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THE EQUIVALENT CIRCUIT OF SPECIALLY DESIGNED INDUCTION MOTOR FOR A MAIN DRIVE SYSTEM OF POLYMERIZATION REACTOR

Abstract: In the paper a construction of specially designed induction motor for a main drive system of polymerization reactor taking into account the power loss in large-size slide bearing made of sintered carbides is described. The constructional details of motor-bearing set allowing for vertical operation of motor are also given [1], [2]. The analysis of power distribution taking into account a slide friction loss in bearing is presented. Resistances of equivalent circuit secondary part as additional vertical branches are determined. The equations describing specially designed induction motor for drive system of polymerization reactor are given. In the equations the loss in large-size slide bearing is taken into account. The equations allow determining static characteristics of the motor. Moreover, in equivalent circuit the phenomenon of agglutination of rotor with stator is taken into account as a result of polymerization phases in reactor chamber where the motor is placed.

1. Description of construction of motor SAR-55/1500/09

Polymerization reactors play the most significant role in technological line of production of polyethylene. A drive system for mixer of polymerization process works in two chambers. The conditions of drive system operation are specific due to the requirement of keeping a constant temperature, ethylene atmosphere and operating pressure up to 2800 atm. The motor in drive system has non-standard dimensions and construction due to the socket fixing in upper chamber of reactor in vertical system. The drive system may be fed directly from mains, motor-generator set or frequency converter. Drive systems in polymerization reactors often damage because of extraordinary operating conditions e.g. feeding the motor by pressure electrodes providing trouble-free operation at difference in pressure up to 2800 atm. The specially designed induction motor with a pipe construction and a large-size slide bearing made of sintered carbides was made as a result of design efforts and alternative develop-ments of prototypes. The rated parameters of the motor are as follows: P_n = 55 kW, U_{1n} = 380V, f_n = 50 Hz, M_n = 374 Nm, M_{max} = 842,85 Nm, n_n = 1420 rpm, p_b = 2, I_{1n} = 108 A, J = 1,02 kg·m^2 , G = 385 kg.

The motor was made as a pipe system whereas the rotor with a bar winding was made on the basis of a hollow shaft. The motor is adapted for vertical operation with alignment of rotor by single-row cylindrical bearing at the top and large-size slide bearing made of sintered carbides with swing fixing of the lower part of bearing at the bottom. The motor is provided with socket-contacts allowing to feed the stator winding by the pressure electrodes.

The basic constructional parameters and technical data of motor prototype SAR-55/1500/09 are as follows: entire length of body 918 mm, entire length of stator core assembly 565 mm, entire length of rotor core assembly 580 mm, diameter of a pipe body 300 mm, diameter of rotor 179 mm, ending of the shaft – internal multi-key, internal diameter of slide bearing 114 mm, external diameter of slide bearing 146 mm, sintered carbide GT-30P-5/6/11/25. The motor in drive systems for polymerization reactors made by English firm Mether-Platt from Manchester was replaced by prototype of motor. Examples of motor prototype construction SAR-55/1500/09 are given in Fig. 1 and 2.

Fig. 1 A view of the pipe bodies of motors SAR-55/1500/09 [1], [2]

Fig. 2 Ending of the bar rotor of induction motor SAR-55/1500/09 from side of slide bearing set [1], [2]

2. Equivalent circuit of specially designed induction motor of drive system for polymerization reactor

Considering the assumed technology, polymerization reactors of ethylene are provided with a pressure chamber where a drive system based on specially designed induction motor works in vertical system containing a mixer. The whole system is suspended on large-size slide bearing located at the bottom of induction motor. The drive system for polymerization reactor based on induction motor is depicted in Fig. 3.

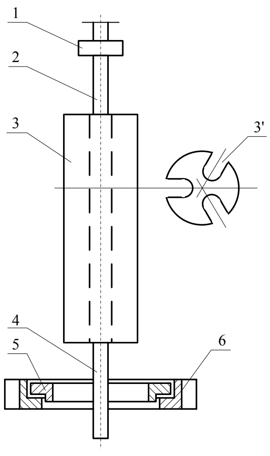

Fig. 3 Suspension of motor SAR-55/1500/09 in drive system for polymerization reactor, where: 1 is upper bearing, 2 is upper ending of motor shaft, 3 is rotor, 4 is lower ending of motor shaft, 5 is the slide ring of lower bearing, 6 is swing part of lower bearing

