3D Finite Element Computation of Axial Flux in Induction Machine

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Abstract — **In the paper results of finite-element calculations of the electromagnetic field in a squirrel-cage induction motor with particular reference to the shaft flux were presented. A three-dimensional field-circuit model of the 300 kW induction motor was developed taking into account supplying the stator winding from the voltage source and the rotary motion of the rotor. Distribution of axial and radial components of the magnetic flux density in the end-winding region and the bearing region as well as transient waveforms of the shaft flux were computed at the initial period of the motor start-up.**

Keywords — Induction motor, axial flux, FEM 3D, eccentricity of the rotor.

I. INTRODUCTION

Due to asymmetries of magnetic and electric circuits in three-phase induction machines, axial magnetic fluxes are produced flowing along the shaft. Asymmetries may arise in the machine as a result of internal faults, such as interturn short circuits or loss of a supply phase in the stator winding, or failures of the rotor bars and end rings, as well as due to non-uniform air gap, for example, rotor eccentricity. Small electric and magnetic asymmetries are also found in fault-free machines due to inherent non-uniformities in the materials or inaccuracies during the production and assembly. Axial fluxes arising in such circumstances do not participate in useful energy conversion but may be the cause of bearing currents and cause additional eddy current losses in the end-region conducting elements as well as within the stator core end laminations. The axial flux passes through the air-gap, magnetic cores of the stator and rotor and the frame and bearing housing (Fig. 1).

In the machine cross-section within the active part of the air-gap, the axial flux density is distributed uniformly and has the same direction, so this is called a homopolar flux [2, 5]. The axial flux flowing through the shaft is often called a shaft flux. This flux flows in the radial direction by the motor bearings and induce currents in them. In addition to the axial shaft flux, there are also axial stray fluxes around the winding overhang.

The main causes of axial fluxes are [2]:

- Non-uniformity of the air-gap manifested by unequal air-gap reluctance under neighboring poles. Axial fluxes are generated if the number of pole pairs of a magnetomotive force harmonic is equal to the order of a reluctance harmonic,
- The existence of a circular current flow varying with time and embracing the shaft.

The shaft flux can be measured by using a search coil which is wound around the shaft of the induction motor [6]. The voltage induced in the coil can be used as a diagnostic signal for detecting and identifying variety of asymmetries occurring in the machine during its operation. For example, basing on the analysis of spectral components of this voltage it can be detected broken bars in the rotor cage, interturn short circuits in the stator winding, an eccentricity of the rotor and so on [3, 4, 6].

Three-dimensional field models of the machine should be used for axial flux calculations. Most commonly used two-dimensional models of an induction machine allow determination of the magnetic field distribution only in the plane of the machine cross-section (radial and circumferential components) generated by currents

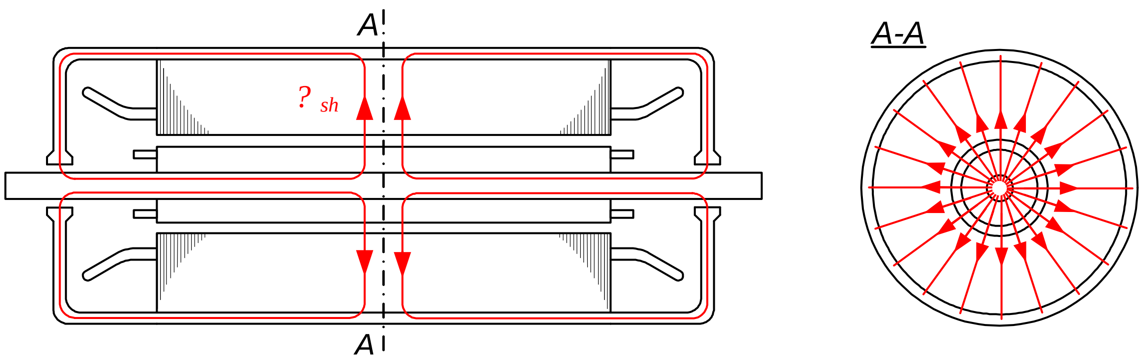

Fig. 1. Paths of homopolar fluxes in induction machine

flowing in the windings in a direction perpendicular to the area of analysis.

The paper presents the calculation of the three-dimensional field and shaft flux waveforms by the finite element method (FEM) at the initial period of start-up of the high-power cage induction motor.

