Dynamic Stability of the Valve Electric Drive in Oscillatory Mode

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Abstract. The analysis results of the dynamic stability of the electric drive in oscillatory mode by means of the supply voltage phase modulation have been provided. The determining procedure of oscillatory electromagnetic torque and its starting and damping components, as well as of motion law for the motor operating element subject to inertial, damping and positional load has been developed and tested. It was shown that the valve electric drive dynamic stability in oscillatory mode can be estimated from the time behaviour of the torque angle under the dynamic transition to the static stable mode. The natural frequency-regulating algorithm of the electric drive has been determined, operating by regulating one of the phase-to-earth voltages, as well as a pull-in criterion operating under the variation of load parameters by the start of the electric drive on the specified oscillatory frequency. A chain diagram of electric drive in oscillatory mode with variable rest frequency has been contributed. The obtained research results can be recommended for use in engineering of low-frequency electromechanical oscillatory complexes in control and vibration test systems.

1. Introduction
Design and development of gearless electric drives in angular oscillatory mode for various purposes are considered to be among the most important tasks, the solution of which enables to meet the increasing requirements imposed on different sectors of the national economy [1–3]. It is enough to note that the oscillatory motion is widely used in mechanical engineering [4–5], chemical and textile industry [6, 7], geology [8] in measurement methods and control engineering [9–10]. As a rule, electric drives in oscillatory mode must provide angular harmonic oscillation or harmonic oscillation with shift of neutral in a frequency range from $10^{-2}$ to $10^2$ Hz and amplitude from $10^{-1}$ to $10^3$ radian [11].

In the research papers [11,12] it was shown that the most prospective design of such electric drives, ensuring modulating control of frequency, amplitude and neutral in technological cycle operation, is one based on an asynchronous and doubly-fed electric machine, running directly in a forced oscillation mode by means of various supply voltage and currents modulations. However, the energy characteristics of such electric drives are low because of the operating motors running in nominal condition with phase currents equal to short-circuit currents. The latter leads to significant overheating of the operating motors and requires developing an additional cooling system.

In contrast with asynchronous and doubly-fed electric machines, permanent magnet synchronous motors running in forced oscillation mode let operate in the steady quasi-synchronous mode with nominal current value. It provides higher energy data. However, the availability of its natural synchronizing torque can cause the loss of dynamic stability of a system as a whole by the sudden
load-on, load-off, self-oscillation or short circuit. All these processes have explicitly dynamic character and require additional investigations.

The aim of the research is to solve the following tasks: to provide dynamic stability of a valve electric drive in oscillatory mode by supply voltage phase modulation; to determine the pull-in criterion and the resonance mode maintenance algorithm operating by adjustment of oscillation frequency.

2. Mathematical model of valve electric drive

The electromechanical and mechanical processes in dynamic and static modes of permanent magnet synchronous motor (PMSM) have been described with the system of equations on its windings circuits and with the electromechanical energy conversion equation, which expresses oscillatory electromagnetic torque as a function of its electrical parameters, supply and load [13]

\[
\begin{align*}
U_d &= i_d R_s + L_d \frac{di_d}{dt} - \omega L_q i_q, \\
U_q &= i_q R_s + L_q \frac{di_q}{dt} + \omega L_p i_d + \omega \Psi_m, \\
M_{\text{elect}} &= p \frac{m}{2} \left[ i_q \Psi_m + i_d i_q (L_d - L_q) \right] = M_{\text{load}} \left\{ \omega_m \frac{dr}{dt}, \omega_m, \frac{d\omega_m}{dt} \right\}, \\
\frac{1}{p} \frac{d\omega_m}{dt} &= \frac{1}{J} \left( M_{\text{elect}} - M_{\text{load}} \right), \frac{d\chi}{dt} = \omega_m.
\end{align*}
\]

where \( U_d, U_p, i_d, i_q \) are voltages and currents in phase windings of PMSM, \( R_s \) is an active resistance of stator winding, \( L_d, L_q \) are longitudinal and transverse inductances of motor windings, \( \Psi_m \) is the maximum magnetic linkage of stator winding with rotor flux, \( \omega, \omega_m \) – electrical and mechanical rates of change of the operating element generalized coordinate, \( \chi \) is a generalized coordinate of the drive operating element, \( M_{\text{elect}}, M_{\text{load}} \) are oscillatory electromagnetic moment and generalized load moment, \( p \) is a number of pole pairs, \( m \) is a number of motor phases.