Operating conditions of drive system for polymerization reactor from energy distribution point of view are depicted in Fig. 4. The aforementioned operating conditions resulting from technology of polymerization cycle cause that energy distribution differs from standard energy distribution in industrial drive systems based on induction motors. Electric energy W_E decreased by energy losses in stator copper and iron ΔW_{em} is transported to rotor as mechanical energy W_{mech}. Mechanical energy W_{mech} is divided into mechanical energy of idling motor, mechanical loss resulting from friction in large-size slide bearing ΔW_{wt} and mechanical loss resulting from polymerization phenomenon that causes agglutination of rotor with stator ΔW_{zl}. The mechanical energy of idling motor is equal to mechanical loss which is independent of motor load. The friction in large-size slide bearing is caused by rotor weight. The output mechanical energy W_{uz} consists of both mechanical energy loss ΔW_{tm} resulting from friction in slide bearing caused by mixer weight and mechanical energy resulting from mixing the ethylene in the upper chamber and mixing of polymerization phases in the lower chamber.

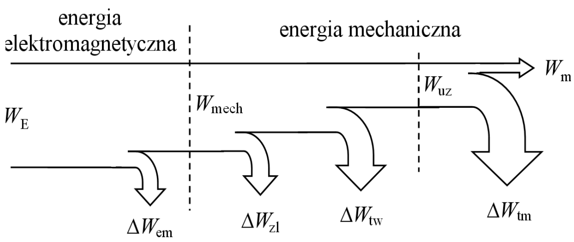

Fig. 4 Diagram of energy distribution in induction motor SAR-55/1500/09 of drive system for polymerization reactor

An equivalent circuit for single phase of induction motor (Fig. 5) is given in order to describe mathematically steady-state processes in drive system for polymerization reactor based on specially designed induction motor. The circuit takes into account both the motor operation in vertical system including large-size slide bearing and agglutination of rotor with stator as a result of polymerization in reactor chamber.

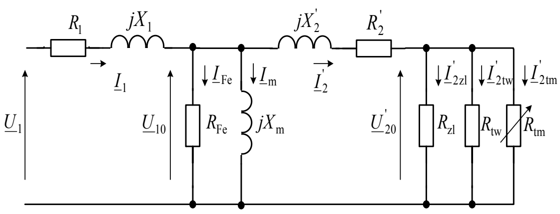

Fig. 5 The equivalent circuit of specially designed induction motor taking into account mechanical loss in large-size slide bearing and mechanical loss caused by agglutination of rotor with stator

The respective elements in equivalent circuit (Fig. 5) have the following meanings: U_1, I_1 are supply voltage and stator phase current, R_1, X_1 are resistance of stator phase winding and stator leakage reactance, $R_2^{'}$, $X_2^{'}$ are resistance of rotor phase winding and rotor leakage reactance both transformed to the stator winding, X_m is main magnetization reactance, R_{Fe} is resistance representing iron loss, R_{zl}, R_{tw}, R_{tm} are resistances representing mechanical losses coming from agglutination of rotor with stator, friction in large-size slide bearing caused by rotor weight and friction in large-size slide bearing caused by mixer weight, respectively.

The power of rotating field corresponding to equivalent circuit shown in Fig. 5 covers practically the torque of idle running which consists of: torque of agglutination of rotor with stator and torques of friction in slide bearing caused by rotor and mixer weights. The power covering load torque resulting from mixing of ethylene is relatively low due to the diameter of mixer. This diameter is comparable with diameter of motor rotor. The load of motor in drive system for polymerization reactor changes significantly if polymerization process appears in lower chamber due to the fact that part of mixer is immersed in polyethylene. The abovementioned operating conditions of drive system require separate analysis of drive system taking into account partial polymerization in chamber on a level of mixer.

3. The loss of agglutination of rotor and stator and the loss in slide bearing of motor

The agglutination of rotor with stator in drive system for polymerization reactor is a phenomenon which should not occur during normal operation of technological line. Construction of motor SAR-55/1500/09 assumes cooling of large-size slide bearing with lateral ethylene stream. The aforementioned cooling results in frequent agglutination of slide bearing parts and stator with rotor at the bottom of motor air-gap. Consequences of polymerization in lower part of motor are shown in Fig. 6 where disassembled motor SAR-55/1500/09 after tests in polymerization reactor is shown.

Determination of additional load torque coming from polymerization process is based on application of operating forces caused by agglutination of surfaces in vicinity of polymerization [1]. Occurrence of the abovementioned forces is depicted in Fig. 7 for flat plates and constant gap between plates. The operating force caused by agglutination of surfaces shown in Fig. 7 may be determined applying an unitary measurement force of agglutination and phase agglutination coefficient.

