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OPTIMIZATION OF TIMES OF START-BRAKING REGIMES OF FREQUENCY-REGULATED ASYNCHRONOUS ENGINE WITH PUMPING LOAD

Purpose. Obtaining the frequency-regulated asynchronous engine (FRAE) with the pumping load of the calculated analytical dependences for the major electromagnetic energy losses of the engine and determining the optimal values of its acceleration and deceleration time for minimizing the loss concerned, as well as checking the feasibility of their optimal values of time in hydraulic systems.

Methodology. The methods of mathematical analysis and determinants, of theories of similarity and of hydraulic shock, of computer simulation were used.

Findings. Analytic dependencies for the calculation of the MEEL for the FRAE loaded with a centrifugal pump (CP) are obtained, with respect to the start-braking regimes for various existing types of the velocity variation. As a result of solving the optimization problem, analytical dependencies are obtained that ensure the calculation of the minimum possible (optimal) values of the MEEL of this engine in the start-braking regimes with the indicated different types of speed variation and allow calculating the optimum time for acceleration and deceleration of the engine corresponding to them. An engineering technique is proposed and with its help based on the permissible value of the hydraulic shock in the hydraulic system, a check on the feasibility of the optimum acceleration and deceleration time for the FRAE loaded with a CP in the start-braking regimes with the mentioned speed trajectories is carried out.

Originality. For the first time, analytical dependencies have been obtained that allow one to quantify the minimum possible MEEL in the start-braking regimes with a pumping and fan load, and also to determine the optimum acceleration and deceleration time values corresponding to these energy losses for linear, parabolic and quasi-optimal velocity trajectories. For the first time, a method has been developed for calculating the maximum value of a hydraulic shock in a hydraulic system when using a centrifugal pump with FRAE.

Practical value. The introduction of the obtained results allows reducing unproductive losses of electric energy in the start-braking regimes of the FRAE, and also increasing the operational reliability of the hydraulic systems with a CP equipped with a frequency- regulated asynchronous engine.

Keywords: *frequency control, asynchronous engine, electromagnetic energy losses, start-braking regimes*

Introduction. Taking into account the widespread introduction of frequency-regulated asynchronous electric drives (of which up to 25 % falls on pumps) and the growing cost of electric energy in many sectors of the economy of Ukraine and other countries of the world, the task of energy saving in these electric drives becomes very topical and in demand. At the same time, the most effective way to solve the energy saving problem is to reduce unproductive electricity, most of which in the electrical part of the electric drive under consideration is, as is known, electromagnetic energy losses in an asynchronous engine.

Analysis of the recent research and publications. Despite the large number of works devoted to the study and calculation of energy losses in a centrifugal pump (CP) and frequency-controlled asynchronous engine (FRAE) in domestic and foreign scientific and technical literature, the vast majority of these publications are limited to the consideration of only established regimes. In particular, with respect to steady-state regimes: in [1] – the power consumption of speed controllers of one or two parallel-working CP is analyzed, an energy-saving control strategy is proposed; in [2] – power losses in a frequency-regulated pump under speed control are investigated, the energy consumption of the CP is analyzed taking into account the typical schedules for changing its load; in [3] – they consider the power consumption at the pump plant, consisting of several CPs controlled by the velocity, the efficiency coefficient of the frequency-regulated asynchronous engine is estimated when the pump load is changed, energy-saving control is proposed; in [4] – taking into account the typical load schedules of a water supply network of a multi-storey house, the losses of power and energy are calculated, as well as the efficiency for a centrifugal pump with a FRAE.

Only a very small part of the well-known publications is devoted to the issues of energy saving in the regimes of the FRAE and optimization of its time of start-braking. The following works are devoted to the issue considered: [5] – for the constant and [6] – for the fan torque of the engine load. Moreover, the analytical calculations of the major electromagnetic losses of energy in [6] and the investigation of the optimum acceleration and deceleration times for the FRAE with fan load are performed for the value of the initial moment of the load resistance equal to zero. Therefore, the calculations and dependences obtained in [6] are not applicable in practice for most centrifugal pumps, which in their work are characterized by a non-zero value of the initial moment of load resistance (caused by the presence of back pressure in the hydraulic system).

The carried out analysis of the state of the investigated matter indicates that at the present time, despite such a demand, there are no applications for a FRAE loaded with a centrifugal pump: the analytical dependences for the calculation in the start-braking regimes of the major electro-magnetic energy losses (caused by the main harmonic components of the stator voltages and current) and the optimum acceleration and deceleration time that minimize these losses, and also the verification of the feasibility of these optimum times in hydro systems.

Objective of the article. Obtaining of the frequency-regulated asynchronous engine (FRAE) with the pumping load of the calculated analytical dependences for the major electromagnetic energy losses of the engine and determining the optimum values of its acceleration and deceleration time providing the minimization of these losses, and also – verification of the feasibility of this optimum time in hydraulic systems.

Presentation of the research and explanation of scientific results. In the course of research, we accept the following assumptions:

- starts and braking of the CP occur with the throttle fully open;

- we take into account the generally accepted idealized representation of an induction engine [2], while taking into account the loss of power in steel (inherent to an undeveloped engine) in one-time [5];

- we neglect the free (damped) components of the stator currents in the start-braking regimes [5];

- the automatic control system by the electric drive supports the law of frequency control that is most widespread for vector control: with the constancy of the module Ψ_r the linkage of the rotor of the engine, equal to its nominal value Ψ_{rn} [2];

- the value of the moment of inertia J of the pump drive is assumed to be unchanged and equal to $J \approx \approx 1.15J_{en}$, where J_{en} is the moment of inertia of the engine (this ratio is given from the book by Florinskiy M. M., Rychagova V. V. Pumps and pumping stations);

- analytical dependencies and calculations are given in the conventional for AC machines relative to the system of aggregates [5];

- the subject of the study included the regimes: acceleration of the FRAE from zero to maximum ω_m speed and deceleration from the maximum ω_m speed to zero speed (where in calculations the value ω_m in relative units was assumed to be equal to unity: $\omega_m = 1$ p.u., which corresponds to the nominal synchronous speed of this engine in relative units);

- studies were carried out for linear, parabolic and energy-saving quasioptimal control [6], with a speed FRAE applied to the parameters (Table 1) of an asynchronous engine of A03-315M-4U3 type with a power of 200kW and a centrifugal pump of SD 450/95-2a type [7].

