CALCULATION OF TRANSIENT PROCESSES OF ELECTRIC DRIVES OF CENTRIFUGAL MECHANISMS

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Abstract

An important stage of an energy efficiency improvement and efficient use of energy in companies is - modernization of electric drives used in enterprises, on the basis of the achievement of energy-saving and new advanced technology by means of automated electric drive.

The article provides an analysis of the main aspects of energy saving when regulated electric centrifugal machines are introduced. The methods of calculating the energy performance have been offered for determination of the energy efficiency, modernization of existing and design of new pumping units. Currently, the regulation modes of centrifugal units is carried out mainly by regulating stop valves, dampers, etc. (throttling). This leads to significant power losses in the regulatory elements associated with overcoming additional hydraulic resistance. By applying controlled electric drive, it can be possible to directly control the speed of rotation of the working part of the centrifugal mechanism (CM), and thus provide the required pressure and flow values.

Keywords: adjustable drive, energy saving, centrifugal mechanism, throttling, asynchronous electric drive.

Introduction

Centrifugal mechanisms (CM) are the most widespread electric power consumers. These plants are widely distributed in all industries, and they perform the main technological and auxiliary functions. Currently, centrifugal regulation modes of centrifugal aggregates is mainly carried out by the regulating valves, dampers, etc. (throttling) -at a constant drive motors speed. This leads to significant power losses in the regulatory elements, which associated with overcoming additional hydraulic resistance.

The magnitude of these losses depends on the depth of control output parameters such as pressure and flow, and can reach up to 50% of a power consumption mechanism. The present level of a development of automated electric drive
allows to transfer control functions directly to centrifugal electric drive units and eliminate these losses. By applying controlled drives, a system directly and smoothly manages a rotation of the impeller speed of CM and thereby provide the required flow rates and flow without throttling valves. The last is installed only for auxiliary purposes and fully open during pumping, thus reduces the overall flow resistance of the system. Since the share of centrifugal pumps (CP), fans, blowers, etc. accounts, according to various sources, 20..35% of the electricity consumed in industry, transferring centrifugal mechanisms for regulated drive systems is an important area of energy saving policy in the industry (1).

Traditionally main operation mode of mechanisms for centrifugal action is considered to be steady state with the established parameters of the electric drive. Therefore, most of the research works on optimization of energy consumption is devoted to the research of the established processes of the CM and the electric drive. However, for example, when the pump being included to the automatic control system of technological process, significant portion of the operating cycle will be transients that are caused by operational on/off functioning of individual elements of the system or changing’s of their operation modes.

In this regard, it is important to study the energy consumption of such electrical drives not only in established, but also in transient operation modes. The proposed mathematical model should allow making a comparative analysis of electromagnetic and electromechanical processes of various schemes of a drive for centrifugal mechanisms.

**Methods**

In studies conducted by different authors at different times, used different approaches, methods of analysis, forms of the mathematical description of the stationary and dynamic operating modes of the asynchronous electric drive systems. One and the same object (IM) is described by the authors in different ways when the system is powered by the Frequency Converter (FC) of stator or rotor. This allows a deep and comprehensive study of the characteristics of each electric drive systems, but it causes a difficulty to carry out a qualitative comparative analysis of electromagnetic processes in the various AED systems with AM, for which it would be logical to use a single mathematical description tool for different control schemes of asynchronous electric drive in all modes of the motor pump unit. Developed by a Japanese scientist Sakae Yamamura spiral - vector theory of AC electrical machines provides a mathematical model of the asynchronous machine, which describes a steady and transients processes.

Variable IM appear as spiral vectors, which are an exponential function of time with a complex coefficient at the argument.
In the complex plane, this feature is a spiral, which at \( \lambda = 0 \) degenerates into a circle corresponding to the magnitude of the variable in the steady engine operation, when \( \omega = 0 \), we have decaying process. Therefore, this method can reflect both the established and transients in AC motor circuits.