II. THREE-DIMENSIONAL FIELD-CIRCUIT MODEL OF THE INDUCTION MACHINE

In the field-circuit model of the machine, the field equations describing time-space distributions of the electromagnetic fields are coupled to Kirchhoff's equations for particular windings of the machine and mechanical equations describing the rotor motion. Boundary-value problems for three-dimensional regions usually are not formulated for a magnetic vector potential, which does not help in solving this case of field equations. In the calculations of three-dimensional electromagnetic fields associated with external electrical circuits, the formulation ($\boldsymbol{T}$-$\boldsymbol{\Omega}$ [7]) is used in which utilizes the electric vector potential $\boldsymbol{T}$ and magnetic scalar potential $\boldsymbol{\Omega}$

$$\boldsymbol{J} = rot\,\boldsymbol{T}\,, \quad \boldsymbol{H} = \boldsymbol{T} - grad\,\boldsymbol{\Omega} \tag{1}$$

A magnetic scalar potential $\boldsymbol{\Omega}$ is used in the whole domain and an electric vector potential in the conducting region [7], which significantly reduces number of unknowns and computational costs. A quantity binding together the field equations and the electrical circuit equations is the induced voltage.

Rotational motion of the rotor is described by equation

$$J\frac{d\omega}{dt} = T_e + T_m \tag{2}$$

where J is a moment of inertia, ω is an angular mechanical velocity of the rotor, T_e, T_m is an electromagnetic and load torque, respectively.

Field-circuital computations have been carried out using the transient solver of the Maxwell-3D program for the cage induction motor with rated data: P_N = 300 kW, U_N = 1000 V, I_N = 210 A, $cos\ \varphi_N$ = 0,86, n_N = 1484 rpm, operating in mining drives.

Fig. 2 shows the 3D model for half of the motor along the shaft axis. Further reduction of the model is not possible due to the need to consider different cases of electric and magnetic asymmetry in the machine.

The model takes into account nonlinear B-H characteristics of ferromagnetic cores, skin effect in cage bars and rotational motion of the rotor. The model does not include skin effect in the stator winding and eddy currents induced in the stator laminations. The stator winding was modeled as external circuits attached to the machine FEM model and supplied from a three-phase voltage source. Within each time step program calculates phase currents in the winding.

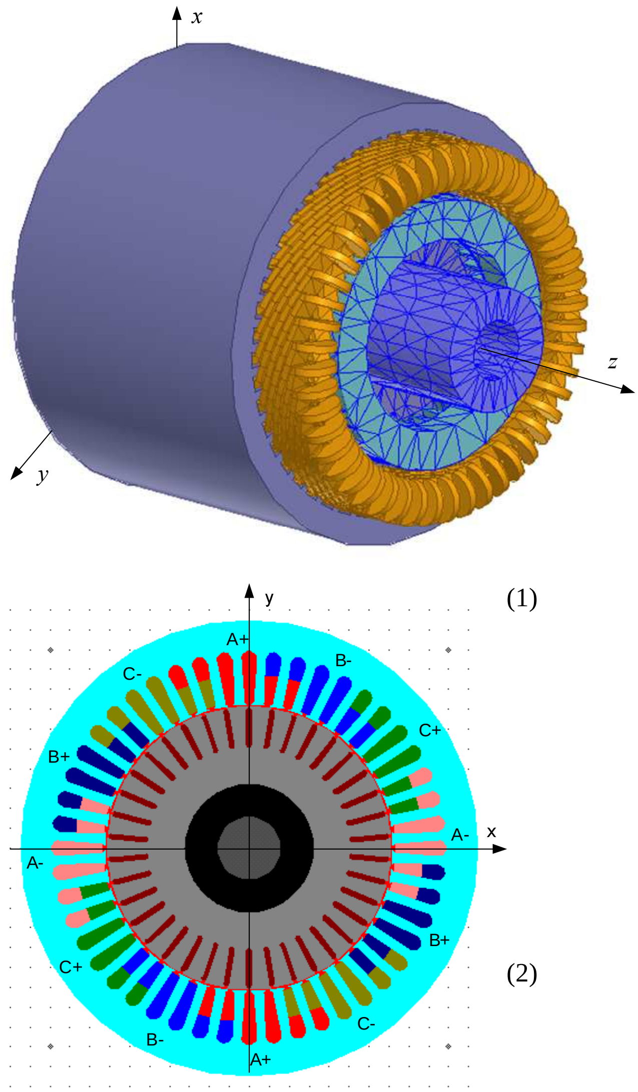

Fig. 2. Three-dimensional model of the induction motor and layout of the winding coils in the stator slots.

