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

**ABSTRACT** *The way of consideration of a loss in large-size slide bearing on the basis of the idle current measurements is presented in the paper. The motor is not loaded by mixer of polymerization reactor. A large-size slide bearing cooled with polyethylene stream in polymerization reactor chamber or a rolling bearing is taken into consideration. A system of equations allowing for determination of the rotor current and electromagnetic torque on the basis of measurements is presented. The electromagnetic torque is equal to the torque occurring in the large-size slide bearing. Results of measurements of the stator current during operation of the motor in polymerization reactor and measurements carried out at a testing station are presented.*

*A bearing set with thrust-rolling bearing was included in the motor.*

**Keywords:** *specially designed motors, equivalent circuits, polymerization reactors, slide bearings.*

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# 1. THE EQUIVALENT CIRCUIT OF THE SPECIALLY DESIGNED INDUCTION MOTOR WITH THE CONSIDERATION OF PHENOMENA IN A POLYMERIZATION REACTOR

Considering the assumed technology, reactors of ethylene polymerization are equipped with a pressure chamber where the drive system, including specially designed induction motor and mixer, works vertically. The movable part of the drive system is hung on the large-size slide bearing located in the lower part of the asynchronous motor. A general view of the specially designed induction motors in a pipe version SAR-55/1500/09 is shown in Figure 1. A motor-in-use system concerning the drive system for polymerization reactor is depicted in Figure 2.

**Fig. 1. General view of the specially designed induction motors in a pipe version SAR-55/1500/09 [1, 2]**

The equivalent circuit of the specially designed induction motor was extended for elements allowing to consider phenomena occurring in polymerization reactor chamber. The phenomena exert an influence on operation of a drive system located in the chamber and concern: friction in large-size slide bearing caused by rotor weight, friction caused by mixer weight and agglutination of rotor with stator during various phases of polymerization. The analysis of a general equivalent circuit is limited to a possibility of experimental verification. The equivalent circuit considering a phase winding of the asynchronous motor is presented in Figure 3. A vertical operation of the motor equipped with the large-size slide bearing as well as an agglutination of the rotor and stator caused by polymerization in reactor chamber are taken into account.

As the analysis is limited to a measurement feasibility, some branches of the equivalent circuit (Fig. 3) are omitted. These branches represent an agglutination of the rotor and stator as well as losses in the large-size slide bearing coming from friction in the bearing and divided into the loss caused by rotor weight and the loss caused by weight of suspension system together with mixer.

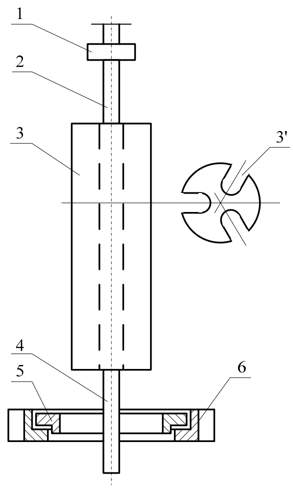


**Fig. 2. Suspension system of the motor SAR--55/1500/09 in the drive system for polymerization reactor, where:**
1 is the upper bearing,
2 is the upper ending of the motor shaft,
3 is rotor,
4 is the lower ending of the motor shaft,
5 is sliding ring of the lower bearing,
6 is self-aligning bushing of the lower bearing [3]