Subject to control function

\[
\begin{align*}
U_d(t) &= U_1 = \text{const}, \\
U_q(t) &= U_2 \sin(\Omega t + \alpha),
\end{align*}
\]

where \( U_1, U_2 \) are amplitudes of motor windings phase voltage; \( \Omega, \alpha \) is an oscillation frequency and initial phase of supply voltage, the first two equation of the system (1) let us determine the expressions for the motor phase current

\[
\begin{align*}
i_d(t) &= U_2 \left[ N_2 \cos(\Omega t + \alpha) + N_6 \sin(\Omega t + \alpha) \right] + U_1 N_3 + N_4, \\
i_q(t) &= U_2 \left[ N_5 \sin(\Omega t + \alpha) + N_6 \cos(\Omega t + \alpha) \right] - U_1 N_7 - N_8,
\end{align*}
\]

where the values of the coefficients \( N_1 - N_8 \) depending on motor parameters, oscillation frequency and velocity of driving element, are presented in the table 1.

| \( \text{№} \) | Design factors |
|----------------|----------------|
| \( N_1 \)   | \( \frac{\omega L_q (\omega^2 L_d L_q + R_s^2 - \Omega^2 L_q L_q)}{(\omega^2 L_d L_q + R_s^2 - \Omega^2 L_d L_q)^2 + \Omega^2 R_s^2 (L_d + L_q)} \) |

Table 1. Coefficients for phase currents calculation.
\[
N_2 \frac{- \omega L_d \Omega R_s (L_d + L_q)}{\left(\omega^2 L_d L_q + R_s^2 - \Omega^2 L_d L_q\right)^2 + \Omega^2 R_s^2 (L_d + L_q)} \\
N_3 R_s \left(\omega^2 L_d L_q + R_s^2\right)^{-1} \\
N_4 - \omega^2 L_d \Psi_m (\omega^2 L_d L_q + R_s^2)^{-1} \\
N_5 \left(\omega^2 L_d L_q + R_s^2 - \Omega^2 L_d L_q\right) + L_d \Omega^2 R_s (L_d + L_q) \\
N_6 \left(\omega^2 L_d L_q + R_s^2 - \Omega^2 L_d L_q\right)^2 + \Omega^2 R_s^2 (L_d + L_q) \\
N_7 L_d \omega^2 L_d L_q + R_s^2 \\
N_8 \omega R_s \Psi_m (\omega^2 L_d L_q + R_s^2)^{-1}
\]

The expressions (1) subject to (2) let us calculate the oscillatory electromagnetic moment, which is developing with PMSM in oscillatory mode and its starting \(M_{\text{start}}\) and damping \(M_{\text{damp}}\) components as

\[
M_{\text{start}} = \frac{m}{2} \left[ \psi_m \left| i_q \right|_{\omega=0} + (L_d - L_q) \left| i_d \right|_{\omega=0} \right] = \left(U_2 d_1 + U_2 d_2 \right) \left[ s_1 \sin(\Omega t + \alpha) + \Omega s_2 \cos(\Omega t + \alpha) \right], \\
M_{\text{damp}} = \omega \frac{m}{2} \left[ \psi_m \frac{di_q}{d\omega} \left|_{\omega=0} + (L_d - L_q) \left( i_q \frac{di_q}{d\omega} \left|_{\omega=0} + i_d \frac{di_d}{d\omega} \left|_{\omega=0} \right) \right) \right] = \omega \left[ - U_1 k_3 + U_1 k_1 - k_2 + U_2 \left[ k_4 - k_3 \cos(2(\Omega t + \alpha)) - k_5 \sin(2(\Omega t + \alpha)) \right] \right].
\]

