Finite element modeling of asynchronous electric motors with electrical defects of stator and rotor

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Abstract: The paper presents results of finite element modeling of induction motor in the growth of stator and rotor fault. Due to the symmetry design of the electric motors relative to the rotor axis the simulation problem is solved in a plane orthogonal axicon. Obtained data the characteristics variation of induction motors with defects: broken rotor bars faults and stator inter-turn short-circuit fault. The results of finite element analysis show the processes occurring in the electric motor for defects and growth. The applied results of modeling are the identification of characteristic diagnostic property there are defects and growth, as well as the development of methods for diagnosing the technical condition of the induction machine.

1. Introduction
Testing the technical condition of an induction machine (IDM) as elements of complex systems is a relevant task of providing an uninterrupted operation of industrial equipment. Improving the effectiveness of IDM testing requires the development of modern methods and tools for monitoring and diagnostics. This will allow you to detect defects at an early stage, assess their degree of development, and prepare for maintenance and do repair work based on the actual status.

Managing engine monitoring IDM by diagnostic parameters requires studying the processes in the induction machine which are originated from growth and defects. Mathematical and finite element models construction allow you to study changes in the diagnostic parameters of IDM for defects and growth. The finite element method is an effective tool for analyzing the physical processes that occur in IDM during operation.

2. Equation finite element modeling.
The IDM design allows to solve the problem of modeling and to calculate magnetic fields in the plane perpendicular to the rotor axis. Based on Maxwell's equations there is the mathematical model with the assumption that the magnetic field doesn’t propagate in the longitudinal axis Z of the rotor [1]

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \]

\[ \nabla \cdot \vec{B} = 0, \] (2)

\[ \nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}, \] (3)

\[ \nabla \cdot \vec{D} = \rho, \] (4)
where $\vec{E}$ is the electric field intensity; $\vec{B}$ is the magnetic flux density; $\vec{H}$ is the magnetic field intensity; $\vec{j}$ is the surface current density; $\vec{D}$ is the electric flux density and; $\rho$ is the volume charge density.

For stationary and quasi-stationary situations of electromagnetic field distribution, the displacement current density $\partial\vec{D}/\partial t$ is being neglected, which reduce equation (3) to form

$$\nabla \times \vec{H} = \vec{j}. \quad (5)$$

In three dimensions, when the divergence of the rotor of any vector field is zero, equation can be obtained [1]

$$\nabla \cdot \vec{j} = \nabla \cdot (\nabla \times \vec{H}) = 0. \quad (6)$$

The properties of material are defined by the equation

$$\vec{j} = \sigma \vec{E}, \quad (7)$$

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 \varepsilon \vec{E}, \quad (8)$$

$$\vec{B} = \mu \vec{H} = \mu_0 \mu \vec{H}, \quad (9)$$

where $\sigma$ is the electric conductivity; $\varepsilon$ is the electric permittivity which is given a $\varepsilon_0 \varepsilon_\varepsilon$; where $\varepsilon_{\varepsilon}$ is the permittivity in free space, $\mu \varepsilon_\varepsilon$ is the relative permittivity that determines the electric field solution in the insulators.; $\mu$ is the magnetic permeability; $\mu_0 \mu \varepsilon$ is the permeability in free space; $\mu_\varepsilon$ is the relative permeability along with the magnetic coercivity determine the magnetic properties of the material.

The solution of the task can be simplified by introducing the concept of magnetic vector potential $A$.

$$\nabla \times \vec{A} = \vec{B}. \quad (10)$$

The magnetic vector potential is defined in the entire desired region and can be related to the electric scalar potential $\phi$ by the following equation

$$\vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t}. \quad (11)$$

The maximum and minimum values of electric scalar potential $\phi$ the position is formed by the two ends of the conducting region. The nonconducting region $\phi$ is equal to zero. By combining equations (5), (6), (10) and (11), calculate the magnetic flux density $\vec{B}$ and current density $\vec{j}$ [1]

$$\vec{j} = \sigma \cdot \vec{E} = -\sigma \left( \frac{\partial \vec{A}}{\partial t} + \nabla \phi \right) = \nabla \times \vec{H} = \nabla \times \frac{\vec{B}}{\mu} = \frac{1}{\mu} \cdot \nabla (\nabla \times \vec{A}). \quad (12)$$

By using Coulomb Gauge,

$$\nabla \cdot \vec{A} = 0. \quad (13)$$

The transient state formulations for electromagnetic field will get the solution as shown in the equation
\[ \nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = \nabla \times \vec{H}_k - \sigma \left( \frac{\partial \vec{A}}{\partial t} + \nabla \phi \right) + \frac{1}{\mu} \nabla (\nabla \cdot \vec{A}), \quad (14) \]

where \( \vec{H}_k \) is the coercive magnetic field.