In particular, for an asynchronous machine with squirrel-cage rotor, invited well-known system of equations represented in the form of a matrix with complex variables:

\[
\begin{bmatrix}
    u_1 \\
    0
\end{bmatrix} =
\begin{bmatrix}
    r_1 + (l_1 + l_m)p & l_mp \\
    l_mp & r_2 + (l_2 + l_m)(p - j\omega)
\end{bmatrix}
\begin{bmatrix}
    i_1 \\
    i_2
\end{bmatrix}
\]

(2)

where: \( u_1 \) - the voltage applied to the IM stator circuit;

\( i_1, i_2 \) - IM stator and rotor currents;

\( l_1, l_2 \) - scattering inductance phase of stator and rotor;

\( l_m \) - magnetizing inductance circuit;

\( \omega \) - angular speed of the rotor;

\( r_1, r_2 \) - the active phase of the resistance of stator and rotor;

\( p = d/dt \) - operator.

The variables \( u_1, i_1, i_2 \) can be expressed through the spiral vectors, in the steady state \( p = j\omega_0 \) and vectors are circular.

Considered equations are written in complex axes. The choice of the coordinate system is due to the research objectives. In the case when power comes from the stator side (shorted AM under schemes FC-IM, TVR-IM) when choosing a converter the real shape of the stator currents and voltages should be considered, that is, to calculate them in a system of \( \alpha, \beta \) coordinates, rigidly connected to the fixed stator. When calculating the converters in cascade schemes we are interested in the values of currents and voltages in the \( d, q \) coordinates of rotating rotor. In both cases, the voltages and currents vary harmonically, which makes the bulky components of a mathematical model. In synchronous coordinates vectors \( x, y \) of electromagnetic quantities are fixed relative to the stator field, and become a constant in the model. A complete system of initial equations describing the processes in the asynchronous electric drive of the centrifugal pumps, consists of four groups: electromagnetic equations of equilibrium (Kirchhoff’s), describing the electromagnetic processes in the induction motor (IM), the equations of Electromechanical energy conversion, equations characterizing features of the mechanical load on the motor shaft and equations, reflecting the parameters and properties of power sources.
We offer the following, the most common version of the description of electromagnetic processes in the investigated CP.

Spiral vector of variable IM, in the system of \( u, v \), coordinates, rotating at an arbitrary rate \( \omega_k \), written in the form

\[
i = A \cdot e^{\delta t} e^{-j\omega_k t},
\]

Or

\[
i = A \cdot e^{\delta_1 t}
\]

Where \( \delta_1 = -\lambda + j(\omega - \omega_k) \)

Equation (2) with regard to the expression (3) takes the form

\[
\begin{pmatrix}
  u_1 \\
  u_2
\end{pmatrix}
 =
\begin{pmatrix}
  r_1 + (l_1 + l_m)(p + j\omega_k) & l_m(p + j\omega_k) \\
  l_m(p + j(\omega_k - \omega)) & r_2 + (l_2 + l_m)(p + j(\omega_k - \omega))
\end{pmatrix}
\begin{pmatrix}
  i_1 \\
  i_2
\end{pmatrix}
\]

We got an equation similar to the equation of the generalized electromechanical converter, in which the variables \( u_1, u_2, i_1, i_2 \) are spiral vectors, described by (3) in any coordinate system. An important advantage of the proposed method is the ability to use mathematical models of various types of asynchronous electric drive from one original equation (4). Different versions of the electric drives and written in different coordinate systems are a special case. Thus, when the system simulation "FC - IM" in the \( \alpha, \beta \) axes in expression (4) we take \( u_2 = 0 \) and \( \omega_k = 0 \); in synchronous axes \( \omega_k = \omega_0 \).

Results and discussion

Expression (4) \( \omega_k = \omega_0 \); The matrix describing the electromagnetic ratios in IM made in the projections of the generalized vectors of voltages and currents on the \( x, y \) axes rotating synchronously with the stator field:

\[
\begin{pmatrix}
  u_{1x} \\
  u_{1y} \\
  u_{2x} \\
  u_{2y}
\end{pmatrix}
 =
\begin{pmatrix}
  r_1 + p(l_1 + l_m) & -\omega(l_1 + l_m) & pl_m & -\omega_0 l_m \\
  \omega_0(l_1 + l_0) & r_1 + p(l_1 + l_m) & \omega_0 l_m & pl_m \\
  pl_m & -\omega_0 sl_m & r_2 + p(l_2 + l_m) & -\omega_0 sl_2 \\
  \omega_0 sl_m & pl_m & \omega_0 s(l_2 + l_m) & r_2 + p(l_2 + l_m)
\end{pmatrix}
\begin{pmatrix}
  i_{1x} \\
  i_{1y} \\
  i_{2x} \\
  i_{2y}
\end{pmatrix}
\]

here \( u_{1x}, u_{1y}, u_{2x}, u_{2y} \) – projections of stator and rotor vectors on synchronous axes;