Provided that generalized load on the electric drive shaft is the whole set of inertial \(L_{\text{mech}}\), positional \(C_{\text{mech}}\) and damping \(R_{\text{mech}}\) forces,

\[
M_{\text{load}} = L_{\text{mech}} \frac{d^2 \chi}{dt^2} + R_{\text{mech}} \frac{d\chi}{dt} + C_{\text{mech}} \chi,
\]

the amplitude and the phase of fundamental harmonic component of motion law for the PMSM operating element in oscillatory mode can be calculated as following

\[
\chi_m = M_{\text{start,m}} \left[ \Omega (R_{\text{mech}} - f_{\text{damp}})(1 + Z_{\text{mech}}^2(\Omega))^2 \right]; \ \psi_1 = \Psi - \arctg(Z_{\text{mech}}(\Omega))^{-1},
\]

where \(f_{\text{damp}} = U_2 k_1 - U_1 k_2 + U_2 k_4 - k_2\) is a permanent component of PMSM electromagnetic damping coefficient; \(Z_{\text{mech}}(\Omega) = (C_{\text{mech}} - L_{\text{mech}} \Omega^2)(\Omega R_{\text{mech}})^{-1}\) is a generalized load coefficient; \(M_{\text{start,m}}\) \(\Psi_1\) is an amplitude and initial phase of starting moment, are determined with the following expressions:

\[
M_{\text{start,m}} = \eta \left( s_1^2 + (s_2 \Omega)^2 \right)^{1/2}; \ \Psi_1 = \alpha + \arctg \left[ k_1 \left( s_2 \Omega \right)^{-1} \right]; \ \xi = U_2 d_1 + U_1 d_2.
\]

The obtained expressions (3, 4) are the basis for the analysis of the valve electric drive dynamic stability in oscillatory mode and for the estimation of its frequency responses.
3. Valve electric drive dynamic stability in oscillatory mode

The estimation of the valve electric drive dynamic stability in oscillatory mode aims to determine the finite, rated disturbances values, under which the system restores the steady quasi-synchronous oscillatory mode [14].

While investigating of dynamic stability we will consider the mechanical transient processes only subject to the PMSM static mechanical responses. In this case, we can judge the process dynamics from the time behaviour of the torque angle under the dynamic transition to the static stable mode.

For the reason that the electromagnetic torque has a periodic nature when there is a phase modulation of supply voltages, it is extremely difficult to use definition of torque angle given in [15], as a difference between the oscillatory electromagnetic force phases and the operating element speed of the valve electric drive. Therefore, it has been suggested to express the torque angle for oscillatory mode by means of the phase mismatch between the instantaneous phase of the magnetic linkage resultant vector and the secondary element speed, as following:

\[ \delta(t) = \phi_0(t) - \psi(t) + \pi / 2, \]

where the current value of initial phase of magnetic linkage resultant vector \( \phi_0(t) \) is calculated for each temporal value through the coefficients, which are determined with operating motor parameters in accordance with the methods [16].

The figure 1 shows the calculation results, which show the variation laws of the operating motor drive coordinate \( \chi(t) \) and the torque angle \( \delta(t) \) for the dynamically unstable mode of slow-speed two-winding PMSM DBM 185-6-0,2-2 by the start on oscillatory frequency \( \Omega = 0,09 \) relative units. As the variable parameters the inertial and damping load components have been considered, which are expressed with relative units out of their basic values corresponding to the dynamic stable mode.

**Figure 1.** (a) the drive operating element motion law; (b) the behaviour of the torque angle law by double load components increase \( L_{\text{mech}}, R_{\text{mech}} \)

Based on the results of the researches conducted, the loss of dynamic stability by the inertial masses increase is shown as the constant shift of the dynamic oscillation neutral. Though, the behavior of the torque angle (curved lines 2) has a quasi-periodical character, and the motor operating element motion law \( \chi(t) \) is changing from the harmonic to the saw-tooth.

The constant shift of the dynamic neutral will lead to the phase mismatch between the electromagnetic fields of primary and secondary PMSM elements, and, as consequence, to the total motor resynchronization.