Fig. 6 Stator of motor SAR-55/1500/09 from side of slide bearing after tests in reactor with consequences of polymerization [1], [2]

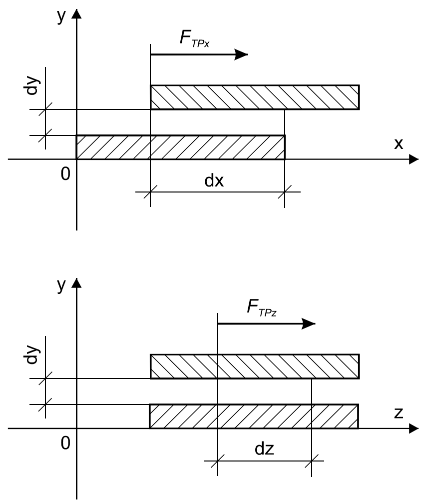

Fig. 7 A set of flat plates allowing to determine an operating force caused by agglutination of surfaces, where: F_{TPx}, F_{TPz} are operating forces caused by agglutination of surfaces in axes x and z; dx, dz are segments of surface in axes x and z; dy is a gap

The unitary measurement force caused by agglutination of surfaces is determined experimentally for given polymerization process and given conditions. This force for polymerization process in polymerization chamber containing drive system with motor SAR-55/1500/09 is expressed as follows [1]

$$F_{ip} = (4{,}6 \div 7{,}5) \cdot 10^{-2} \quad \left[\frac{\mathrm{N}}{\mathrm{m}^2} \right] \tag{1}$$

The polymerization process is characterized by polymerization phases which are determined by phase agglutination coefficient r_p in order to determine the operating force caused by agglutination of surfaces. The coefficient r_p as a function of both a gap between flat surfaces and phase of polymerization process is given in Fig. 8.

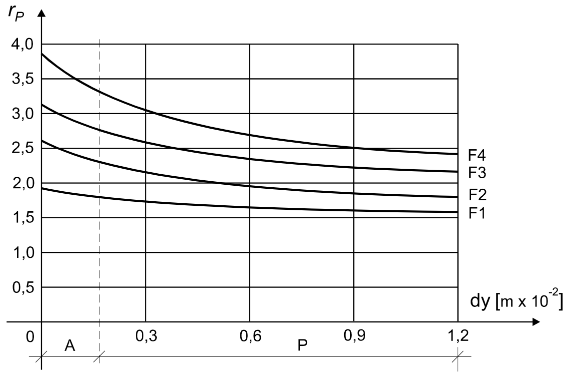

Fig. 8 The phase agglutination coefficient r_p as a function of gap dy between flat surfaces for various phases of polymerization F1 to F4

The unitary operating force F_{iTP} caused by agglutination of surfaces is proportional to unitary measurement force caused by agglutination of surfaces and phase agglutination coefficient. This force is expressed as follows

$$F_{iTP} = F_{ip} \cdot r_p(dy) \tag{2}$$

The whole operating agglutination force F_{zl} is proportional to area of its action and unitary operating agglutination force. The whole operating agglutination force F_{zl} is determined by the following dependency

$$F_{zl} = F_{ip} \cdot r_p(dy) \cdot dx \cdot dz \tag{3}$$

where: *dx, dz* are true dimensions of surface covered by polymerization process, *dy* is gap between surfaces.

The mechanical losses are represented in equivalent circuit of induction motor by resistances occurring on the rotor side transformed to the stator winding.

In the studied induction motor working in drive system for polymerization reactor the entire load torque is consisted of torques caused by: (1) friction in large-size slide bearing as a result of both rotor and mixer weights, (2) agglutination of rotor with stator and (3) resistance of medium mixed in reactor chamber. Assuming that resistance of medium mixed in reactor chamber is negligible (if polymerization products do not occur in lower part of chamber) the entire torque is expressed as follows

$$M_{\Sigma o} = \Delta M_{zl} + \Delta M_{tw} + \Delta M_{tm} \tag{4}$$

where: ΔM_{zl} is increment of torque coming from agglutination of rotor with stator, ΔM_{tw} is increment of torque coming from friction in slide bearing caused by rotor weight, ΔM_{tm} is increment of torque coming from friction in slide bearing caused by mixer weight.

The increments of load torques expressed by (4) correspond with increments of slip giving the entire slip corresponding with entire load torque according to dependency (5).

$$s = \Delta s_{zl} + \Delta s_{tw} + \Delta s_{tm} \tag{5}$$

where: $\Delta s_{zl}, \Delta s_{tw}, \Delta s_{tm}$ are increments of slip corresponding with increments torques ΔM_{zl}, $\Delta M_{tw}, \Delta M_{tm}$, respectively. The dependency between increments of torque (4) and increments of slip (5) is illustrated in Fig. 9.