Electromagnetic fields calculation that emergent the IDM work, the analysis of the transient process in the time domain was used, which allows us to estimate the magnitude of the magnetic field during rotational movement. Figure 1 shows the constructed model of the IDM with a finite element grid.

\[ \text{Figure 1. Model of induction motor with a finite element mesh.} \]

The IDM with a short-circuited AIR63V4 rotor, powered by a three-phase voltage source with an amplitude of 380 V, was chosen as the base model for calculations.

The time interval for modeling is set from 0 to 1 s. with a step of 0.05 ms. Step time was chosen from a compromise between the accuracy of the calculation and the speed of the solution for each area under study, for example, with an air gap of 0.25 mm, a grid of 0.2 mm was selected, for the stator, except for the area of the teeth, the step was 10 mm.

The main characteristics of the simulated IDM are presented in table 1.

| Characteristics | Value |
|-----------------|-------|
| Power, kW       | 0.37  |
| Rotation speed, RPM | 1500 |
| Pair of poles   | 2     |
| Rated current, A| 1.37  |
| Efficiency, %   | 68    |
| Cos \( \phi \)   | 0.7   |
| Slip, %         | 8.7   |
| Bars of the rotor| 18    |
| Slot of the stator | 24   |
| The resistance of stator winding, Ohm | 21.5 |

The simulation was performed using the geometric dimensions and characteristics of the real motor obtained from [2].

3. Broken rotor bars.

Broken rotor bar is one of the commonly encountered induction motor faults. According to various sources, they account from 20 to 40% of IDM faults.
The development of growth can lead to new faults that cause premature failure of the IDM. This fault results in interturn short-circuit fault and interfacial short circuits, deterioration of insulation properties, and early bearing wear faults.

This happens because of the redistribution of the vector magnetic potential and magnetic field lines at the location of the fault. The magnetic field becomes asymmetric due to the lack of flowing current in the broken bars. The presence of an asymmetric magnetic field distribution leads to fluctuations in the IDM rotor rotation speed. The figure 2 graph of the speed of rotation of the rotor when one, two and three fault bars

![Figure 2. Rotor speed of normal motor and the broken bars.](image)

The frequency and amplitude of the rotor speed fluctuations increase with the development of a fault and depend on the slip of IDM value. When the fault bar passes through the positive magnetic pole, the amount of current flowing in the stator winding increases, causing a local increase in the magnitude of the magnetic field, which, acting on the rotor, creates an increase in the torque on the IDM shaft. When the damaged bar passes through the negative magnetic pole, the magnetic field decreases, causing the moment to decrease.

To quantify the value of the change in IDM rotation speed, we calculate the ripple coefficient, expressed in per cent weight to the average value in equation

\[
k_{\text{ripple}} = \frac{n_{\max} - n_{\min}}{n_{\text{main}}} \cdot 100,
\]

where \( n_{\max}, n_{\min}, n_{\text{main}} \) − the maximum, minimum and median speed of rotation of the rotor over the period.

The figure3 are presented the values of the coefficient and fluctuation frequency of rotational speed of the IDM rotor.

![Figure 3. Ripple coefficient of the rotor speed when the bars fault.](image)

For fault s in the rotor bars, in the stator windings, the currents of the reverse sequence flows with frequency \((1 - s) \cdot f_1\), which represent the left side harmonic of the reverse frequency \(f_1\). This creates an additional magnetic field with an angular frequency \((1 - 2s) \cdot \omega[3]\), rotating in the opposite
direction, with regard to the direction of the magnetic field currents of direct sequence with angular velocity $\omega$ rotating the rotor at a speed of $(1-s) \cdot \omega$. In the magnetic field acting on the rotor, there are fluctuations in the speed of rotation and the torque on the shaft. As a result, the appearance of the right side component of the rotation frequency harmonic on the spectrum $(1+s) \cdot f_1$.

The current of the stator of phase A for the case with three broken bars figure 4 (a) and the spectrum of the time signal figure 4 (b).