The damping load effect is shown as being inadequate to the inertial component. The safe operating area of the valve electric drive is restricted by its both increase and decrease (curved lines 1). However, if in the first case the rate of torque angle rise is sufficiently low, so in the second one the speed can reach a large amount through the low mechanical damping. Besides this, another effect of the low mechanical damping are the auto-oscillations, which modulation can make 45% from the amount of statically steady load angle value.
It is determined that the implementation of positional load \((C_{\text{mech}})\) definitely improves the motor dynamic stability: the balancing of the oscillation neutral dynamic shift is achieved and as consequence the form of motion law is improved. It should be noted that the implementation of positional load allows generating a resonance mode, ensuring the high values of power indicators.

The research results have shown that during the first half-period of vibration frequency engine firing in oscillatory mode can withstand significant overload, exceeding its steady-state stability limit. It happens due to the availability of aperiodic current components over initial period. The analogous conclusions have been drawn in the research papers [15, 17] in studies of synchronous machines run-up with unit-directional motion.

One of the important issues by motor run-up in oscillatory mode is its pull-in. This condition is usually characterized with the input moment equal to the maximal resistant torque on the shaft, by which the motor runs up to synchronous speed, being operated from the electric mains with rated current and frequency. However, such approach is not completely proper for the periodic mode of PMSM, because the frequency of one of the power supplies is a variable value, which determines eventually the motor oscillation frequency. The load, in its turn, depends not only on the inertial moment of the vibrating masses, but also includes the damping and positional components. Thereby, when considering the pull-in criterion and providing dynamic stability, it has been suggested to express the pull-in torque for oscillatory mode through the generalized load coefficient \(Z_{\text{mech}}(\Omega)\) as following:

\[
M_{\text{entr}} = \chi_{\text{ entr}} \left[1 + Z_{\text{mech}}(\Omega)\right]^{1/2} \cdot \sin\left[\Omega t + \psi_1 + \arctg\left(Z_{\text{mech}}(\Omega)\right)^{-1}\right].
\]

To develop the pull-in criterion we present the expression for oscillatory electromagnetic effort by the in-phase interaction between the electromagnetic fields and the first harmonic component of the motion law as following:

\[
M_{\text{elect}}(t) = M_{\text{start}} \sin(\Omega t + \Psi) + \int_{t_0}^{t} f_{\text{damp}} \omega + M_{\text{posit}} \omega \, dt,
\]

where \(M_{\text{posit}}\) is a positional moment component of PMSM, generated through interaction of magnetic rotor flux and constant voltage of stator winding \(U_d\). Then, restricted by the first harmonic component of the moment, the task to determine the pull-in criterion is reduced to solution of the following equation:

\[
\omega + M_{\text{posit}}(f_{\text{damp}})^{-1} \int_0^t \omega \, dt = \left[M_{\text{entr}} \sin(\Omega t + \psi_1 + \arctg(Z_{\text{mech}}(\Omega))^{-1})\right](f_{\text{damp}})^{-1} - M_{\text{start}} \sin(\Omega t + \Psi),
\]

where the amplitude of the pull-in torque \(M_{\text{entr}} = \chi_{\text{ entr}} \left[1 + Z_{\text{mech}}(\Omega)\right]^{1/2}\).

Considering the fact that \(\Psi = \psi_1 + \arctg(Z_{\text{mech}}(\Omega))^{-1}\), after integrating the initial expression by parts the equation’s solution can be following:

\[
\omega = -M_{\text{posit}}(f_{\text{damp}})^{-1} \left[\omega_0 + \Omega f_{\text{damp}}(M_{\text{entr}} - M_{\text{start}})(M_{\text{posit}}^2 + \Omega^2 f_{\text{damp}}^2)^{-1}\right] \cdot \exp(-M_{\text{posit}}(f_{\text{damp}})^{-1} t) + \\
+ \Omega(M_{\text{entr}} - M_{\text{start}})(M_{\text{posit}}^2 + \Omega^2 f_{\text{damp}}^2)^{-1/2} \cdot \cos(\Omega t + \Psi - \arctg(\Omega f_{\text{damp}}(M_{\text{posit}})^{-1}) + \omega_0 \right),
\]

where \(\omega_0\) is a value of the operating motor drive coordinate at the moment of time \(t = 0\).