To find and analyze the major electromagnetic losses of power ΔP_{em} FRAE in the vector control with constant flux linkage of the engine rotor, we use the dependence from [5]

$$\Delta P_{em} \approx a + b \cdot (M_r + J\omega')^2 + c \cdot \omega^{1.3}, \quad (1)$$

in which the constant coefficients are calculated through the parameters of the FRAE from the relations

$$\left.\begin{aligned} a &= \left(\Psi_r / L_m\right)^2 \cdot \left(R_s + 0{,}005 \cdot P_n / \eta_n\right) \\ b &= \left(R_s + k_r^2 R_r + 0{,}005 \cdot P_n / \eta_n\right) / \left(k_r^2 \Psi_r^2\right) \\ c &= \Delta P_{Fe.n} \end{aligned}\right\}. \quad (2)$$

The following notation is used in formulas (1) and (2): M_r and J are, respectively, the moment of resis-

Table 1

The basic passport data of the electric engine and centrifugal pump

Parameter name	Units of measurement	Values of parameters
I Engine		A03-315M-4U3
Nominal power	kW	200
Nominal speed	rpm.	1480
Nominal line / phase voltage	V	660/380
Nominal phase current	A	351
Nominal coefficient of efficiency	%	94
Nominal power factor	p.u.	0.92
Moment of inertia of the rotor	kg · m^2	4.75
II Centrifugal pump		SD 450/95–2a
Nominal power	rpm.	1500
Nominal output (consumption)	m^3/h	400
Nominal head	m	78
Rated power at the engine shaft	kW	200
Nominal coefficient of efficiency	%	58.5
Diameter of inlet/outlet nozzle	mm	200/150

tance and the moment of inertia of the drive; Ψ_r and ω are the rotor flux-linkage module and the angular rotational frequency (speed) of the rotor of the engine, respectively; R_s and R_r are active resistances, respectively, of the stator and rotor (driven to the stator) phase windings of the engine; P_n and η_n are nominal values respectively, the useful power on the shaft and the coefficient of efficiency of the engine; $\Delta P_{\text{Fe}.n}$ and k_r are the nominal value of steel losses and the rotor coupling ratio of the engine, respectively; $\omega' = d\omega/dt$ is the first time derivative of the velocity. In this case, by means of a term equal to $0.005 \cdot P_n/\eta_n$ and contained in the first and second formulas of (2), are included in the power loss ΔP_{em} including additional power losses of the engine [5].

The determination of the major electromagnetic energy losses (MEEL) for the FRAE in the regimes of acceleration and deceleration is carried out from the dependencies

$$\Delta W_a = \int_0^{t_a} \Delta P_{em} \cdot dt \quad \text{and} \quad \Delta W_d = \int_0^{t_d} \Delta P_{em} \cdot dt, \tag{3}$$

where t_a and t_d are duration of time of acceleration and deceleration of the engine, respectively.

Substituting (from the above-mentioned book by Florinsky M.M. et al.) into (1) the value of the moment of resistance M_r for centrifugal pump (CP)

$$M_r = M_{ro} + (M_{rn} - M_{ro}) \cdot (\omega/\omega_n)^k, \tag{4}$$

(where coefficient k can take values from 1 to 5), we obtain a dependence for calculating the loss of electromagnetic power in the FRAE, loaded with a CP

$$\Delta P_{em} \approx a + b \cdot (M_{ro} + q \cdot \omega^k + J\omega')^2 + c \cdot \omega^{1.3}. \tag{5}$$

In the expressions (4, 5) the following notation is used: M_{ro} is the initial moment of resistance of CP, which in practice is usually from 0.05 to 0.3 of the nominal moment M_{rn} of resistance load (according to the mentioned book by Florinsky M. M., etc.); coefficient value q is across the nominal speed value ω_n, moment resistance M_{rn} and power P_{rn} pumping load

$$q = \left(M_{rn} - M_{ro}\right)/\omega_n^k \quad \text{and} \quad M_{rn} = P_{rn}/\omega_n. \tag{6}$$

In this case, the values of the initial resistance moment M_{ro} and coefficient k for a static mechanical characteristic $M_r(\omega)$ CP from (4) can be determined (according to the book by Ilyinskyi N. F., Moskalenko V. V. Electric drive: energy and resource saving) through the experimentally obtained static characteristic of mechanical power $P_{mech}(\omega)$ of that pump.

At the *first stage*, we calculate the MEEL in the start-braking regimes of the FRAE for linear tachograms of its acceleration and deceleration, respectively

$$\omega = \omega_m \cdot \left(\frac{t}{t_a}\right) \quad \text{and} \quad \omega = \omega_m \cdot \left(\frac{t_d - t}{t_d}\right). \tag{7}$$

Here and now the current time t at acceleration and braking is counted from the beginning and during the intervals of acceleration or deceleration, respectively: $0 \le t \le t_a$ and $0 \le t \le t_d$.