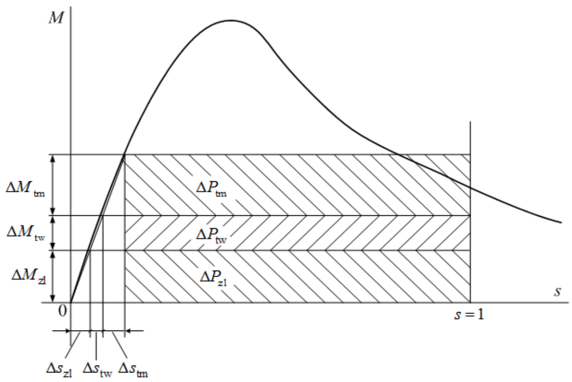

Fig. 9 Distribution of load of induction motor working in drive system of polymerization reactor

The equivalent circuit of specially designed induction motor considering mechanical loss in large-size slide bearing and mechanical loss caused by agglutination of rotor with stator (Fig. 5) is described by the following system of equations

$$\begin{gathered}
\underline{U}_1 - \underline{I}_1(R_1 + jX_1) - \underline{U}_{10} = 0 \\
\underline{U}_{10} - \underline{I}_{Fe}R_{Fe} = 0 ; \ \underline{U}_{10} - \underline{I}_m \cdot jX_m = 0 \\
\underline{I}_1 - \underline{I}_{Fe} - \underline{I}_m - \underline{I}_2' = 0 \\
\underline{U}_{10} - \underline{I}_2'(R_2' + jX_2') - \underline{U}_{20}' = 0 \\
\underline{I}_2' - \underline{I}_{2zl}' - \underline{I}_{2tw}' - \underline{I}_{2tm}' = 0
\end{gathered} \tag{6}$$

$$\underline{U}_{20}^{'} - \underline{I}_{2\mathrm{zl}}^{'} R_{\mathrm{zl}} = 0\,;\ \underline{U}_{20}^{'} - \underline{I}_{2\mathrm{tw}}^{'} R_{\mathrm{tw}} = 0$$

$$\underline{U}_{20}^{'} - \underline{I}_{2\mathrm{tm}}^{'} R_{\mathrm{tm}} = 0$$

The electric losses in resistances of vertical branches of equivalent circuit part deals with rotor winding are described as follows

$$\Delta P_{zl}^{(e)} = \frac{3}{2}\left|\underline{I}_{2\mathrm{zl}}^{'}\right|^2 R_{\mathrm{zl}}$$

$$\Delta P_{tw}^{(e)} = \frac{3}{2}\left|\underline{I}_{2\mathrm{tw}}^{'}\right|^2 R_{\mathrm{tw}} \qquad (7)$$

$$\Delta P_{tm}^{(e)} = \frac{3}{2}\left|\underline{I}_{2\mathrm{tm}}^{'}\right|^2 R_{\mathrm{tm}}$$

Increments of mechanical power resulting from load torques determined by dependencies (4) are given by the following system of equations

$$\Delta P_{zl} = \Delta M_{\mathrm{zl}}\omega_0\left[1 - \left(\Delta s_{\mathrm{zl}} + \Delta s_{\mathrm{tw}} + \Delta s_{\mathrm{tm}}\right)\right]$$

$$\Delta P_{tw} = \Delta M_{\mathrm{tw}}\omega_0\left[1 - \left(\Delta s_{\mathrm{zl}} + \Delta s_{\mathrm{tw}} + \Delta s_{\mathrm{tm}}\right)\right] \qquad (8)$$

$$\Delta P_{tm} = \Delta M_{\mathrm{tm}}\omega_0\left[1 - \left(\Delta s_{\mathrm{zl}} + \Delta s_{\mathrm{tw}} + \Delta s_{\mathrm{tm}}\right)\right]$$

where: $\omega_0 = 2\pi\ f_1/p_{\mathrm{b}}$ is angular velocity of idle running of induction motor, f_1 is frequency of mains voltage, p_{b} is a number of pole couples

The torques being a result of agglutination of rotor with stator and friction in slide bearing coming from the weight of rotor may be expressed with the help of the following dependencies:

$$\Delta M_{zl} = 0{,}5\pi F_{ip} r_p(dy) D_w^{\ 2} l\, c_{zl}^{\ '} c_{zl}^{\ ''}$$

$$\Delta M_{tw} = \frac{1}{3}\mu\frac{G_{tw}}{D+d}\left(D^2 + Dd + d^2\right) \qquad (9)$$

where D_w is diameter of motor rotor, l is length of motor rotor magnetic core, c'_{zl} is coefficient of air-gap agglutination, $c'_{zl} = 0 \div 1$, c''_{zl} is correction coefficient, μ is dynamic slide-friction factor, G_{tw} is weight of rotor magnetic core together with shaft, D is external diameter of slide bearing, d is internal diameter of slide bearing.