The obtained equation allows determining, with \(t \to \infty\), the extreme minimum speed, which PMSM must produce by periodic motion, operating in asynchronous mode on stated load, so that to achieve the quasi-synchronous operating mode under the effect of synchronizing forces. Thus, the pull-in criterion in run-up \((t \to \infty)\) can finally be expressed as following:

\[
\omega \geq \Omega(M_{\text{entr}} - M_{\text{start}})(M_{\text{posit}}^2 + \Omega^2 f_{\text{damp}}^2)^{-1/2}.
\]

From whence the extreme maximum value of the pull-in torque, under which the motor can maintain dynamic stability

\[
M_{\text{entr}} = \omega_0 \Omega^{-1}(M_{\text{posit}}^2 + \Omega^2 f_{\text{damp}}^2)^{-1/2} + M_{\text{start}}.
\]

The obtained expressions can be useful for the analysis of dynamic stability in conditions of a sudden load-on or load-off. According to [14], dynamic behaviour of an oscillating system depends on the moment of disturbance imposition. So, if the load-on occurs at the moment of the time, when \(\omega_0 = 0\) (the operating motor drive coordinate passes over the zero value), the machine has greater stability margin, than at the moment of the time, when the coordinate \(\omega_0\) has maximum value. The reason for
that is the fact, that in the first case, the operating motor element speed has the maximum value and the stored kinetic energy is sufficient for additional load compensation. While in the second case – the PMSM speed tends to zero and the machine is becoming more sensitive to changing of the pull-in torque. However, in both cases the maximum torque angle offset occurs in the first half-period after disturbance.

4. Natural frequency control of the valve electric drive in oscillatory mode

One of the ways to increase the dynamic stability of the valve electric drive in oscillatory mode is to provide a resonant mode of its operation. This is achieved either by introducing a positional load into the oscillatory system in the form of mechanical, hydraulic or pneumatic spring linkages [18], or by introducing the components proportional to the fictitious stiffness of the system into the control voltage, thus, creating a force, proportional to the displacement of the oscillating neutral and directed towards the driving force [19]. This leads to the compensation of the dynamic displacement of the oscillating neutral and, consequently, the form of the motion law is improved. In addition, the formation and maintenance of the resonance mode in a given range of oscillation frequencies under conditions of changing the feedback depth and, accordingly, the frequency of natural oscillations allow providing high values of energy indicators of the electric drive as a whole.

It has been established that for the valve electric drive in oscillatory mode the maintenance of the resonant mode can be carried out by regulation of its own synchronizing moment with by varying the voltage amplitude of one of the phases [20]. The availability of its natural synchronizing torque in PMSM allows ensuring maintenance of energy-optimal resonance mode under adjustment of oscillation frequency through the amplitude variation of one of the phase voltages.

To determine the algorithm of the electric drive natural frequency control we use the expressions (3, 4), under which the amplitude of the first harmonic component of the motion law subject to the periodic components of damping torque can be realized as following:

\[
\chi_{ml} = \frac{(U_2d_1 + U_2U_4d_2)}{\Omega^2(R_{mech} - U_1k_1 - U_2^2k_3 - k_2 + U_2^2k_4 + J_0(\chi_{ml}))(1 + Z_{mech}(\Omega)^2)^{1/2}},
\]

where \(J_0(\chi_{ml})\) are the Bessel function of the first kind.