From (7) we find the values of the velocity derivatives for the time series for linear acceleration and deceleration tachograms, respectively

$$\omega' = \omega_m/t_a \quad \text{and} \quad \omega' = -\omega_m/t_d. \tag{8}$$

Substituting (7, 8) in (5), we obtain the dependences for calculating the major electromagnetic losses of power FRAE during acceleration or deceleration

$$\left.\begin{aligned}
\Delta P_{em.a} &= \left(a + b \cdot M_{ro}^2\right) + \frac{2b \cdot \omega_m M_{ro} J}{t_a} + \frac{b \cdot \omega_m^2 J^2}{t_a^2} + \\
&+ b \cdot \left(\frac{2q \cdot M_{ro} \cdot \omega_m^k}{t_a^k} t^k + \frac{2q\omega_m^{k+1} J}{t_a^{k+1}} t^k\right) + \\
&+ \frac{2bq^2 \cdot \omega_m^{2k}}{t_a^{2k}} t^{2k} + \frac{c \cdot \omega_m^{1,3}}{t_a^{1,3}} t^{1,3} \\
\Delta P_{em.d} &= \left(a + bM_{ro}^2\right) - \frac{2b \cdot \omega_m M_{ro} J}{t_d} + \frac{b \cdot \omega_m^2 J^2}{t_d^2} + \\
&+ b \cdot \left[\frac{2q \cdot M_{ro} \cdot \omega_m^k}{t_d^k} \left(t_d - t\right)^k - \frac{2q\omega_m^{k+1} J}{t_d^{k+1}} \left(t_d - t\right)^k\right] + \\
&+ \frac{2bq^2 \cdot \omega_m^{2k}}{t_d^{2k}} \left(t_d - t\right)^{2k} + \frac{c \cdot \omega_m^{1,3}}{t_d^{1,3}} \left(t_d - t\right)^{1,3}
\end{aligned}\right\}, \tag{9}$$

where the subscripts "*a*" and "*d*" here always refer to the values of FRAE or time durations corresponding to the regimes of acceleration or deceleration.

In accordance with the relations in (3), taking definite time integrals of t from expressions (9) being from 0 to $t_{a,d}$, we obtain an analytical expression for the calculation of the MEEL in the start-braking regimes of the FRAE with a linear change in the velocity

$$\begin{aligned}
\Delta W_{a,d} = &\left(a + b \cdot M_{ro}^2 + \frac{2}{k+1} bqM_r\omega_m^k + \right. \\
&\left. + \frac{1}{2k+1} bq^2\omega_m^{2k} + \frac{c \cdot \omega_m^{1.3}}{2.3}\right) \cdot t_{a,d} \pm \\
&\pm \left(2b \cdot \omega_m M_{ro} J + \frac{2}{3} bq\omega_m^{k+1} J\right) + \frac{b\omega_m^2 J^2}{t_{a,d}^2},
\end{aligned} \tag{10}$$

where here and further from double signs: a sign "+"always corresponds to acceleration, and a sign "–" – to deceleration; $t_{a,d}$ is acceleration and deceleration time.

The analysis of the expression (10) indicates that the MEELs under acceleration and deceleration contain three terms (components): the first is directly proportional to the time value $t_{a,d}$ of acceleration (or deceleration); the second represents a constant value (independent of the acceleration and deceleration times); the third depends inversely on the value of time $t_{a,d}$ of acceleration (or deceleration). Expression (10) is characterized by the fact that with a significant decrease or increase in the duration of time $t_{a,d}$ there is an increase in the value of the MEEL $\Delta W_{a,d}$. This causes the presence of an extremum (minimum) of these MEELs at certain

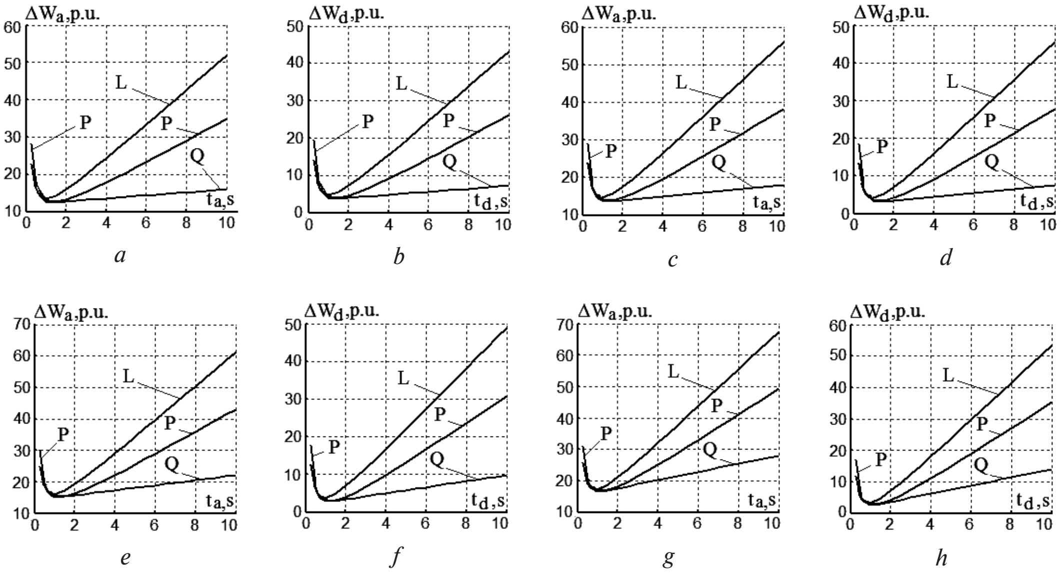

Fig. 1. Dependencies for the major electromagnetic energy losses of the A03-315M-4U3 engine, loaded by a centrifugal pump SD 450/95-2a, in the regimes of acceleration (a, c, e, g) and deceleration (b, d, f, h), for linear (L), parabolic (P), and quasi-optimal (Q) trajectories of velocity variation:

a, b – for $M_{ro} = 0$*; c, d – for* $M_{ro} = 0.1 \cdot M_{rn}$*; e, f – for* $M_{ro} = 0.2 \cdot M_{rn}$*; g, h – for* $Mro = 0.3 \cdot M_{rn}$

(optimal) values of acceleration (deceleration) time of the engine (as confirmed by the graphs of these dependences constructed from (10) for $k = 2$ in Fig. 1 and denoted by the letter L).