There are two coefficients in the first of two dependencies (9). The coefficients have the decisive influence on value of torque resulting from agglutination of rotor with stator. In the normal operating conditions the filling of agglutination do not exceed 25% of surfaces belonging to rotor and stator whereas in the damage conditions (seizing of motor) a torque breaking off the agglutination of rotor and stator exceeds significantly the rated torque of motor. It results in assumption of multiplexing of torque ΔM_{tw} by introducing a correction coefficient in operating calculations.

For comparison purposes the dependencies (9) are related to the rated torque of motor, what is expressed by dependencies (10):

$$\Delta M_{zl}^{\ *} = \frac{\Delta M_{zl}}{M_N}$$

$$\Delta M_{tw}^{\ *} = \frac{\Delta M_{tw}}{M_N} \qquad (10)$$

Considering constructional quantities of motor the dependencies (10) are developed as follows:

$$\Delta M_{zl}^{\ *} = \frac{1{,}88{,}7\pi f c_{zl}^{\ '} c_{zl}^{\ ''}}{p_b P_N} F_{ip} r_p(dy) D_w^{\ 2} l\left(1 - s_N\right)$$

$$\Delta M_{tw}^{\ *} = \frac{\mu f G_{tw}}{p_b P_N}\frac{D^2 + Dd + d^2}{D+d}\left(1 - s_N\right) \qquad (11)$$

Assuming the constructional data of motor SAR-55/1500/09 and $c'_{zl} = c''_{zl} = 1$ for air-gap dy = 0,6 and range of phase agglutination coefficient $r_p(dy) = 1{,}65 \div 2{,}75$ the agglutination torque as a function of polymerization phases was determined (Fig. 10). Furthermore, the torque in slide bearing and a sum of these torques as a function of occurrence of polymerization phases in reactor is presented.

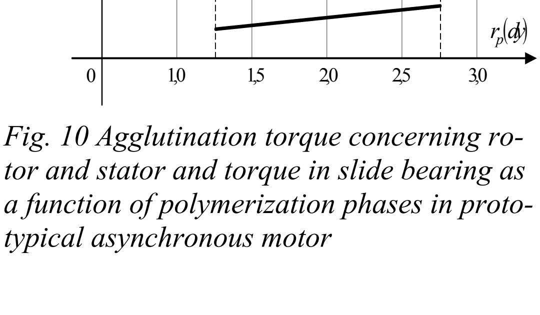

Fig. 10 Agglutination torque concerning rotor and stator and torque in slide bearing as a function of polymerization phases in prototypical asynchronous motor

For operating purposes dealing with work of polymerization reactor the following dependencies: $I_1 = I(s)$, $P_1 = P(s)$, $I_1 = I(M_{uz})$, $P_1 = P(M_{uz})$ taking into account a changing temperature of motor operation are meaningful. The dependencies may be derived from system of equations (6) and additional dependencies. The temperature variability results from technological process of polymerization in reactor where temperature parameter plays special role. The analysis of the selected steady states which has been presented in the paper may be used as a point of reference to the analysis of dynamic states of drive systems for polymerization reactors [4], [5].

4. Conclusions

On the basis of the presented equivalent circuit and systems o equations the following conclusions may be formulated:

1. Equivalent circuit of specially designed induction motor (Fig. 5) is the universal circuit allowing analyzing steady states of motor work in polymerization reactor. The circuit allows for consideration of mechanical losses in slide bearing separately for rotor weight and mixer weight in drive system.
2. The dependencies (11) determining a relative torque coming from agglutination of rotor with stator and torque in slide bearing allow for wide and detailed analysis of these quantities for various constructional parameters of motor in relation to the rated torque of motor.
3. The graphical dependencies given in Fig. 10 allow analyzing the relative torques ΔM^*_{zl}, ΔM^*_{tw} for selected values of air-gap shown in Fig. 8 in determined range of phase agglutination coefficient together with determination of the resultant torque.

The third conclusion is especially meaningful from operating point of view. The conclusion determines the torque as an internal torque for idle running of motor. In the case considered in Fig. 9 this torque achieves 50% of rated torque of motor.

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