Then, calculating the first derivative from \(\chi_{ml}\) by the voltage \(U_1\) and equating it with zero, we determine the condition for the provision of maximum oscillation amplitude value under the frequency variation \(\Omega\):

\[
\frac{d\chi_{ml}}{dU_1} = \frac{\left[R_{mech} - U_1k_1 - U_2^2k_3 - k_2 + U_2^2k_4 + J_0(\chi_{ml})\right]}{\Omega^2(1 + Z_{mech}(\Omega)^2)^{1/2}} \times \frac{U_2d_1 + U_1U_4d_2}{R_{mech} - U_1k_1 - U_2^2k_3 - k_2 + U_2^2k_4 + J_0(\chi_{ml})} = 0.
\]

From whence the algorithm to maintain the oscillatory valve electric drive in resonance mode under adjustment of oscillation frequency will be:

\[
U_1(\Omega) = \frac{\xi \cdot \left[\delta_1^2 + (\Omega s_2)^2\right]^{1/2} \left[1 + Z_{mech}(\Omega)^2\right]^{1/2}}{\Omega^2}.
\]

(5)

On the other hand, as already noted, the maintenance of PMSM in resonance mode can be achieved through the introduction of position feedback [22]. In this case, the regulating functions can be written as

\[
\begin{align*}
U_4(t) &= U_4 = \text{const}, \\
U_3(t) &= U_3 \sin(\Omega t + \alpha) + k_{feed} \cdot \text{sign} \chi,
\end{align*}
\]

where \(k_{feed}\) is a position feedback coefficient of PMSM moving element.

Expanding the expression for sign \(\chi\) in the Fourier series according to the oscillation frequency we get
ric drive operating element in position feedback mode, as well as the

\[ \text{sign } \chi = \frac{1}{2\pi} \sum_{i=0}^{\infty} \sin \left( \frac{(2i-1)\Omega t + \psi_i}{2i-1} \right), \]

where \( i \) is the set of natural numbers; then, taking (6) into account, we substitute it in the system of equations (1) after some mathematical transformations, we obtain expressions for the components of the electromagnetic moment of the PMSM:

\[
f_{\text{damp, feed}} = \frac{m}{2} \sum_{s=1}^{m} \frac{U_2 \Psi_m (2L_d - L_q)}{L_d - L_q} + \frac{U_2^2 I_d R_s (L_d - L_q)}{2(R_s^2 - \Omega^2 L_d L_q)^2 + \Omega^2 R_s^2 (L_d + L_q)^2} + \frac{4k_{\text{feed}} L_r R_s (L_d - L_q) (R_s^2 + \Omega^2 L_d^2) (R_s^2 + \Omega^2 L_q^2)}{[L_d^2 - \Omega^2 L_d L_q]^2 + \Omega^2 R_s^2 (L_d + L_q)^2} \left( \frac{2k_{\text{feed}} + \pi U_2}{\pi^2} \right),
\]

\[
M_{\text{start, feed}} = \frac{m}{2} \sum_{s=1}^{m} \frac{U_2 \Psi_m + U_1 (L_d - L_q)}{L_d - L_q} \left( \frac{\Omega^2 L_d^2}{L_d^2 - \Omega^2 L_d L_q} \right) \xi_1(t) + \frac{2k_{\text{feed}} L_r R_s (L_d - L_q) (R_s^2 + \Omega^2 L_d^2) \xi_2(t)}{[L_d^2 - \Omega^2 L_d L_q]^2 + \Omega^2 R_s^2 (L_d + L_q)^2}
\]

where \( \xi_1(t) = R_s \sin(\Omega t + \alpha) - \Omega L_q \cos(\Omega t + \alpha); \)

\[ \xi_2(t) = R_s \sin \left[ i(\Omega t + \psi_1) \right] - i \Omega L_q \cos \left[ i(\Omega t + \psi_1) \right] \]

The motion law of the electric drive operating element in position feedback mode, as well as the maximum value of the input torque at which the PMSM retains its dynamic stability, are determined according to (4), taking into account the expressions for the starting and damping moments.

The Fig. 2 presents the functional diagram of the valve electric drive in oscillatory mode, which shows implementation of the electromechanical system natural frequency control by adjustment of one of the phase voltages according to the algorithm (5) or with a negative feedback.

**Figure 2.** The functional diagram of the electric drive in oscillatory mode with natural frequency control
In the diagram you can see: driving oscillator (OS), rectifier with the low-pass filter (FIL), function generator (FG), frequency demodulator (FD), summator (SM), selectors (SA1, SA2), relay amplifier (VA), voltage changer (VC), voltage inverter (VI) and position sensor (PS).