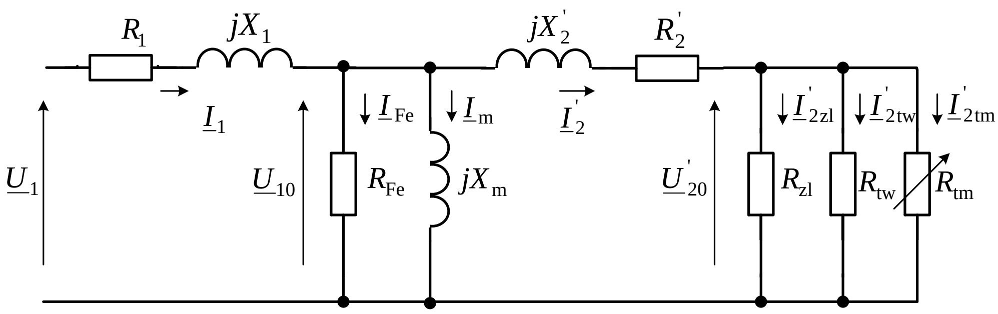


**Fig. 3. Equivalent circuit of the specially designed induction motor of the drive system for polymerization reactor**

The slide bearings having flat or conical or spherical contact between bushing and ring are examples of the most frequent solutions of the slide bearing set. The abovementioned constructional solutions are depicted in Figure 4.

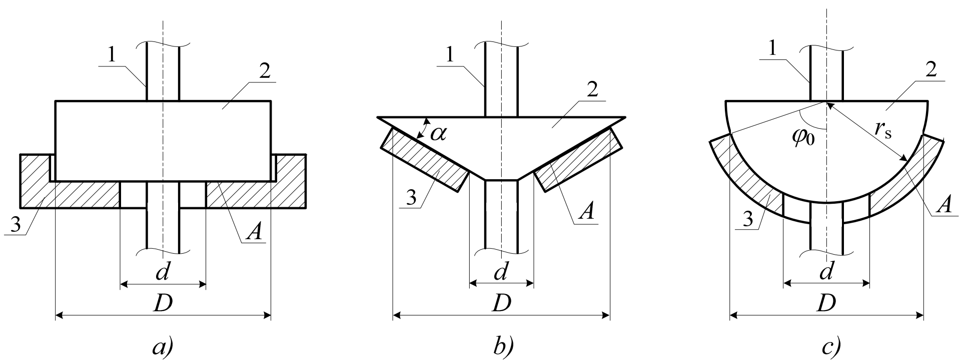


**Fig. 4. Variants of realization of the large-size slide bearing in specially designed induction motors in a pipe version:**
a) flat, b) conical, c) spherical, where: 1 is hollow shaft of the motor, 2 is thrust ring, 3 is bushing [4]

## 2. DETERMINATION OF THE ADDITIONAL ANTI-TORQUE WITH THE USE OF NO-LOAD MEASUREMENTS CONCERNING THE SPECIALLY DESIGNED INDUCTION MOTOR

The current consumed by unloaded motor was measured in order to determine the anti-torque coming from the large-size slide bearing. The following variants were considered:

- measurement of stator current of the unloaded motor with thrust-rolling bearings at testing station;
- measurement of stator current of the unloaded motor with slide bearings in polymerization reactor.

Results of measurements for various constructions of the thrust bearing [3] are presented in Table 1. Measurements in polymerization reactor concerning the respective slide bearings were made in the same conditions, including pressure of ethylene, size of forcing and flow as well as temperature of every level of polymerization reactor chamber.

**TABLE 1**
Measurements for various constructions of the thrust bearing

| Lp. | Construction of the thrust bearing | Figure | $I_p$ [A] | Measurement |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| 1. | Rolling bearing for measurements with single-line thrust path | According to the research work PC-6 T10 2003C/06105 | 12,00 | Testing station |
| 2. | Rolling bearing for measurements with double-line thrust path | According to the research work PC-6 T10 2003C/06105 | 12,96 | Testing station |
| 3. | Slide bearing with a flat construction | Fig. 4a | 56,40 | Polymerization reactor |
| 4. | Slide bearing with a conical construction | Fig. 4b | 68,60 | Polymerization reactor |
| 5. | Slide bearing with a spherical construction | Fig. 4c | 51,40 | Polymerization reactor |

