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ANALYZING THE OPERATING STATES OF THE POLYMERIZATION REACTOR ON THE BASIS OF THE MEASURED PARAMETERS OF THE DRIVING SPECIALLY DESIGNED INDUCTION MOTOR

This article proposes to identify the modes of polymerization reactor on the basis of the measured values of electrical feed parameters of the special induction electric motor, which sets in motion the device of the polyethylene mixing. The algorithm of calculations that allows you to get enough accurate value of useful electromagnetic torque of frequency controlled induction motor taking into account the losses in copper and steel is developed.

Запропоновано ідентифікувати режими роботи полімеризаційного реактора за виміряними значеннями електричних параметрів живлення спеціального асинхронного електродвигуна, який приводить в рух пристрій размішування поліетилену. Розроблено алгоритм розрахунків, який дає змогу отримати достатньо точне значення корисного електромагнітного моменту частотно регульованого асинхронного двигуна з врахуванням втрат у міді та сталі.

Предлагается идентифицировать режимы работы полимеризационного реактора по измеренным значениям электрических параметров питания специального асинхронного электродвигателя, который приводит в движение устройство размешивания полиэтилена. Разработан алгоритм расчетов, позволяющий получить достаточно точное значение полезного электромагнитного момента частотно регулируемого асинхронного двигателя с учетом потерь в меди и стали.

Introduction. The specially designed asynchronous motor (AM) is used to mix the polyethylene mass under high pressure in the polymerizer of ethylene. The motor works vertically whereas its rotor together with the long mixing mechanism is supported on the lower slide bearing. The drive system is fed directly by the grid or the frequency converter. In the drive systems for the polymerization reactors, the prototype of the motor can substitute the motor made by the English METHER-PLATT Co. from Manchester.

The drive system of the polymerization mixer is characterized by the exceptional, untypical construction and especially complicated operating conditions, e.g.:

- the location of the motor of 55 kW in the enclosed pipe socket with the diameter of 302 mm and the entire length of 919 mm;
- the impossibility of using ventilation in the motor as well as the impossibility of a standard feeding due to the operation of the motor directly inside of the reactor under the working pressure up to 2800 atm;
- a single-point suspension system for the vertical operation of the motor together with the mixer in the lower chamber of the reactor (the upper bearing is used in order to align the rotor in the stator);
- the work of a single-point vertical suspension system applying non-greased swinging slide bearing made of large-diameter rings of sintered carbides.

Formulation of the problem. The following phenomena may occur during the work of the drive system for the polymerization reactor. These phenomena exceed the work of standard drive systems and they have a direct influence on the work of the drive system as its load:

- agglutination of the stator and rotor from the driving side as a result of polymerization occurring in this area of the chamber of the polymerization reactor;
- sliding friction in the large-size slide bearing made of sintered carbides and cooled by the ethylene stream through the guide apparatus of a cooling unit;
- the filling of the mixer construction with polyethylene in the mixing chamber of the polymerization reactor;
- sliding friction of the mixer filled with polyethylene in the area of the charge of the mixer chamber of the polymerization reactor by polyethylene;
- the mixing of the ethylene stream by the mixer in the lower chamber of the polymerization reactor in the area unfilled with polyethylene or the mixing of the ethylene stream by the mixer when the drive system works with an uncharged mixer.

The inaccessibility of the AM and the mechanical system makes it impossible to identify these phenomena and the operating states of the drive with the use of traditional ways because it is necessary to keep the parameters of the technological process.

The aim of the paper. The aim of the paper is to develop a method of analyzing the operating states of the polymerization reactor on the basis of the continuous monitoring of the motor operation using the parameters of feeding voltage with variable frequency.

Description of the method. The AM torque is a general parameter which allows distinguishing between the phenomena during the operation of the drive system for the polymerization reactor. If the tests of the asynchronous drive are carried out for two cases, i.e. for the polymerizer with ethylene and without ethylene, the value of the torque increment in the second case determines the level of the filling with polyethylene in the area of the charge of the mixer chamber of the polymerization reactor. The agglutination of the AM rotor and stator can be identified if any torque increment limit is exceeded. Thus, the continuous monitoring requires the development of a calculation method for determining the AM torque on the basis of the measured parameters of the motor feed.