To find the optimal values of acceleration (or deceleration) time, we take the derivative from the expression (10) in time $t_{a,d}$ of acceleration (or deceleration) and equate it to zero

$$\frac{d\left(\Delta W_{a,d}\right)}{dt_{a,d}} = a + b\cdot M_{ro}^2 + \frac{2}{k+1} bqM_{ro}\omega_m^k + \frac{1}{2k+1} bq^2\omega_m^{2k} + \frac{c\cdot\omega_m^{1.3}}{2.3} - \frac{b\omega_m^2 J^2}{t_{a,d}^2} = 0.$$

From the last expression, we will define equal values (for identical parameter values M_{ro} and q static moment M_r) of optimum acceleration time t_a^o and t_d^o FRAE, corresponding to a linear change in the velocity

$$t_a^o = t_d^o = t_{a,d}^o = J\omega_m \times \sqrt{\frac{b}{a + b\cdot M_{ro}^2 + \frac{2bqM_{ro}\omega_m^k}{k+1} + \frac{bq^2\omega_m^{2k}}{2k+1} + \frac{c\cdot\omega_m^{1.3}}{2.3}}}. \quad (11)$$

At the *second stage*, we calculate the MEEL of the engine in the start-braking regimes with parabolic tachograms of acceleration and deceleration, respectively

$$\omega = \omega_m \cdot \left(\frac{t}{t_a}\right)^2 \quad \text{and} \quad \omega = \omega_m \cdot \left(\frac{t_d - t}{t_d}\right)^2. \quad (12)$$

From (12), we determine the velocity derivatives with respect to the time for the parabolic tachogram FRAE in the acceleration and deceleration regimes, respectively

$$\omega' = 2\omega_m t / t_a^2 \quad \text{and} \quad \omega' = -2\omega_m (t_d - t) / t_d^2. \quad (13)$$

Substituting the values from (12, 13) in (5), we find the calculated dependences for the major electromagnetic losses of power FRAE in the parabolic tachograms of acceleration or deceleration

$$\left.\begin{aligned} \Delta P_{em.a} &= a + b\cdot\Bigg(M_{ro}^2 + \frac{4J\omega_m M_{ro}}{t_a^2}\cdot t + 2qM_{ro}\frac{\omega_m^k}{t_a^{2k}}\cdot t^{2k} + \frac{4Jq\omega_m^{k+1}}{t_a^{2k+2}}\cdot t^{2k+1} + \frac{q^2\cdot\omega_m^{2k}}{t_a^{4k}}\cdot t^{4k} + \frac{4J^2\cdot\omega_m^2}{t_a^4}\cdot t^2 \Bigg) + \frac{c\cdot\omega_m^{1.3}}{t_a^{2.6}}\cdot t^{2.6} \\ \Delta P_{em.d} &= a + b\cdot\Bigg(M_{ro}^2 - \frac{4J\omega_m M_{ro}}{t_d^2}\cdot\left(t_d - t\right) + 2qM_{ro}\frac{\omega_m^k}{t_d^{2k}}\cdot\left(t_d - t\right)^{2k} - \frac{4Jq\omega_m^{k+1}}{t_d^{2k+2}}\cdot\left(t_d - t\right)^{2k+1} + \frac{q^2\cdot\omega_m^{2k}}{t_d^{4k}}\cdot\left(t_d - t\right)^{4k} + \frac{4J^2\cdot\omega_m^2}{t_d^4}\cdot\left(t_d - t\right)^2 \Bigg) + \frac{c\cdot\omega_m^{1.3}}{t_d^{2.6}}\cdot\left(t_d - t\right)^{2.6} \end{aligned}\right\}. \quad (14)$$

Taking definite time integrals of the expressions in (14) in the range from 0 to $t_{a,d}$, we obtain, according to (3), the analytical dependence for calculating the MEEL in the start-braking regimes of the FRAE with parabolic velocity variation

$$\Delta W_{a,d}=\left(a+b\cdot M_{ro}^2+\frac{2}{2k+1}bqM_{ro}\omega_m^k+\right.$$
$$\left.+\frac{b}{4k+1}q^2\omega_m^{2k}+c\cdot\frac{\omega_m^{1.3}}{3.6}\right)\cdot t_{a,d}\pm \qquad (15)$$
$$\pm\left(2bJM_{ro}\omega_m+\frac{2}{k+2}bJq\omega_m^{k+1}\right)+\frac{4}{3}bJ^2\omega_m^2\Big/t_{a,d}.$$

To determine the durations of the optimal acceleration (or deceleration) time of FRAE, we calculate the time derivative $t_{a,d}$ acceleration (or deceleration) from the expression (15) and equate it to zero

$$\frac{d(\Delta W_{a,d})}{dt_{a,d}}=a+b\cdot M_{ro}^2+\frac{2}{2k+1}bqM_{ro}\omega_m^k+$$
$$+\frac{1}{4k+1}bq^2\omega_m^{2k}+\frac{c\cdot\omega_m^{1.3}}{3.6}-\frac{4bJ^2\omega_m^2}{3t_{a,d}^2}=0.$$

From this expression, we determine the optimum acceleration time t_a^o and t_d^o FRAE, corresponding to the parabolic change in velocity

$$t_a^o=t_d^o=t_{a,d}^o=J\omega_m\times$$
$$\times\sqrt{\frac{\frac{4}{3}b}{a+b\cdot M_{ro}^2+\frac{2bqM_{ro}\omega_m^k}{2k+1}+\frac{bq^2\omega_m^{2k}}{4k+1}+\frac{c\cdot\omega_m^{1.3}}{3.6}}}. \qquad (16)$$

By substituting the optimal time values $t_{a,d}^o$ acceleration and deceleration from (11) to expression (10) or from (16) into expression (15), we obtain analytical dependencies for calculating the optimal (minimum) values $\Delta W_{a,d}^o$ of MEEL in the starting and braking regimes of FRAE, respectively, with a linear or parabolic change in its speed.

From the analysis of the obtained dependences it follows that in spite of the previously noted equality (at identical values of the static moment M_r) between the optimal acceleration time t_a^o and deceleration t_d^o of FRAE, because of the mentioned different double signs, the optimum values of the MEEL in the acceleration regimes (ΔW_a^o) differ according to Fig. 1 and Table 2 before the series of terms entering into (10, 15) and deceleration (ΔW_d^o).We draw attention to the fact that this conclusion applies not only to the considered linear and parabolic tachograms of FRAE, but also extends to a quasi-optimal kind of change in the speed of an induction engine.

