Electrical asymmetry level influence on quality attributes of an induction motor

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Abstract. The paper is devoted to the evaluation of rotor phase asymmetry level on induction motor operation quality. The problems and characteristic features of an induction motor asymmetric modes modeling, taking into account the saturation of the magnetic circuit are reflected. The modification of the classic mathematical model for currents and torque calculating in conditions of rotor circuit asymmetry is presented, and the results of numerical simulation of this mode are shown. Analysis of the distinctive features of the selected mode compared to the symmetric mode of an induction motor is performed.

1. Introduction
The tasks of qualitative and detailed study of electrical machines operating modes as well as timely diagnosis problems and possible faults prediction take on strategic importance with the growth of the technical and technological level of industry.

A resistive impedance asymmetries of the windings often occur due to a number of reasons at induction motor operating [1]. The tasks of studying asymmetric operating modes are stimulated by the need to accumulate statistical information on the behavior of electrical machines in such modes. The information obtained can be used in the design of fundamentally new ways of organizing automatic protection against asymmetric operating modes in some industries with a continuous production cycle. An example is the clinker furnace at cement plants, where stops during operation are not allowed by the manufacturing method and lead to significant material costs.

The aim of this research is to assess the active impedance asymmetry level of the rotor winding influence on the quality factors of an induction motor. Taking into account specifics of the mode under consideration, the choice of a coordinate system that adequately characterizes the operation of an electric machine is of particular importance.

2. Mathematic modelling
The research based on the well-known mathematical model of an induction motor in a three-phase natural coordinate system [2]. The following assumptions are made when considering the original mathematical model of a three-phase induction motor:
- the magnetic field energy is concentrated in the air gap, in other words it is accepted that the steel magnetic permeability is equal to infinity;
- air loss and mechanical loss are small to negligible;
- air gap is regular;
- power line has infinitely large power.

Using the mathematical model in its original form for the analysis of electromagnetic processes while taking into account the asymmetry in an induction motor winding and steel saturation seems inconvenient. This inconvenience is justified by the fact that the mutual inductances $M_{ab}$, $M_{bc}$, ..., correspond to different parts of the magnetic circuit in different saturation states. The calculation of the resulting mutual inductance in this case is a separate complex task.

As a solution to this problem, the following steps were taken in the mathematical model modification:

- unlike the original system, the equations are not written for each phase, as in the classical notation, but for two adjacent loops — the A and B phases loop and the B and C phases loop;
- the coefficients reflecting the saturation state of each phase magnetic circuit are substantiated and derived. The mutual inductances that change due to saturation are determined by multiplying the equivalent mutual inductances by these coefficients.

The developed mathematical model modification for solving the tasks includes two blocks - for the stator and rotor.

The system of equations for the stator block in this case has the form:

$$
\begin{align*}
&u_A - i_A \cdot R_A - \frac{d\psi_A}{dt} - u_B + i_B \cdot R_B + \frac{d\psi_B}{dt} = 0 \\
&u_B - i_B \cdot R_B - \frac{d\psi_B}{dt} + u_C + i_C \cdot R_C + \frac{d\psi_C}{dt} = 0 \\
&i_A + i_B + i_C = 0
\end{align*}
$$

(1)

The system of equations for the rotor block in this case has the form:

$$
\begin{align*}
&-i_a \cdot R_a - \frac{d\psi_a}{dt} + i_b \cdot R_b + \frac{d\psi_b}{dt} = 0 \\
&-i_b \cdot R_b - \frac{d\psi_b}{dt} + i_c \cdot R_c + \frac{d\psi_c}{dt} = 0 \\
&i_a + i_b + i_c = 0
\end{align*}
$$

(2)

where $u_A$, $u_B$, $u_C$ - instantaneous value of stator phases voltage;

$i_A$, $i_B$, $i_C$, $i_a$, $i_b$, $i_c$ - instantaneous value of stator and rotor phases currents;

$\psi_A$, $\psi_B$, $\psi_C$, $\psi_a$, $\psi_b$, $\psi_c$ - magnetic flux linkages of stator and rotor phases;

$R_A$, $R_B$, $R_C$, $R_a$, $R_b$, $R_c$ - active impedance of stator and rotor phases.