Measurements of current in items 1 and 2 concerning operation of the motor with ball thrust-rolling bearings may be interpreted as measurements of current of the unloaded motor resulting from components $I_{Fe}$ and $I_m$. They may be related to the currents of unloaded motor with slide bearings having different construction. This relation is described by dependencies (1):

$$I_{p1-2} = 0{,}5\left(I_{p1} + I_{p2}\right) \qquad I'_{p1-2} = I_{p1-2}\left(\frac{1}{I_{N1}}\right)$$

$$I_{p3b} = I_{p3} - I_{p1-2} \qquad I'_{p3b} = I_{p3b}\left(\frac{1}{I_{N1}}\right)$$

$$I_{p4b} = I_{p4} - I_{p1-2} \qquad I'_{p4b} = I_{p4b}\left(\frac{1}{I_{N1}}\right)$$

$$I_{p5b} = I_{p5} - I_{p1-2} \qquad I'_{p5b} = I_{p5b}\left(\frac{1}{I_{N1}}\right) \tag{1}$$

The respective increments of the measured stator phase current of the motor with slide bearings over the current of the unloaded motor with ball bearings and their relative value are given in Table 2 while $I_{N1}$ = 95 A.

**TABLE 2**
Increments of the measured stator phase current

| Lp. | Construction of the thrust bearing set | Increment of current $I_{pib}$ over current $I_{p1-2}$ [A] | Relative current $I_p$ |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1. | Thrust-rolling bearing | – | $I'_{p1-2} = 0{,}131$ |
| 2. | Flat slide bearing | $I_{p3b} = 43{,}92$ | $I'_{p3b} = 0{,}462$ |
| 3. | Conical slide bearing | $I_{p4b} = 56{,}12$ | $I'_{p4b} = 0{,}591$ |
| 4. | Spherical slide bearing | $I_{p5b} = 38{,}92$ | $I'_{p5b} = 0{,}410$ |

The following system of equations based on [4] is given for calculation of the anti-torques coming from friction in large-size sidle bearing of the specially designed induction motor:

$$U_{10} = \sqrt{2}\sqrt{I_{\mathrm{p}}^2\left[\left(R_1 + R_{\mathrm{p}}\right)^2 + X_1^2\right] + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{\left(R_1 + R_{\mathrm{p}}\right)^2 + X_1^2}\cos\left(\mathrm{arctg}\frac{X_1}{R_1 + R_{\mathrm{p}}} - \varphi\right)}$$

$$I'_2 = \frac{\sqrt{I_{\mathrm{Fe}}^2 + \left(1 + 2I_{\mathrm{m}}X'_2/U_{10}\right)\left(I_1^2 - I_{\mathrm{m}}^2 - I_{\mathrm{Fe}}^2\right)} - I_{\mathrm{Fe}}}{1 + 2I_{\mathrm{m}}X'_2/U_{10}}$$

$$M_p = \frac{3I'_2}{2\omega_0}\sqrt{U_{10}^2 - \left(I'_2X'_2\right)^2}, \qquad I_{\mathrm{m}} = \frac{U_{10}}{X_{\mathrm{m}}}, \qquad I_{\mathrm{Fe}} = \frac{U_{10}}{X_{\mathrm{Fe}}}$$

$$S = 3U_{\mathrm{f}}I_{\mathrm{p}}, \quad \varphi = \arccos\frac{P}{S} \tag{2}$$

The equations (2) are transformed into the following form:

$$U_{10} = \sqrt{2}\left\{ I_{\mathrm{p}}^{2}\left[\left(R_1 + R_{\mathrm{p}}\right)^2 + X_1^2\right] + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{\left(R_1 + R_{\mathrm{p}}\right)^2 + X_1^2}\cos\left(\mathrm{arctg}\frac{X_1}{R_1 + R_{\mathrm{p}}} - \varphi\right)\right\}^{0,5}$$

$$I_2^{'} = \left\{\left\{\left(\frac{U_{10}}{R_{Fe}}\right)^2 + \left(1 + 2\frac{X_2^{'}}{X_m}\right)\left[I_1^2 - U_{10}^2\left(\frac{1}{X_m^2} - \frac{1}{X_{Fe}^2}\right)\right]\right\}^{0,5} - \frac{U_{10}}{R_{Fe}}\right\}\left(1 + 2\frac{X_2^1}{X_m}\right)^{-1}$$

$$M_p = \frac{3I_2^{'}}{2\omega_0}\left[U_{10}^2 - \left(I_2^{'}X_2^{'}\right)^2\right]^{0,5} \tag{3}$$