At the *third stage*, we calculate the optimal time for the start-braking regimes of the FRAE for quasi-optimal tachograms [6]

$$\omega=\omega_m\cdot\frac{\mathrm{sh}(\xi^*\sqrt{K}\cdot t)}{\mathrm{sh}(\xi^*\sqrt{K}\cdot t_a)}, \qquad (17)$$

when accelerating, or

$$\omega=\omega_m\cdot\frac{\mathrm{sh}\left[\xi^*\sqrt{K}\cdot(t_d-t)\right]}{\mathrm{sh}(\xi^*\sqrt{K}\cdot t_d)}, \qquad (18)$$

when decelerating, where the value of the coefficient ξ^* corresponds to the smallest standard deviation of the quasi-optimal tachogram from the optimum [6], and the coefficient K is found through the engine parameters from the relation [6]

$$K=\frac{0.65c\cdot k_r^2\cdot\Psi_{mn}^2}{(R_s+k_r^2\cdot R_r+0.005P_n/\eta_n)\cdot J^2}.$$

Starting from (17, 18), we calculate the current values of the velocity derivative with respect to time

$$\omega'=\xi^*\sqrt{K}\cdot\omega_m\cdot\frac{\mathrm{ch}(\xi^*\sqrt{K}\cdot t)}{\mathrm{sh}(\xi^*\sqrt{K}\cdot t_a)}, \qquad (19)$$

when accelerating, or

$$\omega'=-\xi^*\sqrt{K}\cdot\omega_m\cdot\frac{\mathrm{ch}\left[\xi^*\sqrt{K}\cdot(t_d-t)\right]}{\mathrm{sh}(\xi^*\sqrt{K}\cdot t_d)}, \qquad (20)$$

when decelerating.

Having determined the current value of the moment of resistance M_r from (4) taking into account (17, 18) and substituting it into the relation (1), we find from the latter the dependence for the major electromagnetic losses of the power of the FRAE with the quasi-optimal trajectory of the velocity variation during acceleration or deceleration taking into account (19, 20)

Table 2

Optimum values of the MEEL and the acceleration and deceleration times of FRAE

Value, p.u.		Optimal time $t_{a,d}^o$, s			Optimal values of the MEEL $\Delta W_{a,d}^o$, , p.u.						ξ*, p.u.
					acceleration			deceleration			
M_{ro}	*q*	*L*	*P*	*Q*	*L*	*P*	*Q*	*L*	*P*	*Q*	*Q*
0	0.8846	0.9564	1.387	1.261	13.40	12.66	12.52	4.654	3.928	3.787	1.89
$0.1M_n$	0.7961	0.9256	1.332	1.335	14.57	13.88	13.73	4.079	3.394	3.251	1.95
$0.2M_n$	0.7077	0.889	1.259	1.22	15.83	15.26	15.11	3.590	3.021	2.875	1.97
$0.3M_n$	0.6192	0.8485	1.176	1.02	17.17	16.78	16.57	3.177	2.793	2.584	1.97

$$\left.\begin{aligned}
&\Delta P_{em.a} = a + b\cdot\Big[M_r^2 + 2\omega_m M_r J\cdot\xi^*\sqrt{K}\times \\
&\times\frac{\mathrm{ch}\left(\xi^*\sqrt{K}\cdot t\right)}{\mathrm{sh}\left(\xi^*\sqrt{K}\cdot t_a\right)} + J^2\left(\omega_m\cdot\xi^*\sqrt{K}\right)^2\times \\
&\times\frac{\mathrm{ch}^2\left(\xi^*\sqrt{K}\cdot t\right)}{\mathrm{sh}^2\left(\xi^*\sqrt{K}\cdot t_a\right)}\Big] + c\cdot\omega_m^{1,3}\cdot\frac{\mathrm{sh}^{1,3}\left(\xi^*\sqrt{K}\cdot t\right)}{\mathrm{sh}^{1,3}\left(\xi^*\sqrt{K}\cdot t_a\right)} \\
&\Delta P_{em.d} = a + b\cdot\Big\{M_r^2 - 2\omega_m M_r J\cdot\xi^*\sqrt{K}\times \\
&\times\frac{\mathrm{ch}\left[\xi^*\sqrt{K}\cdot\left(t_d - t\right)\right]}{\mathrm{sh}\left(\xi^*\sqrt{K}\cdot t_d\right)} + J^2\left(\omega_m\cdot\xi^*\sqrt{K}\right)^2\times \\
&\times\frac{\mathrm{ch}^2\left[\xi^*\sqrt{K}\cdot\left(t_d - t\right)\right]}{\mathrm{sh}^2\left(\xi^*\sqrt{K}\cdot t_d\right)}\Big\} + c\cdot\omega_m^{1,3}\frac{\mathrm{sh}^{1,3}\left[\xi^*\sqrt{K}\cdot\left(t_d - t\right)\right]}{\mathrm{sh}^{1,3}\left(\xi^*\sqrt{K}\cdot t_d\right)}
\end{aligned}\right\}. \quad (21)$$

The complex form of the dependences (21) does not allow us to calculate definite integrals in a general analytic form, and the presence of hyperbolic functions (in the numerator and denominator of a number of its terms) makes it difficult to differentiate these dependences after finding an extremum. This, in turn, prevents the finding in the general form of analytical dependencies for calculating the optimal acceleration and deceleration time corresponding to minimizing the powerless effect of the engine under the quasi-optimal velocity trajectory. Therefore, in order to obtain a more simple form of the calculated analytical dependencies for finding these optimum acceleration and deceleration time, we use the similarity method (for example, considered in the book by V. A. Venikov, Theory of Similarity and Modeling). In the case under consideration, the similarity of the analytical dependences (11, 16) for calculating the optimal values of the time t_a^o and t_d^o for linear and parabolic tachograms, the FRAE consists in the similarity of the general form of these dependencies, which can be represented by a single expression

$$t_a^o = t_d^o = t_{a,d}^o = J\omega_m\times\sqrt{\frac{pb}{a + b\cdot M_{ro}^2 + ybqM_{ro}\omega_m^k + zbq^2\omega_m^{2k} + sc\cdot\omega_m^{1.3}}}. \quad (22)$$

The difference in these dependencies (11, 16) or in (22) is only in the various numerical values of the coefficients *p, y, z* and *s*, given in Table 3. This similarity is, obviously, explained by the general properties of the object under investigation – the FRAE. Proceeding from the similarity method, we will assume that the general form of the dependence (22) is preserved even in the case of calculating the optimal acceleration time t_a^o and deceleration time t_d^o with a quasi-optimal form of the change in engine speed, and a possible difference will consist only in other numerical values of the coefficients *p, y, z, s* in dependence (22).