![Figure 4. Current of the stator phase A winding with three broken bars a) time signal; b) frequency composition.](image)

In figure 4 (a) it is seen that, with growth and fault it is indicated low-frequency modulation of the signal, the amplitude of which increases with the growth of the fault. Due to the increase in the frequency of slip, when the fault grows, the period of this modulation decreases.

Spectral analysis of the signal in figure 4-(a) shows that when the grows fault, the harmonic amplitude of the network frequency increases $- f_2$, frequencies modulation $f_2(1 \pm 2s)$, increases, which increases with the grows fault [4].

If there is a fault detect, the current amplitude in the stator windings will increase, and the shape of the magnetic field distribution in the IDM section will be distorted. There are moment fluctuations on the IDM shaft, leading to uneven rotation of the rotor. The amplitude of these vibrations depends on the IDM slip and increases with the growth of the fault.

4. Stator inter-turn short-circuit.

This fault is the second most common fault of induction machine fault. inter-turn short-circuit faults are caused by damage to the insulation of the stator windings, or may occur as a result of the development of such faults as rotor of bar fault, eccentricity, bearing wear, e.t.c. According to data provided in various sources, this defect accounts for 15% of the total number of failures. The IDM fault scheme with the by figure 5.
Figure 5. Diagram stator inter-turn short-circuit fault of the motor.

When the fault grows, the magnetic field is redistributed in the IDM section, which is associated with a change in the value of the currents in the stator windings. In the figure 6 a change in the magnetic field causes a moment fluctuation on the IDM shaft, resulting fluctuations in rotation speed of rotor.

Figure 6. Rotor speed of normal motor and stator inter-turn short-circuit fault.

The figure 6 shows detected interturn short-circuit, periodic fluctuations in the rotor speed IDM appear in the stator windings. The main oscillation frequency is the frequency $2f_c=100$ Hz. This frequency is associated with an increase in the reverse sequence of currents that form a counter magnetic flux [5]. In this case, there is a braking electromagnetic moment that slows down the rotor [6,7] when the pole passes through the winding of the fault-free phase, the current in which is the smallest by less than the amplitude of the currents in the other two phases. And an increase in the value of the moment when passing the poles of the windings of the other two phases, the current in which is greater because of the redistribution and the presence of a fault.

The dependence of the rotation speed ripple coefficient on the number of winding short-circuit calculated using the equation (15) is shown in figure 7.

Figure 7. Ripple coefficient of the rotor speed when the stator inter-turn short-circuit fault.
In figure 8 the current distribution in the stator windings at 57 wires of short-circuit.

![Current Distribution](image.png)

**Figure 8.** Current of the stator winding of phase A with 57 short-circuit wires

From figure 8 is seen, with the emergence and growth of the fault, there is a distortion of the current waveform in the defective stator winding. In descri cases, the stator current changes little to increase the number of short-circuited wires turns in from 27 to 57. The current increases in the interturn short-circuit as the number of turns in increases.

The spectrum of the current signal in the stator winding is shown in figure 9.

![Spectrum](image.png)

**Figure 9.** Spectrum current of the stator winding of phase A with 57 short-circuit wires.

When stator interturn short-circuit fault occurs, the amplitude of the main harmonic frequency of the electric network $f_e$ and $3f_e = 150$ Hz its third harmonic increases Hz. Harmonics at frequencies $n \cdot p \cdot f_e = (1-n_s \cdot s) \cdot f_e$, here $n = 2, 3, 4, 5, 6, n_s$ – the number of slots of the stator with a defective winding; $p$ – is the number of magnetic poles, caused by the magnetic flux generated by the shading coil. When the number of closed coils increases, the amplitude of these components increases, and their frequency decreases. The 27 short-circuit wires 23 Hz, при 57 –21.9 Hz, because change slip

**5. Conclusion**

In this paper, the results present by a finite element simulation of IDM in the presence of bars squirrel cage rotor and stator windings. As a result of the simulation, changes in the electromagnetic moment and mechanical characteristics of IDM were detected during the emergence and growth of faults. The harmonics amplitude of current in the stator windings at spectral analysis detect of signals can serve as a diagnostic property the presence at test faults of the rotor bars and stator windings. The results
conclusions reached of the simulation can be used to improve IDM technical condition the monitoring systems, protection and reduce the risk of faults in the bars of squirrel cage rotor and stator windings.

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