Introducing the additional terms, the formula for calculation of the anti-torque coming from friction in the large-size slide bearing is given as follows. The anti-torque is determined by measurements and parameters of the equivalent circuit of the asynchronous motor.

$$M_p = \frac{3}{2\omega_0}\left\{-\sqrt{2}\frac{R_{Fe}^{-1}}{C}\left(I_{\mathrm{p}}^{2}B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)^{0,5} + C^{-1}\left[2\left(I_{\mathrm{p}}^2 B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)R_{Fe}^{-2} + C\left[I_1^2 - \left(2B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)\left(X_m^{-2} - R_{Fe}^{-2}\right)\right]\right]\right\}^{0,5} \times$$

$$\times\left\{2\left(I_{\mathrm{p}}^2 B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right) - (X_2^{'})^2\left[-\sqrt{2}\frac{R_{Fe}^{-1}}{C}\left(I_{\mathrm{p}}^2 B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)^{0,5} + C^{-1}\left[2\left(I_{\mathrm{p}}^2 B + U_{\mathrm{f}}^2 - 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)R_{Fe}^{-2} + C\left(I_1^2 - 2\left(I_{\mathrm{p}}^2 B + U_{\mathrm{f}}^2 2I_{\mathrm{p}}U_{\mathrm{f}}\sqrt{B}\cos A\right)\left(X_m^{-2} - R_{Fe}^{-2}\right)\right)\right]^{0,5}\right]^2\right\}^{0,5} \tag{4}$$

where: $A = \mathrm{arctg}\dfrac{X_1}{R_1 + R_{\mathrm{p}}} - \varphi$, $B = \left(R_1 + R_{\mathrm{p}}\right)^2 + X_1^2$, $C = 1 + 2\dfrac{X_2^{'}}{X_{\mathrm{m}}}$

The torque given by (4) is a function of constructional parameters of the motor, measurements and angular velocity $\omega_0$. The anti-torque coming from friction in large-size slide bearing of the specially designed induction motors in a pipe version is significant in relation to the rated torque. Therefore, the relative additional anti-torque of the motor referred to the rated torque is determined (5) in order to compare of anti-torques among the various constrictions of the specially designed induction motor with large-size slide bearing.

$$M_p^{'} = 4\pi^2 \left( \frac{f_1}{p_b} \right)^2 \frac{1-s_N}{P_N} M\left(I_p, U_f, k_{sz}\right)$$
$$M\left(I_p, U_f, k_{sz}\right) = M_p \omega_0^{-1} \tag{5}$$

where: $I_p$ is the measured stator phase current, $U_f$ is the measured phase voltage, $k_{sz}$ is parameter of the equivalent circuit coming from dependency (4).

The shortened formula for calculation of the relative torque coming from friction in large-size sidle bearing (5) was obtained by introducing the additional term $M_p = \omega_0 M\left(I_p, U_f, k_{sz}\right)$. Taking into account the dependency (5) and measurements made for the same operating parameters of the polymerization reactor, the relative anti-torque coming from friction in large-size slide bearing was determined for various constructions of the slide bearing:

- flat bearing (Fig. 4a) $M'_{p-1} = 0{,}4116$
- conical bearing (Fig. 4b) $M'_{p-2} = 0{,}5202$
- spherical bearing (Fig. 4c) $M'_{p-3} = 0{,}3865$.

