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An Algorithm for Estimating the Stable Operation Conditions of the Synchronous Motor of the Ore Mill Electric Drive

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Abstract**—**An algorithm for estimating the stable operation conditions of the synchronous motor of the ore mill electric drive is proposed. The stable operation conditions of the synchronous motor are revealed, taking into account the estimation of the θ angle change and the technological factors. The stability condition obtained allows to ensure the stable operation of the motor in the synchronous mode, taking into account the nonlinear character of the mill loading. The developed algorithm gives an opportunity to present the undesirable phenomena, arising in the electric drive system. The obtained stability condition can be successfully applied for the optimal control of the electromechanical system of the mill.

Keywords**—**Electric drive, synchronous motor, ore mill, stability, technological factors.

I. Introduction

THE investigation of the ore mill operation modes shows that the low reliability of its electric drive system is conditioned by the fact that at maintaining the electric drive synchronous motor, besides the regular synchronous mode, can appear in a short-term asynchronous mode as well. The latter differs from the regular mode in which the motor operates in a slip different from zero in a certain time interval [1].

The short-term asynchronous mode can be:

- Maintenance – in case of an asynchronous start-up of the synchronous motor,
- Emergency – in case of different situations arising in the system, in particular, when the motor comes out of the synchronous mode conditioned by a decrease in the motor power supply, as well as by an increase in the resistance moment of the mill.

The issues on investigating and ensuring the stable operation conditions of the synchronous motor have been considered in a number of scientific works [2]-[4]. It is impossible to apply the known investigations to study the irregular modes of the ore mill electric drive synchronous motor, and to ensure the stable operation of the motor. This can be explained by the fact that conditioned by the peculiarities of the grinding technological process, the mechanical characteristics of the electric drive motor and the mill are nonlinear. Based on the fact mentioned above, a necessity has arisen to reveal the stable operation conditions of the synchronous motor of the ore mill electric drive which is the main goal of the work.

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II. The Statement of the Problem

The investigation of the synchronous motor operation in the ore mill electromechanical system shows that it can occur in different modes conditioned by the nonlinear characteristics of the resistance moment generated by the mill. The change of the θ angle of the mill electric drive synchronous motor in case of different values of the load moment, and the power supply of the network (Figs. 1 and 2) has been studied. As it can be seen, in case of an increase in the load moment and a decrease in the net voltage, the amplitude value of the θ angle increases. This fact confirms the importance of considering the θ angle to ensure the normal operation of the electric drive system.

It is well-known that it is possible to ensure the stable operation of the synchronous motor when the operating point, corresponding to the resistance moment is on the $M= f(\theta)$ rising part of the synchronous motor angular characteristics.

The introduced analysis shows that the provision of the synchronous motor stable operation modes is possible by estimating the θ angle change, while the known investigation of estimating the change in the θ angle [5], [6] cannot distinctly determine the stable operation conditions of the motor ensuring the mill electric drive.

The goal of the present work is to develop an algorithm for estimating the stable operation conditions of the synchronous motor of the ore mill electric drive by considering the technological factors.

III. An Algorithm for Estimating the Stable Operation Conditions of the Synchronous Motor

To determine the motor stability condition, the differential equation, characterizing the dependence of the motor and the mill mechanical characteristics is used:

$$T_m \frac{ds}{dt} + M\sin\theta + M_{as} = M_a \tag{1}$$

where T_m is the inertia constant; s - the slip; θ - the phase shift angle between the main electromotive force and the network voltage vectors; M_a - the resistance moment of the mill; M - the synchronous moment of the motor; M_{ac} - the asynchronous component of the synchronous motor moment which is determined [6]:

$$M_{ac} = \frac{2M_K(\omega_c - \omega_d)}{s_K \omega_c} \tag{2}$$

where ω_c is the synchronous angular velocity of the motor; ω_d - the rotation angular velocity of the motor shaft; M_K – the critical moment; s_K - the critical slip.