It was assumed that laminated iron cores consist of isotropic steel sheets. The global anisotropy of the laminations is modeled by specifying a stacking factor and stacking direction, which is perpendicular to the plane of the lamination.

III. RESULTS OF FIELD CALCULATIONS

Using the developed FEM model of the induction motor, calculations of transients are conducted during direct start-up after supplying the stator with rated three-phase voltage at no-load conditions.

Fig. 3 shows the distribution of the radial and axial components of the magnetic flux density (at the initial period of the motor starting) in the longitudinal cross-section of the motor. The rotor axis was shifted with respect to the stator axis (static eccentricity) with eccentricity factor

$$\varepsilon_{\%} = \frac{\varepsilon}{\delta} 100\% \approx 57\%$$

where δ is the nominal air-gap length.

a)

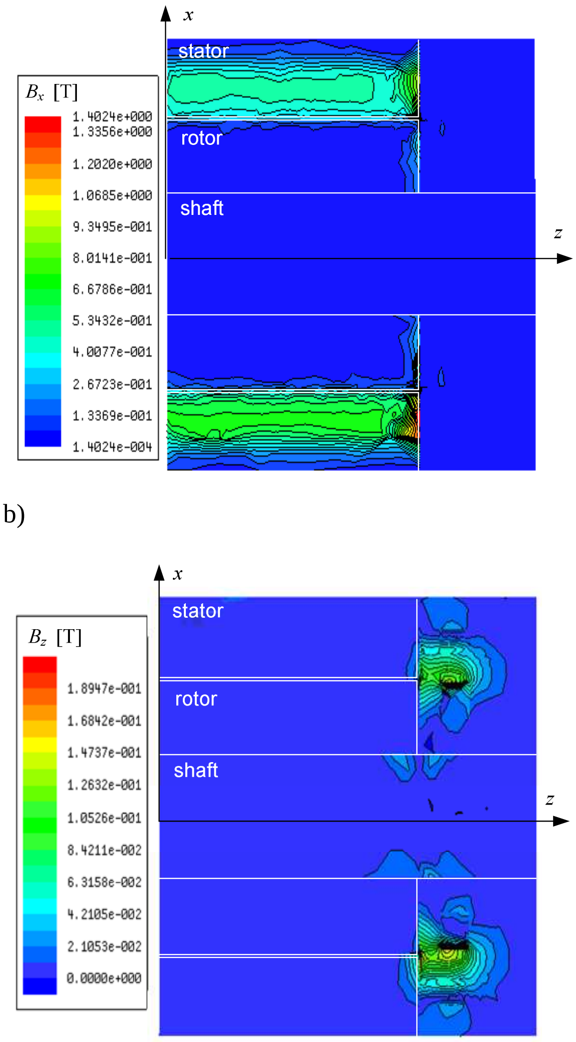

Fig. 3. Distribution of the radial (a) and axial (b) components of the flux density in the plane passing through the axis of the shaft in the motor with rotor eccentricity at the initial period of the start-up

The distribution of the magnitude and the axial component of the flux density in the air-gap (a) and in the shaft (b) along lines parallel to the shaft axis is shown in Fig. 4 for the motor with uniform air-gap at the initial period of the start-up. In the machine end region the axial component of the flux density B_z is being dominant.

The magnetic flux flowing along the shaft was calculated by integration of the flux density over the cross-section of the shaft

$$\Phi_{sh} = \int_s \boldsymbol{B} \cdot d\boldsymbol{s} \tag{3}$$

Fig. 5 shows the waveforms of the magnetic axial flux calculated by FEM at the beginning of the starting process for the motor with uniform air-gap in three cross-sections of the shaft. Larger values of the axial flux are at the ends of the rotor core.

