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Mathematical Model Of An Asynchronous Motor In Full-Phase Operation

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Abstract *— The process of forming a mathematical model of an asynchronous motor as part of electric drives of hazardous industrial objects in an incomplete-phase emergency mode of operation, taking into account the fields of direct and negative sequence, which makes it possible to take into account the effect of an elliptical field in an incomplete-phase emergency modes of operation. The process of switching to the emergency two-phase operation mode is performed using the motor fault matrix. The results of simulation of transient processes in case of phase failure of the motor stator are presented. A comparison of the time diagrams obtained experimentally in terms of rotation frequency and current using an automated test bench and using a simulation model in the Matlab Simulink environment is performed. The adequacy of the proposed mathematical model is shown, which makes it possible to study an asynchronous electric motor in an emergency two-phase operation of a three-phase electric motor.*

Keywords — Mathematical model of an asynchronous motor, half-phase operation mode, positive and negative sequence field, motor failure matrix, motor phase failure.

Investigation of emergency conditions of an induction motor as part of executive electric drives of hazardous industrial facilities involves considering the operation of the engine in non-full-phase modes of operation. Providing fault-tolerant control with the property of survivability of an asynchronous electric drive involves the development of algorithms for restoring operability with full or partial restoration of operability with a circular rotating field.

When considering the two-phase mode of operation of a three-phase asynchronous motor, two different modes can be distinguished:

• work in emergency mode with an elliptical field in an unregulated electric drive;

• operation in emergency mode with algorithmic formation of a circular rotating field in a frequency-controlled electric drive [1].

The purpose of this article is to form a mathematical model of an asynchronous motor, taking into account the effect of an elliptical field in non-full-phase modes of operation.

When considering the emergency two-phase operation of the engine with an elliptical field in the air gap, it can be decomposed into fields of positive and negative sequence using the method of symmetric components. The generalized model of an electric machine takes into account only the direct sequence field. There are two options for representing the model of an asynchronous motor operating with an elliptical field - a model of a generalized electric machine with two stators and two rotors, a model of a generalized electric machine with two stators and one rotor [2]. The first model is simpler in description, but gives inaccurate results of modeling transient processes, while the second model has more complex expressions for the resulting electromagnetic torque, but gives more accurate calculation results in dynamic modes of operation.

In connection with the above-mentioned features of the mathematical description of a generalized electric machine with an elliptical field, a model with two stators and two rotor was chosen to form a mathematical model (Fig. 1).

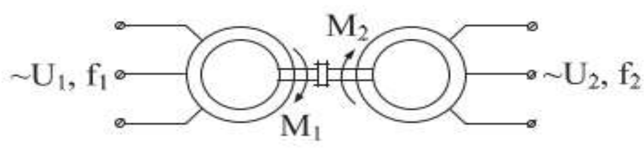

Figure: 1. Diagram of an electric machine with two stators and two rotors

When studying asymmetric machines taking into account spatial harmonics or in the presence of non-sinusoidal supply voltages, it is illegal to bring the machine to a two-phase one, since the fields in the gap of two-phase and multi-phase machines under these conditions differ from each other [2]. Since an asynchronous motor is asymmetrical when one of the phases of the supply network is broken, a generalized electric machine in a three-phase coordinate system can be taken as a mathematical model.

When drawing up equations and considering the transient processes of asynchronous machines, the generally accepted assumptions and limitations associated with the concept of "idealized machine" were used: the machine is not saturated, we

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neglect the losses in steel; phase windings are symmetrical and shifted by an angle of 120 electrical degrees; the magnetizing forces of the windings and magnetic fields are distributed sinusoidally along the circumference of the air gap; the air gap is uniform; the rotor is symmetrical. The real distributed winding is replaced by a concentrated one, the phase axes of which are shifted by the phase angle, and its magnetizing force is equal to the magnetizing force of the real winding.

As a basis, the equations of the model of an induction motor in a braked coordinate system were taken [1]. To simplify the calculations, equations for the fields of direct and negative sequence are represented by separate systems.

When determining the voltages applied to the windings of machines responsible for the fields of positive and negative sequence, it was taken into account that with a constant supply voltage U1 = UA = UB = UC = const, the voltage of the positive and negative sequence depends on slip [3].