In view of the above-mentioned impossibility of the analytical integration of the obtained complex expression (21), after substituting this expression into (3), they were calculated by numerical integration methods for

Table 3

The numerical values of the coefficients *p, y, z* and *s*

Type of tachogram	Values of the coefficients, p.u.			
	p	y	z	s
Linear	1	$\frac{2}{k+1}$	$\frac{1}{2k+1}$	$\frac{1}{2.3}$
Parabolic	$\frac{4}{3}$	$\frac{2}{2k+1}$	$\frac{1}{4k+1}$	$\frac{1}{3.6}$
Quasi-optimal	0.3094	–0.1812	0.0146	1/18.18

the start-braking regimes of the A03-315M-4U3 engine under consideration, loaded with the SD-450 / 95-2a pump , the dependence of MEEL ΔW_a and ΔW_d on the duration of the acceleration time t_p and deceleration time t_m for a quasi-optimal trajectory of the change in engine speed, which are plotted as graphs (for $k = 2$) in Fig. 1. Analysis of the graphs shows that each of them has also a "U"-like appearance (as with linear and parabolic tachograms) and is characterized by a single extreme (minimum) value. The minimum values of the MEEL $\Delta W_{a,d}^o$ and the corresponding optimal values $t_{a,d}^o$ of time of acceleration and deceleration of the FRAE are presented in Table 2.

A technique is proposed for finding the values of the coefficients in the universal calculated dependence (22) for a quasi-optimal tachogram FRAE:

1) using the pre-numerical methods defined from Fig. 1 for quasioptimal tachograms, the optimal acceleration (deceleration) time: $t_{a,d1}^o$ – for M_{ro1}; $t_{a,d2}^o$ – for M_{ro2}; $t_{a,d3}^o$ – for M_{ro3}; $t_{a,d4}^o$ – for M_{ro4} (the values of which are given in Table 2), in accordance with the relationship (22) we will compose a system of algebraic equations

$$\left.\begin{aligned}
&\left(a + b\cdot M_{ro1}^2\right) + ybq_1M_{ro1}\omega_m^k + zbq_1^2\omega_m^{2k} + \\
&+ sc\omega_m^{1.3} = p\left[bJ^2\omega_m^2\Big/\left(t_{a,d1}^o\right)^2\right] \\
&\left(a + b\cdot M_{ro2}^2\right) + ybq_2M_{ro2}\omega_m^k + zbq_2^2\omega_m^{2k} + \\
&+ sc\omega_m^{1.3} = p\left[bJ^2\omega_m^2\Big/\left(t_{a,d2}^o\right)^2\right] \\
&\left(a + b\cdot M_{ro3}^2\right) + ybq_3M_{ro3}\omega_m^k + zbq_3^2\omega_m^{2k} + \\
&+ sc\omega_m^{1.3} = p\left[bJ^2\omega_m^2\Big/\left(t_{a,d3}^o\right)^2\right] \\
&\left(a + b\cdot M_{ro4}^2\right) + ybq_4M_{ro4}\omega_m^k + zbq_4^2\omega_m^{2k} + \\
&+ sc\omega_m^{1.3} = p\left[bJ^2\omega_m^2\Big/\left(t_{a,d4}^o\right)^2\right]
\end{aligned}\right\},$$

containing four equations and four unknown variables *p, y, z* and *s*, where q_1, q_2, q_3 and q_4 are coefficient values *q* from Table 2, corresponding to the values of the initial moment of resistance, equal to M_{ro1}, M_{ro2}, M_{ro3} and M_{ro4};

2) we transform this system of algebraic linear equations of the fourth order to the canonical form of the algebraic system of linear equations of the third order;

3) by the method of determinants we find the values of the required coefficients: *p, y, z* and *s* (Table 3).

For centrifugal pumps in which the initial value of the resistance is present in expression (4): $M_{ro} = 0$ (which is also known for centrifugal fans [6]), the universal design dependence (22) for determining the optimum acceleration and deceleration times for linear, parabolic and quasi-optimal velocity trajectories is simplified to the form

$$t_a^o = t_d^o = t_{a,d}^o = J\omega_m \cdot \sqrt{\frac{pb}{a + zbq^2\omega_m^{2k} + sc\cdot\omega_m^{1.3}}}, \quad (23)$$

where for linear, parabolic and quasioptimal tachograms, the values of the coefficients *p,z,s* from Table 3 are preserved.

With respect to quasi-optimal tachograms of FRAE, loaded with a fan load, the methodology for determining the coefficients *p, z, s* for the dependence (23) is transformed to a different form:

1) using the previously determined numerical methods determined from Figs. 1, *a, b* for quasioptimal tachograms, optimal acceleration (deceleration) time: $t_{a.d1}^o$, $t_{a.d2}^o$ and $t_{a.d3}^o$, corresponding to three different values of the coefficients calculated from (6) q_1, q_2 and q_3 (for example, with respect to the maximum values of the fan load moment, which are equal to: $0.5M_{rn}$; $0.75M_{rn}$ and M_{rn}), – a system of algebraic equations is constructed with allowance for (23)

$$\left.\begin{aligned} a + zbq_1^2\omega_m^{2k} + sc\cdot\omega_m^{1.3} &= p\left[bJ^2\omega_m^2\Big/\left(t_{a.d1}\right)^2\right]\\ a + zbq_2^2\omega_m^{2k} + sc\cdot\omega_m^{1.3} &= p\left[bJ^2\omega_m^2\Big/\left(t_{a.d2}\right)^2\right]\\ a + zbq_3^2\omega_m^{2k} + sc\cdot\omega_m^{1.3} &= p\left[bJ^2\omega_m^2\Big/\left(t_{a.d3}\right)^2\right]\end{aligned}\right\},$$

containing three equations and three unknown variables: *p, z, s*;

2) after transformation of the given system to the canonical form, the values of the sought coefficients *p, z* and *s* are found by the method of determinants.