In these equations magnetic flux linkages of stator and rotor phases are given by:

$$
\begin{align*}
\psi_A &= L_A \cdot i_A + M_{AB} \cdot i_B + M_{AC} \cdot i_C + \\
&+ M_{Am} \cdot i_a \cdot \cos \left( \gamma + \frac{2 \cdot \pi}{3} \right) + M_{Am} \cdot i_c \cdot \cos \left( \gamma - \frac{2 \cdot \pi}{3} \right); \\
\psi_B &= M_{BA} \cdot i_A + L_B \cdot i_B + M_{BC} \cdot i_C + \\
&+ M_{Bm} \cdot i_a \cdot \cos \left( \gamma - \frac{2 \cdot \pi}{3} \right) + M_{Bm} \cdot i_b \cdot \cos \left( \gamma + \frac{2 \cdot \pi}{3} \right) + M_{Bc} \cdot i_c \cdot \cos \left( \gamma + \frac{2 \cdot \pi}{3} \right); \\
\psi_C &= M_{CA} \cdot i_A + M_{CB} \cdot i_B + L_C \cdot i_C + \\
&+ M_{Cm} \cdot i_a \cdot \cos \left( \gamma + \frac{2 \cdot \pi}{3} \right) + M_{Cm} \cdot i_b \cdot \cos \left( \gamma - \frac{2 \cdot \pi}{3} \right) + M_{Cc} \cdot i_c \cdot \cos \left( \gamma \right);
\end{align*}
$$

(3, 4, 5)
\[
\Psi_a = M_{aa} \cdot i_A \cdot \cos(\gamma) + M_{ab} \cdot i_B \cdot \cos\left(\gamma - \frac{2 \cdot \pi}{3}\right) + M_{ac} \cdot i_C \cdot \cos\left(\gamma + \frac{2 \cdot \pi}{3}\right) + L_a \cdot i_a + M_{ab} \cdot i_b + M_{ac} \cdot i_c ; \\
\Psi_b = M_{ba} \cdot i_A \cdot \cos\left(\gamma + \frac{2 \cdot \pi}{3}\right) + M_{bb} \cdot i_B \cdot \cos(\gamma) + M_{bc} \cdot i_C \cdot \cos\left(\gamma - \frac{2 \cdot \pi}{3}\right) + M_{ba} \cdot i_a + L_b \cdot i_b + M_{bc} \cdot i_c + M_{bb} \cdot i_b ; \\
\Psi_c = M_{ca} \cdot i_A \cdot \cos\left(\gamma - \frac{2 \cdot \pi}{3}\right) + M_{cb} \cdot i_B \cdot \cos\left(\gamma + \frac{2 \cdot \pi}{3}\right) + M_{cc} \cdot i_C \cdot \cos(\gamma) + M_{ca} \cdot i_a + M_{cb} \cdot i_b + L_c \cdot i_c , \\
\]

where \( \gamma \) - angle of rotor phase winding position to relevant same-name stator phase winding; 
\( L_A, L_B, L_C, L_a, L_b, L_c \) - inductive impedance of stator and rotor phases; 
\( M_{AB}, M_{AC}, M_{BA}, M_{BC}, M_{CA}, M_{CB} \) - mutual inductance between stator phases; 
\( M_{ab}, M_{ac}, M_{ba}, M_{bc}, M_{ca}, M_{cb} \) - mutual inductance between rotor phases; 
\( M_{Aa}, M_{Ba}, M_{Ca}, ... \) - mutual inductance between relevant stator and rotor phases.