The equations of a generalized electric machine with two stators and one rotor for a positive sequence field are:

$$U_{1A} = R_s i_{1A} + \frac{d\Psi_{1A}}{dt};$$

$$U_{1B} = R_s i_{1B} + \frac{d\Psi_{1B}}{dt};$$

$$U_{1C} = R_s i_{1C} + \frac{d\Psi_{1C}}{dt};$$

$$0 = R_r i_{1a} + \frac{d\Psi_{1a}}{dt} + (\Psi_{1b} - \Psi_{1c})\omega / \sqrt{3};$$

$$0 = R_r i_{1b} + \frac{d\Psi_{1b}}{dt} + (\Psi_{1c} - \Psi_{1a})\omega / \sqrt{3};$$

$$0 = R_r i_{1c} + \frac{d\Psi_{1c}}{dt} + (\Psi_{1a} - \Psi_{1b})\omega / \sqrt{3}.$$

Coupling flux for all phases:

$$\Psi_{1A} = L_S i_{1A} - \frac{1}{2} L_m i_{1B} - \frac{1}{2} L_m i_{C} + $$
$$+ L_m i_{1a} - \frac{1}{2} L_m i_{1b} - \frac{1}{2} L_m i_{1c};$$

$$\Psi_{1B} = -\frac{1}{2} L_m i_{1A} + L_S i_{1B} - \frac{1}{2} L_m i_{1C} - $$
$$- \frac{1}{2} L_m i_{1a} + L_m i_{1b} - \frac{1}{2} L_m i_{1c};$$

$$\Psi_{1C} = -\frac{1}{2} L_m i_{1A} - \frac{1}{2} L_m i_{1B} + L_S i_{1C} - $$
$$- \frac{1}{2} L_m i_{1a} - \frac{1}{2} L_m i_{1b} + L_m i_{1c};$$

$$\Psi_{1a} = L_m i_{1A} - \frac{1}{2} L_m i_{1B} - \frac{1}{2} L_m i_{1C} + $$
$$+ L_R i_{1a} - \frac{1}{2} L_m i_{1b} - \frac{1}{2} L_m i_{1c};$$

$$\Psi_{1b} = -\frac{1}{2} L_m i_{1A} + L_m i_{1B} - \frac{1}{2} L_m i_{1C} - $$
$$- \frac{1}{2} L_m i_{1a} + L_R i_{1b} - \frac{1}{2} L_m i_{1c};$$

$$\Psi_{1c} = -\frac{1}{2} L_m i_{1A} - \frac{1}{2} L_m i_{1B} + L_m i_{1C} - $$
$$- \frac{1}{2} L_m i_{1a} - \frac{1}{2} L_m i_{1b} + L_R i_{1c}.$$

Reverse sequence equations:

$$U_{2A} = R_s i_{2A} + \frac{d\Psi_{2A}}{dt};$$
$$U_{2B} = R_s i_{2B} + \frac{d\Psi_{2B}}{dt};$$
$$U_{2C} = R_s i_{2C} + \frac{d\Psi_{2C}}{dt};$$
$$0 = R_r i_{2a} + \frac{d\Psi_{2a}}{dt} + (\Psi_{2b} - \Psi_{2c})\omega / \sqrt{3};$$
$$0 = R_r i_{2b} + \frac{d\Psi_{2b}}{dt} + (\Psi_{2c} - \Psi_{2a})\omega / \sqrt{3};$$
$$0 = R_r i_{2c} + \frac{d\Psi_{2c}}{dt} + (\Psi_{2a} - \Psi_{2b})\omega / \sqrt{3}.$$

Coupling flux for all phases:

$$\Psi_{2A} = L_S i_{2A} - \frac{1}{2} L_m i_{2B} - \frac{1}{2} L_m i_{2C} + $$
$$+ L_m i_{2a} - \frac{1}{2} L_m i_{2b} - \frac{1}{2} L_m i_{2c};$$
$$\Psi_{2B} = -\frac{1}{2} L_m i_{2A} + L_S i_{2B} - \frac{1}{2} L_m i_{2C} - $$
$$-\frac{1}{2} L_m i_{2a} + L_m i_{2b} - \frac{1}{2} L_m i_{2c};$$
$$\Psi_{2C} = -\frac{1}{2} L_m i_{2A} - \frac{1}{2} L_m i_{2B} + L_S i_{2C} - $$
$$+\frac{1}{2} L_m i_{2a} - \frac{1}{2} L_m i_{2b} + L_m i_{2c};$$
$$\Psi_{2a} = L_m i_{2A} - \frac{1}{2} L_m i_{2B} - \frac{1}{2} L_m i_{2C} + $$
$$+ L_R i_{2a} - \frac{1}{2} L_m i_{2b} - \frac{1}{2} L_m i_{2c};$$
$$\Psi_{2b} = -\frac{1}{2} L_m i_{2A} + L_m i_{2B} - \frac{1}{2} L_m i_{2C} - $$
$$-\frac{1}{2} L_m i_{2a} + L_R i_{2b} - \frac{1}{2} L_m i_{2c};$$
$$\Psi_{2c} = -\frac{1}{2} L_m i_{2A} - \frac{1}{2} L_m i_{2B} + L_m i_{2C} - $$
$$-\frac{1}{2} L_m i_{2a} - \frac{1}{2} L_m i_{2b} + L_R i_{2c}.$$