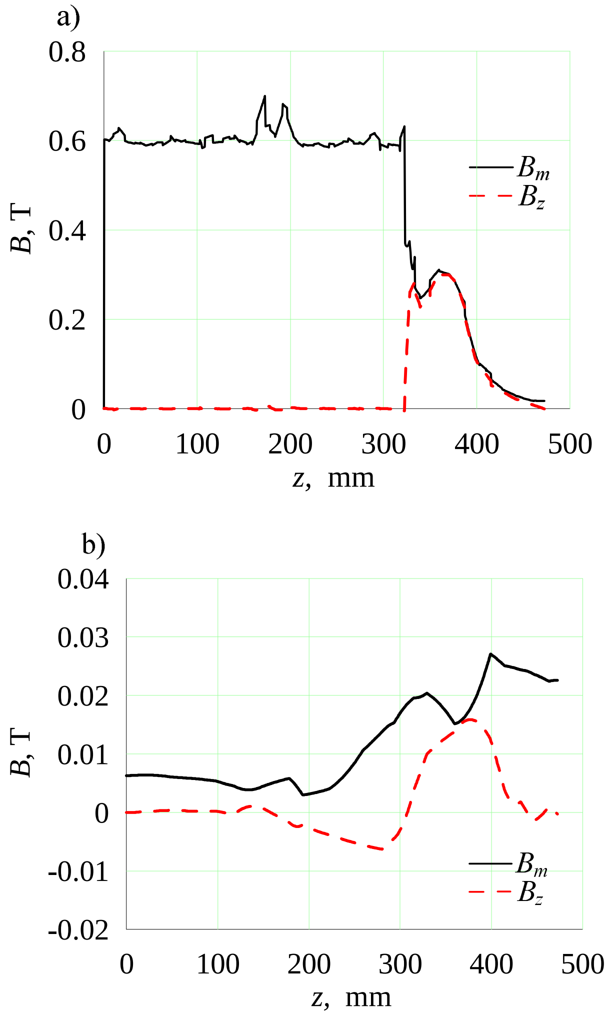

Fig. 4. Distribution of the magnitude B_m and the axial component B_z of the flux density in the air-gap (a) and in the shaft (b) in the plane passing through the axis of the shaft in the motor with uniform air-gap at the initial period of the start-up

IV. CONCLUDING REMARKS

Shaft flux waveforms can be used to detect a variety of asymmetry in the induction machine caused by internal faults. For this purpose the voltage induced in the search coil linked with this flux is measured under steady-state operating conditions of the machine.

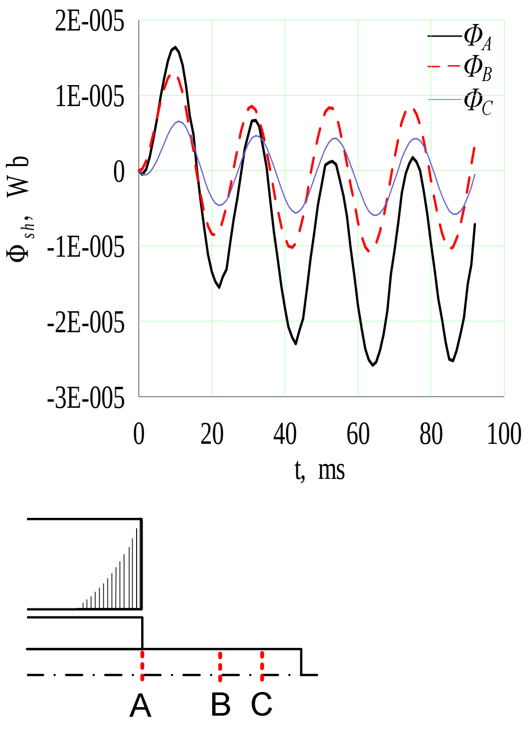

Fig. 5. Waveforms of shaft fluxes computed at the initial period of the start-up of the motor with uniform air-gap in the three shaft cross-sections *A*, *B*, *C*

Using three-dimensional field-circuit model of an induction machine solved by the finite element method, it is possible to compute waveforms of the magnetic shaft flux and performing detailed and multi-variant investigations. Field calculations must cover the complete transient state leading to the steady state under specified operating condition of the machine. Calculations are very time-consuming and require powerful computers. To accurately determine higher harmonics of the shaft flux, it is necessary to use suitably small time step and appropriately dense finite element mesh, which significantly increases the computation time.

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