\( i_{1x}, i_{1y}, i_{2x}, i_{2y} \) – appropriately stator’s and rotor’s vectors projections on \( x, y \) axes;

\( l_1, l_2 \) – leakage inductances of stator and rotor phase;

\( l_m \) – inductance of magnetizing circuit;

\( r_1, r_2 \) – active resistances of stator and rotor phase.
The inclusion in equation (1) \( u_2 \) voltages and writing vectors in the form of projections allow us to calculate current values and the integral characteristics of the currents and voltages in IM with the various connections of converters (to stator, to rotor) and various schemes of these converters more easily.

The choice of the coordinate system due to the following reasons. In the case of stator-side supply (IM with squirrel-cage rotor by FC-IM, TVR-IM schemes) when choosing converter, it is necessary to take into consideration the real shape of the currents and voltages of the stator, in other words to calculate them in the \( \alpha, \beta \) coordinate system, rigidly connected with the fixed stator. When calculating converters in cascade schemes we are interested in values of currents and voltages in the rotating rotor’s \( d,q \) coordinates. The procedure of transformation of the \( \alpha, \beta - d,q - x,y \) (synchronous axis) coordinates is quite routine, but the conversion to the coordinates of the stator and rotor of equations written in a synchronous axes, perform the same operation and simplifies the calculation. Therefore, further calculations are performed in the \( x,y \) coordinate system, rotating with the frequency of the IM stator field.

Electromechanical ratios in the program are calculated by components of the equations of motion of the electrical drive

\[
M - M_C = J \frac{d\omega}{dt}
\]  

(6)

The interaction of the stator and rotor fields of IM creates electromagnetic torque:

\[
M = \frac{3}{2} p_m l_m i_x i_y - l_y i_z
\]  

(7)

When the load is centrifugal the resistance torque of mechanism \( M_C \) is rather complicated function of the speed.

In the simplest case when \( H_C = 0 \) (horizontal pipe), \( s_H \approx 0 \) and value of efficiency is constant dependence (7) becomes quadratic:

\[
M_C \approx M_H (1 - s)^2
\]  

(8)

With the introduction of parameters, the program generates the vector of right parts of the system of differential equations of the electromagnetic balance of the electric drive. For reduction to canonical form, it is necessary to solve the system (5) with respect to the first derivatives of the current projections (four equations) for the specific schema of the drive (FC-IM, TVR-IM). In addition, the slip value is taken as another variable. In accordance with (6) and (7):

\[
\frac{ds}{dt} = -\frac{1}{\omega_0} \frac{d\omega}{dt} = -\frac{1}{I\omega_0} (2p_m l_m (i_y i_x - i_z i_x) - M_C) \]  

(9)

Another equation in the system \((dM_C/dt \) value) obtained by derivation of equation (4):
By writing the numerical equations (1)?, (5)? and (6)? in the normalized form, we get the system ready to be calculated by one of the numerical methods:

\[
\begin{align*}
\frac{dl_{1x}}{dt} &= \frac{1}{l_{1y} - l_{2y}} (r_{1y} i_{1x} + \omega l_{1y} i_{1y} - \omega s l_{1x} + r_{2y} l_{2y} + \omega s l_{2x} - \omega s l_{2x} + (l_{1y} - l_{1x})), \\
\frac{dl_{2x}}{dt} &= \frac{1}{l_{2y} - l_{2y}} (r_{2y} i_{2x} - \omega l_{2y} i_{2x} - \omega l_{2x} - \omega s l_{2x} + r_{2y} l_{2y} + (l_{2x} - l_{1x})), \\
\frac{ds}{dt} &= -\frac{3p_{m} l_{m}}{J_{m}} i_{1y} i_{2y} + \frac{3p_{m} l_{m}}{J_{m}} i_{1x} i_{2y} + \frac{M_{c}}{J_{m}}, \\
\frac{dM_{c}}{dt} &= \frac{3p_{m} l_{m}}{J_{m}} i_{1y} i_{2y} - \frac{3p_{m} l_{m}}{J_{m}} i_{1x} i_{2y} + \frac{1}{J_{m}} (3p_{m} l_{m} i_{1y} i_{2y} - 3p_{m} l_{m} i_{1x} i_{2y} + \frac{2M_{c}}{J_{m}} + \frac{2M_{c} M_{c}}{J_{m}}).
\end{align*}
\]