Electromagnetic torque of an induction motor can be found as partial derivative of motor total electromagnetic energy storage with respect to geometric angle. Motor total electromagnetic energy storage can be described by expression:

\[
W_p = \frac{1}{2} \left[ \Psi_A \cdot i_A + \Psi_B \cdot i_B + \Psi_C \cdot i_C + \psi_a \cdot i_a + \psi_b \cdot i_b + \psi_c \cdot i_c \right] . \\
\]

Hence the electromagnetic moment of the induction motor is defined as:

\[
M = \frac{\partial W_p}{\partial \gamma} \cdot Z_p , \\
\]

where \( Z_p \) - number of pairs of poles.

Equation of motion is given by:

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

where \( M_c \) - static load torque; 
\( J \) - drive inertia moment normalized to motor shaft; 
\( \omega \) - angular frequency of rotor, radian per second.

By substituting (3) – (8) equations into sets of equation (1) and (2) and with account (9) – (11) equations, as result of common mathematic manipulations and representing the equations in matrix form, the equations for calculating the magnitude of currents and the electromagnetic moment of an induction motor in electrical asymmetry conditions are obtained:

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
i_a \\
i_b \\
i_c 
\end{bmatrix} = \begin{bmatrix} A^{-1} \times B \end{bmatrix},
\]

where
As it was already mentioned, the magnetic circuits steel saturation in the presence of electrical asymmetry is taken into account by multiplying the equivalent mutual inductance by the coefficients reflecting the effect of saturation on this phase and the magnetic flux displacement into the magnetic circuit slots.

Based on the foregoing, the implementation of the magnetic circuits steel saturation account by the system of equations (12) is presented in the form:

\[
A = \begin{bmatrix}
-\frac{1}{2}L_{m} - 3 \cdot \frac{L_{m}}{2} & L_{m} + 3 \cdot \frac{L_{m}}{2} & -3 \cdot \cos(\varphi + \frac{\pi}{3}) \cdot L_{m} & -3 \cdot \cos(\varphi + \frac{2\pi}{3}) \cdot L_{m} \\
-\frac{1}{2}L_{m} - 3 \cdot \frac{L_{m}}{2} & -2 \cdot L_{m} - 3 \cdot L_{m} & 3 \cdot \cos(\varphi + \frac{2\pi}{3}) \cdot L_{m} & -3 \cdot \cos(\varphi) \cdot L_{m} \\
3 \cdot \cos(\varphi + \frac{2\pi}{3}) \cdot L_{m} & -3 \cdot \cos(\varphi + \frac{4\pi}{3}) \cdot L_{m} & -L_{m\sigma} - 3 \cdot \frac{L_{m}}{2} & L_{m\sigma} + 3 \cdot \frac{L_{m}}{2} \\
3 \cdot \cos(\varphi + \frac{4\pi}{3}) \cdot L_{m} & -3 \cdot \cos(\varphi) \cdot L_{m} & -2 \cdot L_{m\sigma} - 3 \cdot L_{m}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
u_{A} - u_{B} - i_{A} \cdot R_{A} + i_{B} \cdot R_{B} + i_{A} \cdot \omega_{r} \cdot L_{m} \cdot 3 \cdot \sin(\varphi + \frac{\pi}{3}) + i_{b} \cdot \omega_{r} \cdot L_{m} \cdot 3 \cdot \sin(\varphi + \frac{2\pi}{3}) \\
u_{B} - u_{C} - i_{A} \cdot R_{C} - i_{B} \cdot (R_{B} + R_{C}) + i_{A} \cdot \omega_{r} \cdot L_{m} \cdot (-3 \cdot \sin(\varphi + \frac{2\pi}{3})) + i_{b} \cdot \omega_{r} \cdot L_{m} \cdot 3 \cdot \sin(\varphi) \\
-i_{A} \cdot R_{A} + i_{B} \cdot R_{B} + i_{A} \cdot \omega_{r} \cdot L_{m} \cdot (-3 \cdot \sin(\varphi + \frac{2\pi}{3})) + i_{b} \cdot \omega_{r} \cdot L_{m} \cdot 3 \cdot \sin(\varphi + \frac{4\pi}{3}) \\
-i_{A} \cdot R_{C} - i_{B} \cdot (R_{B} + R_{C}) + i_{A} \cdot \omega_{r} \cdot L_{m} \cdot (-3 \cdot \sin(\varphi + \frac{4\pi}{3})) + i_{b} \cdot \omega_{r} \cdot L_{m} \cdot 3 \cdot \sin(\varphi)
\end{bmatrix}
\]