## 3. CONCLUSIONS

On the basis of the abovegiven dependencies for calculation of the additional anti-torque coming from friction in large-size slide bearing and on the basis of the proposed method of calculation of this anti-torque with the use of measurements made for unloaded motor, the following conclusions may be formulated:

- the additional anti-torque coming from friction in large-size slide bearing and given by dependencies (4) and (5) may be determined considering all parameters of the equivalent circuit on the basis of the measurements of voltage, current and power in switching station feeding the specially designed induction motors placed in polymerization reactors;
- the large-size slide bearing causes the additional load of the specially designed induction motor being equal to 30-50% of the rated torque.

The carried out measurements and analysis show that the additional calculations done in order to determine the additional anti-torque of the motors with large-size slide bearings, applied in the drive systems for polymerization reactors, are necessary. The assumed rated torque of the motor resulting from the technological process should be increased by the determined additional anti--torque at the stage of the designing efforts concerning construction of the motor.

The abovegiven analysis deals with steady states of the drive system. However, the analysis may also be applied in order to widen the mathematical models for analysis of dynamical states of the drive systems containing the induction motors with large-size slide bearings [5].

## LITERATURE


1. Government grant no. 6 T10 2003C/06105: Opracowanie i wykonanie silnika indukcyjnego specjalnego wykonania z przetwornicą częstotliwości o zmodyfikowanym układzie sterowania do uruchomienia produkcji głównych układów napędowych reaktorów polimeryzacji – część I – Opis badań, p. 230, Czestochowa University of Technology, Faculty of Electrical Engineering (unpublished study), 2005.
2. Government grant no. 6 T10 2003C/06105: Opracowanie i wykonanie silnika indukcyjnego specjalnego wykonania z przetwornicą częstotliwości o zmodyfikowanym układzie sterowania do uruchomienia produkcji głównych układów napędowych reaktorów polimeryzacji – część II – Wyniki badań i dokumentacja, p. 219, Czestochowa University of Technology, Faculty of Electrical Engineering (unpublished study), 2005.
3. Research work no. BZ-3-302/3/2003: Opracowanie modelu matematycznego i analiza obliczeniowa napędu głównego reaktora polimeryzacji, p. 62, Czestochowa University of Technology, Faculty of Electrical Engineering (unpublished study), 2003.
4. Rusek A.: Schemat zastępczy indukcyjnego silnika asynchronicznego specjalnego wykonania do pracy w układzie napędowym reaktora polimeryzacji z uwzględnieniem straty mocy w wielkogabarytowym łożysku ślizgowym z węglików spiekanych, International Symposium on Electrical Machines SME’2011, Szczecin, 2011.
5. Popenda A., Rusek A.: Model matematyczny i wybrane stany nieustalone głównego napędu reaktora polimeryzacji przy uwzględnieniu parametrów pracy komory mieszalnika, Electrical Reviev 5’2008, p. 84-87, 2008.


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# SCHEMAT ZASTĘPCZY SILNIKA INDUKCYJNEGO SPECJALNEGO WYKONANIA DO PRACY W UKŁADZIE NAPĘDOWYM REAKTORA POLIMERYZACJI

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**STRESZCZENIE** *W artykule przedstawiono sposób uwzględniania strat w wielkogabarytowym łożysku ślizgowym na podstawie pomiarów prądu biegu jałowego dla pracy silnika nieobciążonego mieszadłem z wielkogabarytowym łożyskiem ślizgowym chłodzonym strugą etylenu w komorze reaktora polimeryzacji oraz dla pracy silnika nieobciążonego mieszadłem z zespołem tocznego łożyska oporowego na stanowisku pomiarowym. Przedstawiono układ równań umożliwiający wyznaczanie w oparciu o przeprowadzone pomiary prądu wirnika oraz momentu elektromagnetycznego silnika, który dla biegu jałowego przedstawia moment występujący w wielkogabarytowym łożysku ślizgowym. Przedstawiono wyniki pomiarów prądu stojana podczas pracy silnika w reaktorze polimeryzacji oraz pomiary przeprowadzone w stacji prób dla zespołu łożyskowego z łożyskiem oporowo-tocznym.*