The electromagnetic moments M1 and M2 created by the fields of positive and negative sequence are determined by the following expressions:

$$M_1 = p\frac{\sqrt{3}}{2} L_m \begin{bmatrix} (i_{1A} i_{1c} + i_{1B} i_{1a} + i_{1C} i_{1b}) - \\ -(i_{1A} i_{1b} + i_{1B} i_{1c} + i_{1C} i_{1a}) \end{bmatrix};$$
$$M_2 = p\frac{\sqrt{3}}{2} L_m \begin{bmatrix} (i_{2A} i_{2c} + i_{2B} i_{2a} + i_{2C} i_{2b}) - \\ -(i_{2A} i_{2b} + i_{2B} i_{2c} + i_{2C} i_{2a}) \end{bmatrix}.$$

The equation of motion of the electric drive, taking into account the moments of the direct and reverse sequence:

$$M_1 + M_2 - M_c = \frac{J_\Sigma}{p} \frac{d\omega}{dt}.$$

Final expressions for direct sequence field equations:

$$\frac{d[i_1]}{dt} = [L_1]^{-1}\left\{[U_1] - \left([R] + [L_2]\frac{\omega}{\sqrt{3}}\right)[i_1]\right\},$$

for a reverse sequence field:

$$\frac{d[i_2]}{dt} = [L_1]^{-1}\left\{[U_2] - \left([R] + [L_2]\frac{\omega}{\sqrt{3}}\right)[i_2]\right\},$$

Where [i1], [i2] is a matrix of unknowns (stator and rotor currents of direct and reverse sequences); [U1], [U2] - matrix of voltages of direct and negative sequences; [R] - resistance matrix; [L1], [L2] - inductance matrices; [L1] –1 - inverse matrix of stator inductances:

$$[i_1] = \begin{bmatrix} i_{1A} \\ i_{1B} \\ i_{1C} \\ i_{1a} \\ i_{1b} \\ i_{1c} \end{bmatrix}; \quad [U_1] = \begin{bmatrix} U_{1A} \\ U_{1B} \\ U_{1C} \\ 0 \\ 0 \\ 0 \end{bmatrix}; \quad [i_2] = \begin{bmatrix} i_{2A} \\ i_{2B} \\ i_{2C} \\ i_{2a} \\ i_{2b} \\ i_{2c} \end{bmatrix};$$

$$[U_2] = \begin{bmatrix} U_{2A} \\ U_{2B} \\ U_{2C} \\ 0 \\ 0 \\ 0 \end{bmatrix}; \quad [R] = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_r & 0 & 0 \\ 0 & 0 & 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r \end{bmatrix};$$

$$[L_1] = \begin{bmatrix} L_S & -L_m/2 & -L_m/2 & L_m & -L_m/2 & -L_m/2 \\ -L_m/2 & L_S & -L_m/2 & -L_m/2 & L_m & -L_m/2 \\ -L_m/2 & -L_m/2 & L_S & -L_m/2 & -L_m/2 & L_m \\ L_m & -L_m/2 & -L_m/2 & L_R & -L_m/2 & -L_m/2 \\ -L_m/2 & L_m & -L_m/2 & -L_m/2 & L_R & -L_m/2 \\ -L_m/2 & -L_m/2 & L_m & -L_m/2 & -L_m/2 & L_R \end{bmatrix};$$

$$[L_2] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a & -a & 0 & b & -b \\ -a & 0 & a & -b & 0 & b \\ a & -a & 0 & b & -b & 0 \end{bmatrix},$$

$$a = \frac{3}{2}L_m, \quad b = \left(L_R + \frac{1}{2}L_m\right).$$

Conclusion

1. Developed a mathematical model of asynchronous motor to study the partial-phase emergency operation, taking into account the fields of positive and negative sequence using the matrix of motor failures.
2. On the basis of the developed simulation model in the Matlab Simulink environment and the conducted confirmatory experiments for the case of a phase failure of the stator of an induction motor with an elliptical rotating field, the discrepancy in the results for the current was 2.3%, for the frequency of rotation - 2.5% in the steady state, in the three-phase In the steady-state mode of operation, the discrepancy in the results for current was 2.8%, for the frequency of roation, 6%, which confirms the adequacy of the developed mathematical model.

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