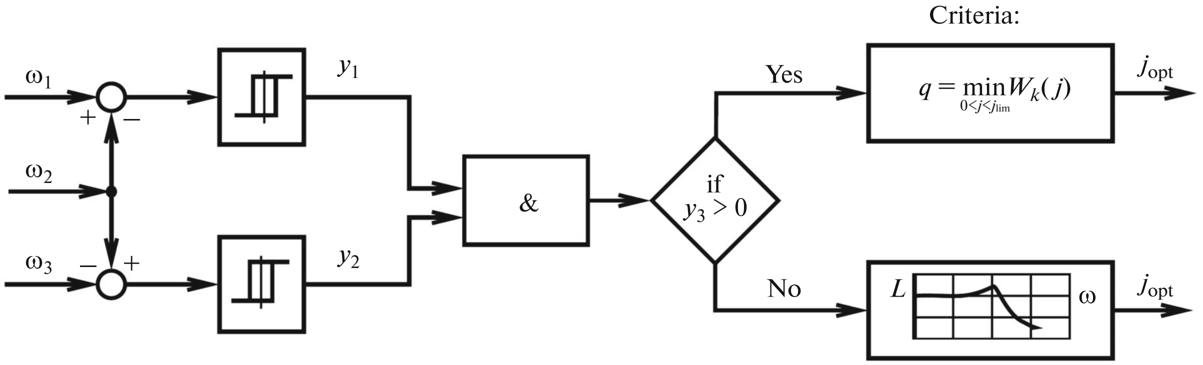

Fig. 5. Optimization of the third segment of motion: selection of maximum speed.

mum structure and variables of the sequential adjusting device of a position controller, it is necessary to take into account that, by providing minor stability of a system with sufficient reserve, it is possible to achieve unstable operation of an electric drive at high deviation signals of preset and actual value of adjustable variables.

When selecting the variables of a position controller, it is necessary to take into account that significant overloads with regard to torque are allowed in a multiphase synchronous reaction electric drive, which allows one to increase the preset values in the limiting unit of a speed controller and, thus, to expand the range of linear operation of the electric-drive control system. It should be taken into account that the operation time in the overload area is limited by heating and depends on the method of cooling the electric machine [4]. If, after the design of an electric drive in terms of heating, the motor does not satisfy the preset load schedule, it is recommended to consider liquid cooling of the motor, since the selection of an electric machine of higher installed capacity can lead to higher dynamic loads and, thus, will not be able to solve the issue of overheating of an electric machine.

Figure 1 shows curves *1'–3'* of transient processes obtained for an experimental electric drive. The variables of power equipment and correcting feedbacks of control-system units were selected according to the developed procedure.

In the first segment of the transient process, the response time in the torque controller is reached using a sequential correcting device with variable structure and shifting from thyristor sources to transistor ones. The existence of gaps in mechanical transmission prevented an increase in the time response of current controller by more than by two times.

In the second segment, due to the elongated motor, is was possible to decrease the inertia torque by about two times, but the overall time of transient process decreased by about 25–30%. This is, first, related with the fact that the fraction of the inertia torque of the motor was 30–40% of cumulative inertia torque of the electric drive–working body and second, with the fact that the acceleration segment was expanded due to an increase in the operating speed of the electric drive.

In the third segment, the required transfer number was calculated from the minimum kinetic energy, which required minor correction of j. The motor speed increased by about 1.5 times. In the existing power-circuit layout, maximum motor speed was limited by the allowable carrier frequency of the thyristor converter according to the terms of the Nyquist theorem and was equal to 25 Hz. Modern frequency converters operating at carrier frequency in the range from 2 to 16 kHz provide a steady output frequency four times higher than do direct frequency converters. Taking into account the applied correction, the optimum speed plot approached a triangular shape.

The required braking intensity was achieved on the basis of an active rectifier that did not have any apparent additional engineering advantages over a thyristor frequency converter, but, due to an increase in the time response in the speed-controller circuit by 1.5 times, the lengths of segments *3* and *5* (Fig. 1b) decreased by 30% and segment *4* was absent, since the speed plot changed its trapezoidal shape to triangular.

In the last segment, the time response of the position controller was increased by about 60% due to the use of a nonlinear position controller and by increasing the preset value of a limiting unit. It was deemed that the maximum values of electromagnetic torque (up to 4 M_R) were achieved in an electric drive.

The engineering work that was carried out made it possible to decrease the total positioning time of the working body (segments *1–7*, Fig. 1b) by about two times. It needs to be noted that, in Fig. 1a, there is no precise interrelation between the curves of the electromagnetic torque and speed as is required by the main equation of electric-drive motion. This can be attributed to an uneven load schedule, which initially, upon separation of the pipe from the mandrel, requires a higher resistance torque.

CONCLUSIONS

(1) The existing methods of designing power electric equipment of high-precision drives can be supplemented using certain stages. This is especially important for equipment operating in a wide range of loads on the working shaft and/or containing elements with mechanical compliance in the control channel.

(2) The proposed procedure can also be applied in systems with conventional variables for mechanisms operating with frequent starts or brakes. For instance, eliminating the ratios of rotor length to diameter that are conventional for asynchronous motors in some cases allows losses to be approximately halved.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of the Russian Federation, grant no. 13.9662.2017/VR.

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Translated by I. Moshkin