The energy diagram (Fig. 1) reflects the operating conditions of the drive for the polymerizer of ethylene. The electric energy W_{E} consumed by the AM is transformed into mechanical energy of the rotor W_{mech} and the respective losses of electromagnetic energy ΔW_{em} in copper and steel of the AM. A part of the produced mechanical energy ΔW_{zl} is lost due to the overcoming of the agglutination of the rotor and the stator. The main part of mechanical energy is transformed into thermal energy ΔW_{tl} as a result of friction in the lower bearing. This part may be divided into three parts: the loss ΔW_{tw} coming from friction caused by the rotor weight, the loss ΔW_{tm} coming from friction caused by the mixer weight and the loss ΔW_{tp} coming from friction caused by the polyethylene weight. The first one and the second one may be interpreted as constant internal losses of the drive. The third one, depending on the filling of the mixer with polyethylene, should be interpreted as external losses caused by the technological process. The last part of the mechanical energy together with the energy ΔW_{w} caused by the friction of the mixer against the air (ventilation loss) and the energy ΔW_{p} caused by friction of the polyethylene against the reactor wall may be interpreted as the output energy W_{uz}.

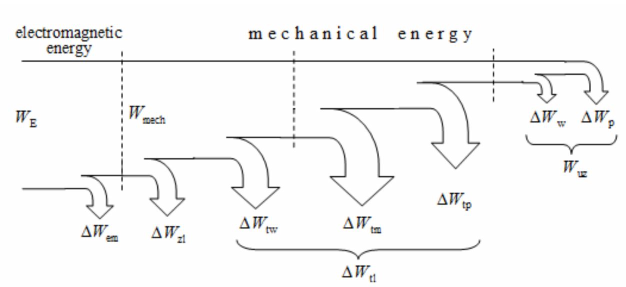

Fig.1. Energy diagram illustrating the work of the drive for the polymerizer of ethylene

The well-known equivalent circuit of the AM [1] may be used and developed in order to describe mathematically the steady-state processes in the drive for the polymerizer of ethylene. This development concerns the part of the equivalent circuit connected with the mechanical load according to the energy diagram shown in Fig. 1. The quantities describing the equivalent circuit of the phase winding of the symmetrical AM are as follows: $\underline{U}_1$ and $\underline{I}_1$ are complex voltage and the current of the stator respectively, R_1 and X_1 are resistance and leakage reactance of the stator phase winding, $R_2^{'}$ and $X_2^{'}$ are resistance and leakage reactance of the rotor phase winding transformed into the stator phase winding, X_{m} is magnetization reactance, R_{Fe} is resistance corresponding to the iron loss, $\underline{I}_2^{'}$ is the complex current of the rotor transformed into the stator winding, $\underline{U}_{20}^{'}$ is the complex voltage of rotor (EMF) transformed into the stator winding. The electromagnetic power in the air-gap of the AM converted into the power of the mechanical load is divided into three parts being equal to the losses of mechanical energy: ΔW_{zl}, ΔW_{tl} and W_{uz} respectively, and they are represented by resistances R_{zl}, R_{tl} and R_{uz} in a parallel connection.

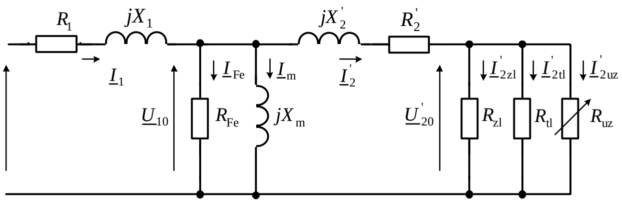

Fig.2. Equivalent circuit of the AM phase winding

In accordance with the theory of the asynchronous motor, the mechanical load is represented in equivalent circuit by the following resistance

$$R_2^{'}\frac{1-s}{s}=R_2^{'}\left(\frac{1}{s}-1\right),$$

where s is slip.