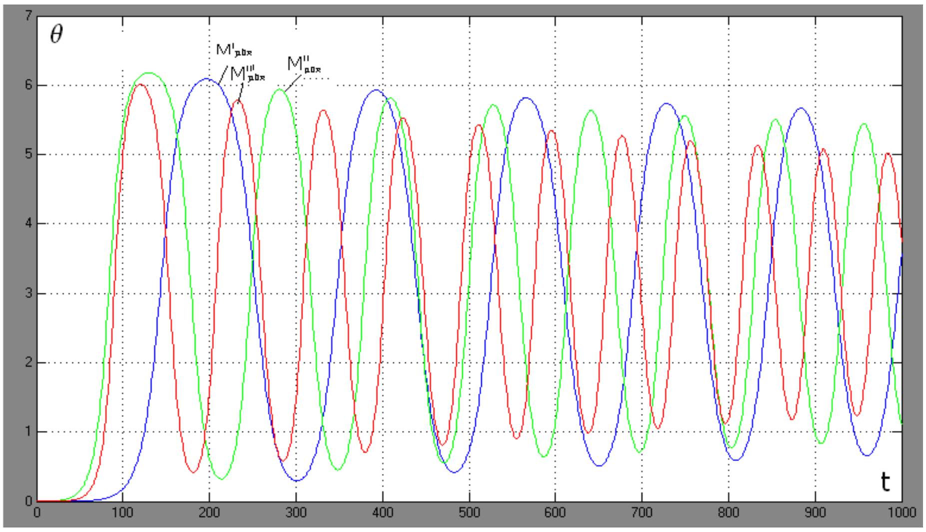

Fig. 1 The change of the θ angle of the mill electric drive synchronous motor in case of different values of the load moment ($M'_a > M''_a > M'''_a$)

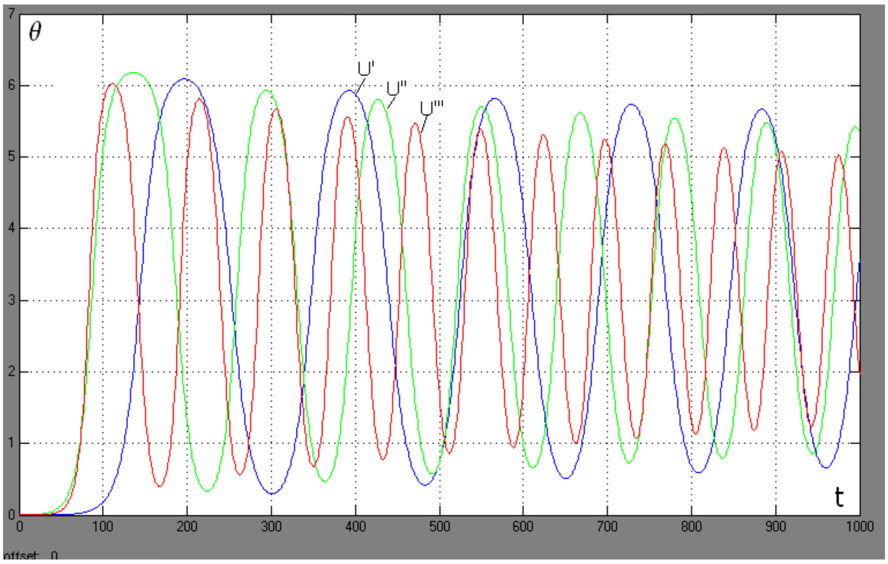

Fig. 2 The change of the θ angle of the synchronous motor in case of the supply net oscillations ($U'<U''<U''$)

The introduced value of the mill resistance moment is determined in the following way:

$$M_a = \frac{1000V\gamma g\left(f\sqrt{\ell_x^{\,2} + \ell_z^{\,2}} + \ell_y\right)}{0{,}105\omega_d\eta_m\eta_d} \tag{3}$$

where γ – is the specific density of the ground material; g – the free fall acceleration; V – the volume of the intramill load, f – the friction coefficient; η_m - the transfer efficiency from the motor shaft to the mill drum; η_d - the motor efficiency; ℓ_x, ℓ_y, ℓ_z , - the distances of the gravity center from the x, y, z axes respectively.