At the *fourth stage* with the help of Fig. 1 for the considered FRAE and CP (Table 1) on the approximate measure of the linear tachogram, we estimate the expected annual energy savings during the transition in the start-braking regimes from the time $t_{a,d}$, equal to 10 s, to optimal time $t_{a.d}^o$, equal to 0.8485 s. This energy savings at the sewage pumping station (with an annual pump operating time of 8700 h and an average annual number of pump inclusions per hour of five) will be for one pump, kWh

$$E_y = \frac{A_b\cdot 8700\cdot 5}{3600}\left[\Delta W_a(t_a) - \Delta W_a(t_a^f) + \right. \left. + \Delta W_m(t_m) - \Delta W_m(t_m^o)\right] \approx 894,$$

where A_b = 0.7367 kJ is the basis energy value; $\Delta W_a(t_a) - \Delta W_a(t_a^o) =$ 50.2 p.u. is energy saving at one acceleration (Fig. 1, *g*); $\Delta W_d(t_d) - \Delta W_d(t_d^o) =$ 50.2 p.u. – energy saving with one deceleration (Fig. 1, *h*); 3600 – conversion factor (from kJ to kWh).

At the *fifth stage*, it is possible in the start-brake regimes, proceeding from the permissible value of the hydraulic shock in the hydraulic system, to check the feasibility of the optimum acceleration and deceleration time for the FRAE (for the example of the considered engine and the pump from Table 1, installed at the sewage pumping station with the parameters of the hydraulic system: the density of the pumped liquid ρ = 1100 kg/m^3, highest working pressure Po = 0.2MPa at the inlet of the pump and the input iron pipe of Ductile iron with an internal diameter d = 200 mm, wall thickness δ = 6.3 mm, length L = = 20 m and permissible operating pressure P_m = 6.2 MPa). The phenomenon of hydraulic impact is considered only for the braking regime, since during acceleration with a fully open throttle the hydro-impact does not occur.

The essence of the calculation procedure (in absolute units) is:

1) to determine the velocity of propagation of the shock wave in the input tube (using here and further analytical relationships for hydraulic calculations from the book by Agroskina I. I, Dmitrieva G. T., Pikalova F. I. Hydraulics), m/s

$$C = 1425\Big/\sqrt{1 + (d/\delta)\cdot(E_w/E_m)} \approx 1115, \quad (24)$$

where 1425 m/s is speed of sound in water; E_w/E_m, Pa is the ratio of the elastic moduli of water and the material of the pipe walls (for cast iron E_w/E_m = 0.02);

2) to determine the duration of the phase of hydraulic shock, s

$$\tau_o = 2L/C \approx 0.0359; \quad (25)$$

3) to find the cross-sectional area of the inlet pipe, m^2

$$S = \pi d^2/4 \approx 0.03142; \quad (26)$$

4) from the data in Table 1, we calculate the nominal flow (feed) per second, m^3/s

$$Q = 400/3600 \approx 0.1111; \quad (27)$$

5) to determine the maximum speed of the pumped liquid in the inlet pipe, m/s

$$V_m = Q/S \approx 3.536; \quad (28)$$

6) taking into account the directly proportional relationship between the speed of the pumped liquid and the angular frequency of rotation ω FRAE, we calculate the velocity (in m/s) of the pumped liquid in a time interval equal to the phase of the hydraulic shock, after the pump starts to brake for linear, parabolic and quasi-optimal velocity trajectories

$$\left.\begin{aligned} V_L(\tau_o) &= V_m\cdot\left(1 - \tau_o/t_d\right) \approx 3.39\\ V_P(\tau_o) &= V_m\cdot\left(1 - \tau_o/t_d\right)^2 \approx 3.32\\ V_Q(\tau_o) &= V_m\cdot\frac{\mathrm{sh}\left[\xi^*\sqrt{K}\cdot(t_d - \tau_o)\right]}{\mathrm{sh}\left(\xi^*\sqrt{K}\cdot t_d\right)} \approx 3.31\end{aligned}\right\}; \quad (29)$$

7) to determine the maximum values of pressure increase (in MPa) with a hydraulic shock for linear, parabolic and quasi-optimal velocity trajectories

$$\left.\begin{aligned} \Delta P_L &= \rho\cdot C\cdot\left[V_m - V_L(\tau_o)\right]\approx 0.18 \\ \Delta P_P &= \rho\cdot C\cdot\left[V_m - V_P(\tau_o)\right]\approx 0.26 \\ \Delta P_Q &= \rho\cdot C\cdot\left[V_m - V_Q(\tau_o)\right]\approx 0.28 \end{aligned}\right\}; \qquad (30)$$

8) to check the feasibility of the optimum acceleration times, based on the condition

$$P_o + \Delta P \le P_m. \qquad (31)$$

The pressure increase charts calculated from (24–30) for a hydraulic impact (in MPa) for linear, parabolic and quasi-optimal velocity trajectories with a variation in the length of the input pipe from 20 to 400 m are shown in Fig. 2. Condition (31) for the example under consideration (with L = 20 m) is satisfied with a margin equal to: 5.82, 5.74 and 5.72 MPa, respectively, for linear, parabolic and quasi-optimal tachograms of FRAE.

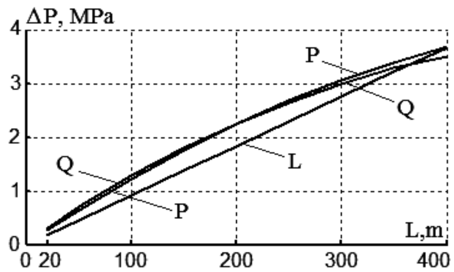

Fig. 2. Maximum values of pressure increase in a hydraulic impact, depending on Pipe length at pump inlet

Conclusions.