In the first case, the selectors SA1, SA2 are respectively in positions 2 and 2. Meanwhile, the sinusoidal frequency voltage \( \Omega \) transfers from the driving oscillator to the frequency demodulator, which controls by means of the function generator in accordance with the introduced algorithm (5). The voltage, incoming from the function generator, increases through the voltage changer and feeds one of the PMSM phase windings. The second motor winding is connected directly through the voltage inverter with the driving oscillator. In order to ensure the minimum distortions and high values of energy indicators, the voltage changer is implemented with the power transistor switch with the control system, which regulates the balance of the required and stored energy [22, 23]. Thus, when adjusting the driving oscillator frequency, the voltage \( U_d \) is changed, ensuring the resonance mode of the valve electric drive in the specified frequency oscillation range.

Figure 3 shows the amplitude-frequency characteristics of the drive operating element in a two-phase PMSM DBM–6–0,2–2, obtained from simulation in the Matlab / Simulink software environment with and without application of the algorithm (5), which provides control of the electric drive natural frequency.

![Figure 3](image)

**Figure 3.** Amplitude-frequency characteristics without (curve line 1) and with (curve line 2) the algorithm of the natural frequency control.

The analysis shows that in the second case (curve 2), the oscillations amplitude of the operating drive element is increased by 48%. Meanwhile the speed and the oscillatory electromagnetic force increase. That consequently leads to an increase of the maximum input torque, thereby increasing the dynamic stability of the drive as a whole.

With the introduction of position feedback the selectors SA1, SA2 are set in positions 1 and 1. In this case, the voltages of the form (6) power windings of the PMSM. Because of the interaction of the voltages \( U_1 \) and \( U_2 \sin(\Omega t + \alpha) \) in the PMSM air gap, an oscillating electromagnetic field is formed, and through the interactions between \( U_1 \) and \( k_{\text{feed}} \) sign \( \chi \) a positional electromagnetic force is created. By changing the transmission coefficient of the amplifier (VA) the value of the positional electromagnetic force is controlled, putting the system in the resonant mode for a given frequency \( \Omega \).

The Figure 4 shows the amplitude-frequency characteristics of the electric drive for different values of the position feedback depth \( k_{\text{feed}} \) for a PMSM with the parameters presented in the table 2 [24].
Table 2. Parameters of PMSM.

| Parameters of motor | $R_s$ | $L_d$ | $L_q$ | $\Psi_m$ | $J$ | $p$ | $m$ |
|---------------------|-------|-------|-------|----------|-----|-----|-----|
| Units of measure    | $\Omega$ | $H$ | $H$ | $Wb$ | $Kg\cdot m^2$ | – | – |
| Values              | 0.96  | 5.25e-3 | 2.25e-3 | 0.183 | 13e-3 | 4  | 3  |

Figure 4. Amplitude-frequency characteristics 1– $k_{feed} = 0$ V; 2– $k_{feed} = 1$ V; 3– $k_{feed} = 2$ V; 4– $k_{feed} = 3$ V.

They clearly illustrate the possibility of forming a resonance mode of the PMSM in a given range of oscillations when there is introduction of position feedback in the form of a fictitious positional load. Moreover, at higher frequencies higher kinematic characteristics of the drive are achieved in comparison with the regulation of the natural frequency with the algorithm (5).

Since most of industrially manufactured PMSMs have built-in rotor position sensors in their design, the technical implementation of these electric drives is significantly simplified and can be recommended for various systems that reproduce low-frequency angular oscillations.

Conclusions
The developed analysis procedure for dynamic stability of the valve electric drive, operating directly in oscillatory mode by means of the supply voltage phase modulation, can be recommended not only for the estimation of a quasi-steady mode, but also for the operating modes with sudden load-on or load-off. As far as all these processes have clearly defined dynamic character, under which the PMSM operating element speed is an undetermined and variable value, so the extreme maximum value of the pull-in torque can serve as the pull-in criterion. In order to ensure maintenance of energy-optimal resonance mode, regulation of the PMSM natural synchronizing torque through the variation of one of the motor phase voltages depending on oscillation frequency was suggested.

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