\[
\begin{bmatrix}
i_{A} \\
i_{B} \\
i_{C} \\
i_{b}
\end{bmatrix} = -A^{-1} \times K \times B ,
\]

where \( K = \begin{bmatrix}
K_{A} \\
K_{B} \\
K_{C} \\
K_{b}
\end{bmatrix} \) - matrix of equivalent mutual inductance due to the influence of magnetic circuit steel saturation coefficients. A detailed justification and derivation of these coefficients are given in other works of the authors [3].

3. Results of modelling

The object of research is high-voltage induction motor AKZ 13-62-8UHL4 with wound rotor with power of 630kW and nominal rotational speed of 750 rev/min. This type of motor is used as clinker furnace drive.

Based on equations presented above, the induction motor operation at rotor phase breakage mode was modeled using MatLab software. Figure 1 shows stator and rotor phase currents, rotor angular frequency–time depends and electromagnetic torque–time depends of the motor in case of phase breakage in rotor phase at 25% of nominal load. The family of static mechanical characteristics with various values of the rotor phase resistances (figure 2) was constructed to establish the rotor phase asymmetry level effect on the electromagnetic torque dip magnitude.
Figure 1. Stator currents (top left), rotor currents (top right), electromagnetic torque (bottom left) and rotor angular frequency (bottom right) at rotor phase breakage mode of induction motor AKZ 13-62-8UHL4 type

Figure 2. Electromagnetic torque – slip depend at various rotor phase asymmetry level
4. Discussions of the results
Analyzing the results it can be concludes that in the rotor phase breakage mode in comparison with the symmetric mode:
- stator and rotor phase current magnitudes are increase, both in transition and in steady state. As a result of this the efficiency decreases and the heating of the windings increases, which means premature failure of the motor since an excess of the winding insulation temperature by 8°C leads to a reduction of the machine service life by about 2 times;
- in the stator phase currents there are $2 \cdot f_1 \cdot s$ frequency pulsations caused by the frequency difference of the stator direct sequence current component and rotor reverse sequence current component;
- the motor mechanical characteristic has a dip at the slip of 0.5 area. As a result induction motor rotor does not accelerate to rated speed, but gets stuck at a speed close to half;
- pulsations of the electromagnetic torque noticeable in figure 1 (bottom left) cause additional vibration which reduces the service life of individual motor parts. In some cases, the permissible level of asymmetry is limited not by the heating conditions but by the level of mechanical overload during motor frame vibrations.
- as can be seen from figure 2, with an increase of the rotor phase resistance the magnitude of the dip in the motor torque also raises. It should be noted that if the magnitude of this dip becomes so large that the motor torque in the slip area is less than the load moment, the motor will not be able to accelerate above half speed rotation. In addition, with an increase in the rotor phase resistance the nominal slip also increases which leads to increase in motor losses and, as a result, to increase in windings heating.

5. Conclusions
Modeling of induction motor AKZ 13-62-8UHL4 type in the presence of electrical asymmetry in the rotor winding was performed using the developed tools. The influence of the Goerges effect associated with the appearance of reverse sequence currents in the stator winding due to the rotor winding phase breakage influence on the electromagnetic torque curve dip is estimated. The influence of the rotor electrical asymmetry level on the dip of the electromagnetic torque is established.

References
[1] Kopylov I P and Klokov B K 1988 Handbook of electrical machines (Moscow: Energoatomizdat) p 456
[2] Vinogradov A B 2008 Vector equation of an AC drive (Ivanovo: Ivanovo State Power University) p 298
[3] Lavrenov E O, Temlyakova Z S and Vilberger M E 2018 Proc. 14th Int. Scient. Tech. Conf. vol 1 (Russia: Novosibirsk State Technical University Publ.) pp 233-237