By placing (2) and (3) into (1), as well as considering that in case of $S=0$, the θ angle of the motor is constant, and that the slip is relative to the $d\theta/dt$ change [3], and that the bigger is the S slip, the more quickly the θ angle changes, we obtain the following differential equation:

$$\frac{d^2\theta}{dt^2}=\frac{1}{T_m}\left[\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)\frac{d\theta}{dt}+M\sin\theta-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right] \quad (4)$$

where,

$$K_K=\frac{2M_K}{s_K},\ L=f\sqrt{\ell_x^{\ 2}+\ell_z^{\ 2}}+\ell_y$$

By applying the Maclaurin series to the third member introduced in the right part of (4), we will obtain a differential equation which will give an opportunity to determine the synchronous motor's stable operation condition [8]:

$$\frac{d^2\theta}{dt^2}+a_1\frac{d\theta}{dt}+a_2\theta=0 \quad (5)$$

where,

$$a_1=\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right),\qquad a_2=\frac{M}{T_m}$$

Substituting $\theta=e^{kx}$, we will obtain the characteristic equation:

$$k^2+a_1k+a_2=0 \quad (6)$$

Let us denote the roots of the characteristic equation (6) by k_1 and k_2. The stability or instability of the solution of (5) is determined by the character of the k_1 and k_2 roots:

$$k_{1,2}=-\frac{a_1}{2}\pm\sqrt{\frac{a_1^{\ 2}}{4}-a_2}$$

The system stability will be ensured if all the coefficients of k are positive, while the roots are either real negative or complex with a negative real part [7].

Let us consider all the possible cases. Regardless of the roots of the characteristic equation, it is necessary that all its coefficients should be positive, and therefore, let us consider the a_1 and a_2 coefficients.

$a_2>0$ always takes place; however, in case of $a_1>0$, it is necessary that the following condition should be fulfilled:

$$\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)>0 \quad (7)$$

Let us discuss the k_1 and k_2 roots determined by the θ angle ensuring the stability of the characteristic (6).

The following cases have been considered:

Case 1. The characteristic equation roots are real and negative. It will occur if the equation parameters satisfy the following conditions [8]:

$$\begin{cases}a_1^2-4a_2>0\\ a_1>0\\ a_2>0\end{cases} \quad (8)$$

Equation (8) makes sense in the case when the product of the characteristic equation roots is positive, while the sum – negative.

$$\begin{cases}k_1k_2>0\\ k_1+k_2<0\end{cases} \quad (9)$$

By placing the values of the characteristic equation roots in (9), we will obtain:

$$\begin{cases}\left[\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)\right]^2-\frac{4M}{T_m}\geq 0\\ \frac{M}{T_m}<0\\ -\frac{1}{T_m}\left(K_K-\frac{1000V\gamma g\left(f\sqrt{\ell_x^{\ 2}+\ell_z^{\ 2}}+\ell_y\right)}{0{,}105\omega_d\eta_m\eta_d}\right)<0\end{cases} \quad (10)$$

By making some transformations, we will obtain:

$$\begin{cases}\left[\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)-2\sqrt{\frac{M}{T_m}}\right]\left[\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)+2\sqrt{\frac{M}{T_m}}\right]\geq 0\\ \frac{M}{T_m}<0\\ \frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)>0\end{cases}$$

Case 2. The roots of the characteristic (6) are complex with the negative real part, $k_1=x_1+jy_1$, $k_2=x_2+jy_2$. This is possible if the characteristic equation parameters satisfy the following conditions:

$$\begin{cases}\left[\frac{1}{T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)\right]^2-\frac{4M}{T_m}>0\\ \mathrm{Re}\left[-\frac{1}{2T_m}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)\right]\pm\sqrt{\frac{1}{4T_m^{\ 2}}\left(K_K-\frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)^2-\frac{M}{T_m}}<0\end{cases}$$