The load may be divided into three abovementioned parts corresponding to the increments of the load torques: ΔM_{zl}, ΔM_{tl}, ΔM_{uz} respectively. These increments cause increments of slip while the general slip is as follows: $s=\Delta s_{\mathrm{zl}}+\Delta s_{\mathrm{tl}}+\Delta s_{\mathrm{uz}}$. Hence, the following terms of the parallel connection of the resistances representing the load are obtained

$$R_{\mathrm{zl}}=R_2^{'}\frac{1-s}{\Delta s_{\mathrm{zl}}};\quad R_{\mathrm{tl}}=R_2^{'}\frac{1-s}{\Delta s_{\mathrm{tl}}};\quad R_{\mathrm{uz}}=R_2^{'}\frac{1-s}{\Delta s_{\mathrm{uz}}}.$$

The AM in a version SAR-55/1500/09 is used in order to drive the polymerizer. The rated parameters of the AM are as follows

$$P_{\mathrm{n}} = 55\ \mathrm{kW},\quad U_{1\mathrm{n}} = 380\mathrm{V},\quad f_{\mathrm{n}} = 50\ \mathrm{Hz},\quad M_{\mathrm{n}} = 374\ \mathrm{N{\cdot}m},$$
$$M_{\max} = 842{,}85\ \mathrm{N{\cdot}m},\quad n_{\mathrm{n}} = 1420\ \mathrm{rpm},\quad p_{\mathrm{b}} = 2,$$
$$I_{1\mathrm{n}} = 108\ \mathrm{A},\quad J = 1{,}02\ \mathrm{kg{\cdot}m^2},\quad G = 385\ \mathrm{kg}. \qquad (1)$$

The parameters of the stator winding, the rotor winding and the magnetization branch are as follows

$$R_1 = 0{,}156\ \mathrm{Ohm},\quad X_1 = 0{,}4765\ \mathrm{Ohm},$$
$$R_2^{'} = 0{,}156\ \mathrm{Ohm},\quad X_2^{'} = 0{,}4765\ \mathrm{Ohm},$$
$$R_{\mathrm{Fe}} = 200\ \mathrm{Ohm},\quad X_{\mathrm{m}} = 16{,}286\ \mathrm{Ohm}. \qquad (2)$$

Mathematical model of the drive for the polymerizer. In accordance with the directions of voltages and current flows marked in Fig. 2, on the basis of the first and the second Kirchhoff's law, the following system of equations for complex variables may be written [2]

$$\underline{I}_1(R_1+jX_1)+\underline{U}_{10}=\underline{U}_1,$$
$$\underline{I}_{\mathrm{Fe}}R_{\mathrm{Fe}}=\underline{U}_{10},$$
$$\underline{I}_{\mathrm{m}}\cdot jX_{\mathrm{m}}=\underline{U}_{10},$$
$$\underline{I}_1-\underline{I}_{\mathrm{Fe}}-\underline{I}_{\mathrm{m}}-\underline{I}_2^{'}=0,$$

$$\underline{I}_2^{'}\left(R_2^{'} + jX_2^{'}\right) + \underline{U}_{20}^{'} = \underline{U}_{10} \, ,$$
$$\underline{U}_{20}^{'} = \underline{I}_2^{'} R_2^{'} \frac{1-s}{s} \, . \tag{3}$$

The values of feeding phase voltage U_{f}, line current I_{p} and active power P consumed from the supply grid may be measured on the input of the asynchronous drive. These measurements allow determining the following variables of the equivalent circuit

$$\underline{U}_1 = \sqrt{2}\, U_{\mathrm{f}} \, ,$$
$$\underline{I}_1 = \sqrt{2} I_{\mathrm{p}}\, \mathrm{e}^{-j\varphi} \, , \tag{4}$$

where φ is phase angle and S is apparent power of the drive

$$\varphi = \arccos \frac{P}{S} \, ,$$
$$S = 3 U_{\mathrm{f}} I_{\mathrm{p}} \, .$$

Considering the parameters of the equivalent circuit (2) and the measured input quantities of the drive, the four variables of a working point: $\underline{I}_2^{'}$, $\underline{I}_{\mathrm{Fe}}$, $\underline{I}_{\mathrm{m}}$ and s come from the system of equations (3). These variables can be obtained using a computer method of numerical calculations. On the basis of the obtained variables, the following variables may be calculated afterwards:

- electromagnetic torque of the motor [3]

$$T = \frac{P_{\mathrm{mech}}}{\omega} = \frac{\frac{3}{2}\left|\underline{I}_2^{'}\right|^2 R_2^{'} \frac{1-s}{s}}{\omega_0 (1-s)} = \frac{3\left|\underline{I}_2^{'}\right|^2 R_2^{'}}{2\omega_0 s} \, , \tag{4}$$

where P_{mech} is mechanical power of an asynchronous motor, ω is angular velocity of a motor, $\omega_0 = 2\pi \, f_1 / p_{\mathrm{b}}$ is angular velocity of an idle-running motor, f_1 is frequency of the feeding voltage, p_{b} is number of pole pairs;

– angular velocity of a motor

$$\omega = \omega_0 (1-s) ; \tag{5}$$

– iron loss of a motor

$$\Delta P_{\mathrm{Fe}} = \left|\underline{I}_{\mathrm{Fe}}\right|^2 R_{\mathrm{Fe}} \, . \tag{6}$$

Values of resistances and reactances of the AM equivalent circuit can be obtained as a result of investigations into the idle run and short-circuit, whereas the resistance R_{Fe} representing a steel loss is unknown. This resistance is changed by frequency variation of the AM feeding voltage. A number of equations in the system is sufficient in order to calculate the value of resistance R_{Fe} if the additional equation of active power balance (7) is taken into consideration

$$\left|\underline{I}_1\right|^2 R_1 + \left|\underline{I}_{\mathrm{Fe}}\right|^2 R_{\mathrm{Fe}} + \left|\underline{I}_2^{'}\right|^2 \frac{R_2^{'}}{s} = \frac{2}{3} P \, . \tag{7}$$

However, the numerical calculations, which were carried out in the MathCad environment, showed that the obtained system of equations is not convergent. Thus, another method of calculation has to be applied.

Analytical solution of the mathematical model of the polymerizer driver. The following vector diagram corresponds to the equivalent circuit of the asynchronous drive shown in Fig. 3.

Applying the vector diagram shown in Fig. 3 and the measured data including input voltage, current and active power of the AM for the polymerizer, an approximate but not accurate enough analytical solution of the system of equations (3) and (7) can be found.

Applying the results of measurements and the law of cosines, the exact absolute value of voltage $\underline{U}_{10}$ may be calculated, which is shown in Fig. 3

$$\left|\underline{U}_{10}\right|^2 = \left|\underline{I}_1 Z_1\right|^2 + \left|U_1\right|^2 - 2\left|\underline{I}_1 Z_1\right| \left|U_1\right| \cos(\alpha - \varphi) , \tag{8}$$

where $Z_1 = \sqrt{R_1^2 + X_1^2}$ and $\alpha = \mathrm{arctg}(X_1 / R_1)$.

Considering the measured data, the dependency (8) may be transformed into the following form

$$U_{10} = \sqrt{2} \sqrt{\begin{aligned} & I_{\mathrm{p}}^2 \left(R_1^2 + X_1^2\right) + U_{\mathrm{f}}^2 - 2 I_{\mathrm{p}} U_{\mathrm{f}} \sqrt{R_1^2 + X_1^2} \times \\ & \times \cos\left[\mathrm{arctg}(X_1/R_1) - \varphi\right] \end{aligned}} \, .$$

A fragment of the vector diagram (Fig. 4) is taken into account for further calculations. Henceforth absolute values of variables will be considered.