Authors have developed universal program for calculation transient processes of the asynchronous electric drives in "Mathcad"(MathSoft) software environment, which contains firmware for the numerical solution for systems of differential equations of first and higher orders. Fig. 1 illustrates flowchart of the algorithm of calculation.

Type of the transient process and its parameters together with the load parameters define the vector of initial conditions. In addition, by using subprogram "Calculation of du/dt", it is possible to set form and intensity of increasing of the control impact signals. Further, the numerical method of calculation of the system (Runge-Kutta’s method with fixed or adapted step, Bullies-Stoer method and so on), interval and step of calculation are selected.

Results are displayed in tabular or graphical form.

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**Fig.1. Flowchart of the algorithm of the calculation of dynamic characteristics of the centrifugal pump.**
For clarity, here were given results of calculation of electromagnetic torque and stator current of 4АНК 315 4У3 induction motor with following parameters:

\[ U_N = 380 \text{ V}, \quad I_{1N} = 212 \text{ A}, \quad r_1 = 0.0379, \quad r_2 = 0.0448, \quad l_1 = 0.00077, \quad l_2 = 0.00074, \quad l_m = 0.01867, \quad p = 2, \quad s_N = 0.025. \]

Fig. 2. Electromagnetic torque of the IM when the centrifugal pump was started directly.

Fig. 3. Stator current of the induction motor when the centrifugal pump was started directly.

As an example (Figures 4, 5) the results of the calculation of the electromagnetic torque and the stator current of the induction motor 4АНК 315 4У3 are given for a direct start of the pump and for the exponential build-up of voltage on the stator.

1.3 - The active components; 2.4 - Reactive components

**Figure 4.** IM current at direct (3-4) and smooth (1.2) starting with the centrifugal load

**Figure 5.** IM torques in the direct (2) and smooth (1) starting with the centrifugal load.
The absence of sharp fluctuations in the electromagnetic torque at a controlled \( \text{du} / \text{dt} \) value allows to avoid sudden overloads of hydraulic components of the pump unit.

As a result, the monitor in tabular or graphical form outputs:

- The instantaneous values of the projections of the stator and rotor currents \( i_{1x}(t), i_{1y}(t), i_{2x}(t), i_{2y}(t) \);
- The instantaneous values of the IM rotor speed \( \omega(t) \);
- Instantaneous torque resistance of \( M_{c}(t) \) mechanism and electromagnetic torque of IM \( M(t) \);
- Maximum and minimum values of these parameters.

This information is sufficient to use for a further developed software module "Calculation of energy characteristics", to receive power data in dynamic mode (Figure 6).

\[
P(t) = 3(u_{1x}(t)i_{1x}(t) + u_{1y}(t)i_{1y}(t))
\]

Figure 6. The block scheme of calculating the energy performance of CP actuator in dynamic conditions.
\[ Q(t) = 3(u_{1x}(t)i_{1y}(t) + u_{1y}(t)i_{1x}(t)) \]

\[ S(t) = 3(\sqrt{u_{1x}^2 + u_{1y}^2}) \sqrt{i_{1x}^2 + i_{1y}^2} \] (12)

Since in the preparation of the electromagnetic equilibrium equations of the stator voltage vector is aligned with the axis of \( x \) synchronous coordinates, in (5) the projection \( u_{1y} = 0 \).