by denoting,

$$\sqrt{\frac{1}{4T_m^2}\left(K_K - \frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right)^2 \pm \frac{M}{T_m}} = x + jy$$

let us consider the possible cases of root k_1 when,

$$k_1 = -\frac{a_1}{2} + \sqrt{\frac{a_1^2}{4} - a_2} = x_1 + jy_1$$

Let us make transformations:

$$\left(-\frac{a_1}{2} + \sqrt{\frac{a_1^2}{4} - a_2}\right)^2 = (x_1 + jy_1)^2$$

$$\frac{a_1^2}{4} + \frac{a_1^2}{4} - a_2 - 2\frac{a_1}{2}\sqrt{\frac{a_1^2}{4} - a_2} = x_1^2 - y_1^2 - 2jx_1y_1$$

$$\frac{a_1^2}{4} - a_2 + y_1^2 = \left(x_1 + \frac{a_1}{2}\right)^2 + 2j\left(x_1 + \frac{a_1}{2}\right)y_1$$

The possible cases for the real and false parts of the root are discussed below:

$$\left(x_1 + \frac{a_1}{2}\right) = 0, \quad y_1 \neq 0 \quad \begin{cases} x_1 = -\dfrac{a_1}{2} \\ y_1^2 = -\dfrac{a_1^2}{4} + a_2 \end{cases},$$

$$y_1 = 0, \qquad \frac{a_1^2}{4} - a_2 = \left(x_1 + \frac{a_1}{2}\right)^2$$

Let us discuss the possible cases when,

$$k_2 = -\frac{a_1}{2} - \sqrt{\frac{a_1^2}{4} - a_2}$$

$$-\frac{a_1}{2} - \sqrt{\frac{a_1^2}{4} - a_2} = x_2 + jy_2$$

$$\left(-\frac{a_1}{2} - \sqrt{\frac{a_1^2}{4} - a_2}\right)^2 = (x_2 + jy_2)^2$$

$$\frac{a_1^2}{4} - a_2 = \left(x_2 + \frac{a_1}{2}\right)^2 - y_2^2 + 2j\left(x_2 + \frac{a_2}{2}\right)y_2$$

$$\left(x_2 + \frac{a_1}{2}\right) = 0, \quad y_2 \neq 0 \quad \begin{cases} x_2 = -\dfrac{a_1}{2} \\ -y_2^2 = \dfrac{a_1^2}{4} - a_2 \end{cases},$$

$$y_2 = 0, \ \frac{a_1^2}{4} - a_2 = \left(x_2 + \frac{a_1}{2}\right)^2$$

by grouping the conditions obtained for the k_1 and k_2 roots, we will obtain:

$$\begin{cases} x_1x_2 = \left(-\dfrac{a_1}{2}\right)^2 > 0 \\ x_1 + x_2 = -2\dfrac{a_1}{2} < 0 \end{cases} \text{or,} \begin{cases} \dfrac{a_1}{4} > 0 \\ a_1 > 0 \end{cases} \tag{11}$$

In case of complex roots, we obtain the following conditions:

$$\frac{1}{T_m}\left(K_K - \frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right) > 0$$

In the result of grouping all the possible cases, we obtain the following condition, ensuring the stable operation of the synchronous motor:

$$\frac{1}{T_m}\left(K_K - \frac{1000V\gamma gL}{0{,}105\omega_d\eta_m\eta_d}\right) > 0 \tag{12}$$

In case of satisfying condition (12), the change of the θ angle will ensure the regular operation of the motor in the synchronous mode.

IV. Conclusions

In the result of the investigations carried out, the stable operation condition of the synchronous motor in the ore mill electric drive system has been revealed. The obtained stability condition allows to ensure the stable operation of the motor in the synchronous mode taking into account the nonlinear character of the mill loading and the impact of the technological factors.

The developed model can be successfully applied to prevent the undesirable phenomena arising in the electric drive system. The stabilization condition obtained can be successfully applied in the optimal control system of the mill electric drive electromechanical system, thus favoring the optimization of the maintenance conditions of the system.

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