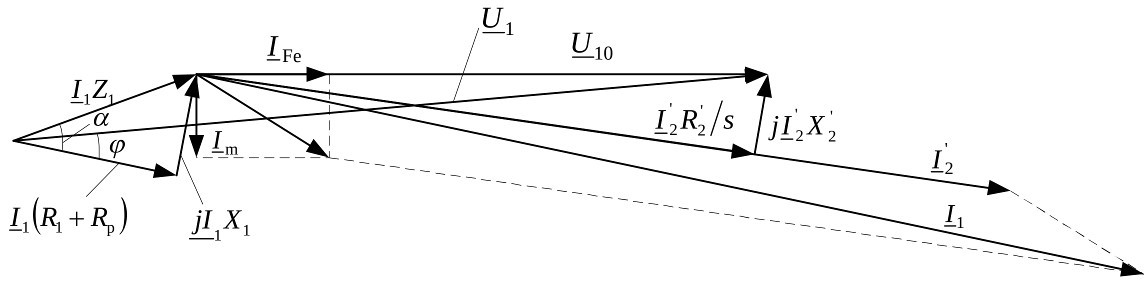

Fig.3. Vector diagram corresponding to the equivalent circuit

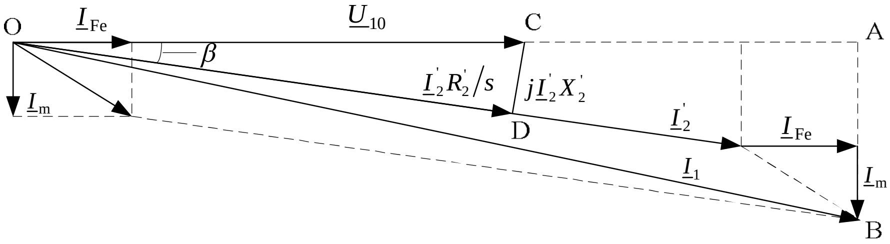

Fig.4. Fragment of the vector diagram shown in Fig. 3

The sine term follows from the triangle OCD

$$\sin\beta = \frac{I_2^{'}X_2^{'}}{U_{10}}. \qquad (10)$$

The values of the triangle sides are given as follows

$$\mathrm{OA} = I_2^{'}\cos\beta + I_{Fe}, \quad \mathrm{AB} = I_2^{'}\sin\beta + I_m.$$

In accordance with the Pythagorean theorem, the following dependency among the triangle sides may be written

$$\left(I_2^{'}\cos\beta + I_{Fe}\right)^2 + \left(I_2^{'}\sin\beta + I_m\right)^2 = I_1^2. \qquad (11)$$

Putting the term (10) and $I_m = U_{10}/X_m$, $I_{Fe} = U_{10}/R_{Fe}$ into the dependency (11), assuming subsequently $\cos\beta \approx 1$ in order to solve the dependency analytically and finally applying the measured data (4), the following meaning of the rotor phase current is found

$$I_2^{'} = \frac{-U_{10}/R_{Fe} + \sqrt{\begin{array}{l}(U_{10}/R_{Fe})^2 + \left(1 + 2X_2^{'}/X_m\right) \times \\ \times\left[2I_p^2 - (U_{10}/X_m)^2 - (U_{10}/R_{Fe})^2\right]\end{array}}}{1 + 2X_2^{'}/X_m}. \qquad (13)$$

The slip comes from the triangle OCD

$$s = \frac{R_2^{'}}{\sqrt{\left(\frac{U_{10}}{I_2^{'}}\right)^2 - X_2^{'2}}}. \qquad (14)$$

Applying the formula (14), the electromagnetic torque of the motor given by (4) is transformed as follows:

$$T = \frac{3I_2^{'}}{2\omega_0}\sqrt{U_{10}^2 - \left(I_2^{'}X_2^{'}\right)^2}. \qquad (15)$$

Thus, the system of equations (9), (13), (14) and (15) describes analytically the operation of the asynchronous drive for the polymerizer of ethylene. There is one parameter – R_{Fe} – that is difficult to evaluate, apart from the known parameters of the equivalent circuit of the motor. This parameter can be found by solving the system of equations with the use of the method of successive approximations. The measured values of the AM feeding variables should be considered in the system of equations. The voltage U_{10} is independent of R_{Fe}. This voltage is calculated according to (9). In the first approximation, the steel loss may be omitted by assuming the infinite value of R_{Fe}. Applying the equations (13), (14) and (15) respectively, the variables $I_2^{'}$, s and T may be calculated and as a result, the active power may be derived from the equation (7)

$$P = \frac{3}{2}\left(I_1^2R_1 + \frac{U_{10}^2}{R_{Fe}} + I_2^{'2}\frac{R_2^{'}}{s}\right), \qquad (16)$$

and compared with the measured value. If errors of calculations exceed the acceptable level, the new value of R_{Fe} should be found for the measured value of P and then the calculations according to the formulas (13), (14) and (15) have to be repeated. A simple computer program may be used in order to calculate the accurate values of variables $I_2^{'}$, s, T, R_{Fe} according to the above algorithm.

Conclusions. The proposed method of calculations of the AM torque is simple and also accurate enough. It allows for a continuous analysis of the operating states of the polymerization reactor of ethylene on the basis of the measured variables of the electric energy consumed by the AM. Future researches will be direct to experimental study of proposed method of analyzing of the modes of the polyethylene polymerization reactor.

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