Figures 7 and 8 shows the results of calculations of the instantaneous values of power consumption of an induction motor with direct start of the centrifugal pump and the instantaneous motor power factor

\[ K_M(t) = \frac{P(t)}{S(t)} \] (13)

Figure 7. Direct start of CP. 1 - active power \( P(t) \); 2 – reactive power \( Q(t) \); 3 – apparent power \( S(t) \);

Figure 8. The power factor of IM with CP direct start.

Further, the instantaneous value of available capacity is calculated in the program on the motor shaft during the transition process (Figure 9)

\[ P_B(t) = \omega(t)M_\omega(t) \] (14)

and instantaneous efficiency (Figure 10).

\[ \eta(t) = \frac{P_B(t)}{P(t)} \] (15)
Proposed program also includes the withdrawal of the maximum values of current, torque and power of IM in the transition mode, which is useful in calculating the protection and formation of transients.

Figure 9. CP direct start. 1 - consumed active power \( P(t) \); 2 – IM shaft power \( P_e(t) \) BP;

Figure 10. The efficiency of IM with CP direct start.

In addition to the character of electromagnetic and electromechanical transients in the design of the electric drive system is useful to know the integral characteristics for all time, for example, starting. These data are obtained by integrating the relevant variables within the time course of the transition process:

\[
P_n = \frac{1}{t_n} \int_{t_{n_{ave}}}^{t_n} P_N(t) dt, \quad Q_n = \frac{1}{t_n} \int_{t_{n_{ave}}}^{t_n} Q_N(t) dt, \quad S_n = \frac{1}{t_n} \int_{t_{n_{ave}}}^{t_n} S_N(t) dt, (16)
\]

where \( t_n \) - the duration of the transition process.

Accordingly, the integrated value of power factor and efficiency for the transient are determined as

\[
K_{Mn} = \frac{P_n}{S_n}, \quad \eta_n = \frac{P_{Bn}}{P_n}
\]

Application of soft start is an important factor to avoid hydraulic shocks in the system. We have studied the influence of the shape and intensity of the voltage rise at the starting power characteristics. Integral characteristics are shown in Table 1.
Table 1:

<table>
<thead>
<tr>
<th>Timeconstant T, с</th>
<th>$P_n$, кВт</th>
<th>$Q_n$, кВАр</th>
<th>$S_n$, кВА</th>
<th>$K_{sn}$</th>
<th>$\eta_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>570.7</td>
<td>2029</td>
<td>2133</td>
<td>0.267</td>
<td>0.396</td>
</tr>
<tr>
<td>0.1</td>
<td>602.2</td>
<td>2226</td>
<td>2334</td>
<td>0.259</td>
<td>0.348</td>
</tr>
<tr>
<td>0.2</td>
<td>688.4</td>
<td>2593</td>
<td>2719</td>
<td>0.254</td>
<td>0.330</td>
</tr>
<tr>
<td>0.5</td>
<td>980.1</td>
<td>4091</td>
<td>4265</td>
<td>0.230</td>
<td>0.219</td>
</tr>
</tbody>
</table>

Conclusion

For the development of spiral - vector theory of AC electrical machines offered a single mathematical formalism to describe the electromagnetic processes in an asynchronous motor at different control schemes and modes of operation of the electric centrifugal units.

To estimate energy consumption in transient operating conditions of centrifugal units designed a model of the dynamic processes of the asynchronous electric drives. A complete system of initial equations describing processes in asynchronous electric centrifugal pumps, composed of four groups: electromagnetic equilibrium equations (Kirchhoff), describing the electromagnetic processes in the engine, an electromechanical energy conversion equations, the equations describing the features of a mechanical load on the motor shaft and the equations that reflect the output parameters and properties of power supplies.

Established on the basis of «Mathcad» mathematical computer model application is universal, because it covers all variants of IM control.

By setting the required initial conditions all kinds of transients are simulated (start, stop, reverse, reset, and load impingement), various forms of defining actions for their formation (6).

Calculation of the instantaneous values of currents, moments, accompanied by capacity calculation of integral characteristics - capacity during the transition process, power factor and efficiency. The model takes into account the basic technical characteristics of the CP and the pipeline.

Thus, the proposed method and a program for calculating the energy performance allows us to estimate the nature of transients and determine the energy consumption in dynamic modes of different electric centrifugal machine systems.

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