1. The obtained analytical dependences (9, 10), (14, 15), (21, 3) allow calculating the current electromagnetic power losses ΔP_{em} and basic electromagnetic energy losses ΔW_a and ΔW_d in the start-braking regimes of the FRAE with pump loading for linear, parabolic and quasi-optimal trajectories of its speed. The necessary information for performing these calculations includes the passport data and parameters of the pump and its drive engine, the value of the static head of the hydraulic system.

2. The analytical dependences (11, 16, 22, 23) obtained as a result of the solution of the optimization problem ensure the calculation of the optimum values of acceleration and deceleration time of the engine and allow calculating the corresponding minimum possible (optimal) values of the basic losses of electromagnetic energy ΔW_a^o and ΔW_d^o FRAE with pump and fan loads in the start-braking regimes with the mentioned different speed trajectories.

3. The proposed engineering technique allows for any trajectories of the change in the speed of the drive engine, proceeding from the possible occurrence (in case of unsteady fluid flows) of the formation of a hydraulic shock in hydraulic systems, to verify the feasibility for centrifugal pumps of the optimal time for their acceleration and deceleration.

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Оптимізація часів пуско-гальмівних режимів частотно-регульованого асинхронного двигуна із насосним навантаженням

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Мета. Отримання стосовно до пуско-гальмівних режимів частотно-регульованого асинхронного двигуна (ЧРАД) з насосним навантаженням розрахункових аналітичних залежностей для основних електромагнітних втрат енергії (ОЕВЕ) двигуна та визначення оптимальних значень його часу розгону й гальмування, що забезпечують мінімізацію даних втрат, а також – перевірку реалізації їх оптимальних значень часу в гідросистемах.

Методика. Математичного аналізу та визначників, теорії подібності й гідравлічного удару, комп'ютерного імітаційного моделювання.

Результати. Отримані аналітичні залежності для розрахунку ОЕВЕ для ЧРАД, навантаженого відцентровим насосом (ВН), стосовно пуско-гальмівних режимів при різних існуючих видах зміні швидкості. У результаті рішення оптимізаційного завдання отримані аналітичні залежності, що забезпечують обчислення мінімально можливих (оптимальних) значень ОЕВЕ цього двигуна в пуско-гальмівних режимах при зазначених різних видах зміни швидкості й дозволяють розрахувати відповідні їм оптимальні значення часу розгону й гальмування двигуна. Запропонована інженерна методика та з її допомогою здійснена перевірка, виходячи з допустимого значення гідравлічного удару в гідросистемі, можливості реалізації цих значень часу розгону й гальмування ЧРАД, що навантажено ВН, у пуско-гальмівних режимах зі згаданими траєкторіями зміни швидкості.

Наукова новизна. Уперше отримані аналітичні залежності, що дозволяють кількісно оцінити мінімально можливі ОЕВЕ в пуско-гальмівних режимах ЧРАД із насосним і вентиляторним навантаженням, а також визначити відповідні цим втратам енергії оптимальні значення часу розгону й гальмування двигуна для лінійної, параболічної та квазіоптимальної траєкторій зміни швидкості. Уперше розроблена методика розрахунку максимального значення гідравлічного удару в гідросистемі при використанні в ній відцентрового насоса із ЧРАД.

Практична значимість. Упровадження отриманих результатів дозволяє знизити непродуктивні втрати електроенергії в пуско-гальмівних режимах ЧРАД, а також підвищити експлуатаційну надійність гідросистем із ВН, забезпеченими частотно-регульованим асинхронним двигуном.

Ключові слова: *частотне регулювання, асинхронний двигун, електромагнітні втрати енергії, пуско-гальмівні режими*

Оптимизация времен пуско-тормозных режимов частотно-регулируемого асинхронного двигателя с насосной нагрузкой

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Цель. Получение применительно к пуско-тормозным режимам частотно-регулируемого асинхронного двигателя (ЧРАД) с насосной нагрузкой расчетных аналитических зависимостей для основных электромагнитных потерь энергии (ОЭПЭ) двигателя и определение оптимальных значений его времени разгона и торможения, обеспечивающих минимизацию данных потерь, а также – проверка реализуемости их оптимальных значений времени в гидросистемах.

Методика. Математического анализа и определителей, теорий подобия и гидравлического удара, компьютерного имитационного моделирования.

Результаты. Получены аналитические зависимости для расчета ОЭПЭ для ЧРАД, нагруженного центробежным насосом (ЦН), применительно к пуско-тормозным режимам при различных существующих видах изменения скорости. В результате решения оптимизационной задачи получены аналитические зависимости, обеспечивающие вычисление минимально возможных (оптимальных) значений ОЭПЭ этого двигателя в пуско-тормозных режимах при указанных различных траекториях скорости и позволяющие рассчитать соответствующие им оптимальные значения времени разгона и торможения двигателя. Предложена инженерная методика и с ее помощью осуществлена проверка (исходя из допустимого значения гидравлического удара в гидросистеме) реализуемости этих значений времени разгона и торможения ЧРАД, нагруженного ЦН, в пуско-тормозных режимах с упомянутыми траекториями изменения скорости.

Научная новизна. Впервые получены аналитические зависимости, которые позволяют количественно оценить минимально возможные ОЭПЭ в пуско-тормозных режимах ЧРАД с насосной и вентиляторной нагрузками, а также определить соответствующие этим потерям энергии оптимальные значения времени разгона и торможения двигателя для линейной, параболической и квазиоптимальной траекторий изменения скорости. Впервые разработана методика расчета максимального значения гидравлического удара в гидросистеме при использовании в ней центробежного насоса с ЧРАД.

Практическая значимость. Внедрение полученных результатов позволяет снизить непроизводительные потери электроэнергии в пуско-тормозных режимах ЧРАД, а также повысить эксплуатационную надежность гидросистем с ЦН, снабженными частотно-регулируемым асинхронным двигателем.

Ключевые слова: *частотное регулирование, асинхронный двигатель, электромагнитные потери энергии, пуско-тормозные режимы*

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