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Differential Scattering Phase Rotor Windings of Asynchronous Machine

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Abstract — *In clause expressions for calculation of a field the air backlash, by a created winding of a wound rotor of the asynchronous machine and a method of calculation of differential leakage of this winding on a picture of distribution of a field in a backlash are resulted. Comparison with settlement methods existing now is made.*

Keywords — differential leakage, wound rotor, asynchronous machines.

In practice, the design of an asynchronous motor with a wound rotor, the differential leakage inductive reactance of its rotor winding is determined by the magnitude of the leakage magnetic conductivity coefficient [1,2]. However, the calculation formulas for these coefficients are usually semi-empirical and it is difficult to take into account a number of design and operating factors that affect them.

In this work, the inductive resistance of differential scattering of a three-phase symmetric winding of a phase rotor of an induction machine is determined from the pattern of the magnetic field distribution in the air gap created by this winding. Based on the expression of the radial component of the magnetic field strength in the air gap, obtained by solving the Laplace equation for the scalar magnetic potential, written in a cylindrical coordinate system, expressions for the field in the air gap of a current sheet, a coil, a group of coils and a single-phase double-layer rotor winding were compiled [3]. In particular, for the latter case, an expression is given in the following form

$$\mathrm{H_o} = 2\mathrm{w}_{\kappa 2}\sum_{n=1}^{\infty}\left[\mathrm{C}_n\rho^{(n-1)} - \mathrm{D}_n\rho^{-(n+1)} - \frac{i}{2\pi n}\mathrm{b}^n\rho^{-(n+1)}\right]\frac{\sin n\alpha_2}{\alpha_2}\sin\frac{\beta_2}{2}\frac{\sin n\left(\mathrm{q}_2\frac{\alpha_{z2}}{2}\right)}{\sin n\left(\frac{\alpha_{z2}}{2}\right)}\times$$
$$\times\left\{\cos n\varphi - \cos n\left(\varphi - \frac{\pi}{\mathrm{p}}\right) + \cos n\left(\varphi - \frac{2\pi}{\mathrm{p}}\right) - \ldots - \cos n\left[\varphi - \frac{\pi}{\mathrm{p}}(2\mathrm{p}-1)\right]\right\}, \qquad (1)$$

Making transformations and introducing the notation from (1), we obtain

$$\mathrm{H_o} = 4\mathrm{w}_{\kappa 2}\mathrm{q}_2\mathrm{p}\sum_{n=1}^{\infty}\mathrm{K}_n\kappa_{\text{об}n}\kappa_{\mathrm{pq}n}\sin n\left(\varphi - \frac{2\mathrm{p}-1}{\mathrm{p}}\frac{\pi}{2}\right), \qquad (2)$$

Similarly to (2), the formula for calculating the radial component of the magnetic field strength in the air gap of the machine created by a three-phase two-layer rotor winding with integer q2 when a symmetric sinusoidal current with a frequency f2 flows through it will have the form

$$\mathrm{H_т} = 4\mathrm{pq}_2\mathrm{w}_{\kappa 2}\sum_{n=1}^{\infty}\mathrm{K}_n\kappa_{\text{об}n}\kappa_{\mathrm{pq}n}\left[\sin n\left(\varphi - \frac{2\mathrm{p}-1}{\mathrm{p}}\frac{\pi}{2}\right)\sin\left(\omega_2\mathrm{t} + \frac{2\pi}{3}\right) + \right.$$
$$\left. + \sin n\left(\varphi - \frac{2\mathrm{p}-1}{\mathrm{p}}\frac{\pi}{2} - \frac{2\pi}{3\mathrm{p}}\right)\sin\left(\omega_2\mathrm{t} - \frac{2\pi}{3}\right) + \sin n\left(\varphi - \frac{2\mathrm{p}-1}{\mathrm{p}}\frac{\pi}{2} - \frac{4\pi}{3\mathrm{p}}\right)\sin\omega_2\mathrm{t}\right]. \qquad (3)$$

An expression similar to (3) for a three-phase single-layer rotor winding when a symmetrical sinusoidal current flows through it will be

$$H_т = 2w_{к2}pq_2\sum_{n=1}^{\infty}K_n к_{обn} к_{оqn}\left[\cos n\left(\varphi - \frac{p-1}{p}\pi\right)\sin\left(\omega_2 t + \frac{2\pi}{3}\right) + \right.$$

$$\left. + \cos n\left(\varphi - \frac{p-1}{p}\pi - \frac{2\pi}{3p}\right)\sin\left(\omega_2 t - \frac{2\pi}{3}\right) + \cos n\left(\varphi - \frac{p-1}{p}\pi - \frac{4\pi}{3p}\right)\sin\omega_2 t\right], \quad (4)$$

For a three-phase two-layer rotor winding with a fractional number of slots per pole and phase with a fractional base equal to two, the expression for the radial component of the magnetic field strength in the air gap created by this winding when a symmetrical sinusoidal current flows through it, similarly to (3) and (4), will have the form

$$H_т = 2w_{к2}p\sum_{n=1}^{\infty}K_n к_{сл.n} к_{уn} к_{оqn}\left[к'_{ркn}(f_г + 1)\cos n\left(\varphi + \frac{\pi}{p}\right) + к''_{ркn} f_г \cos n\varphi\right] \times$$

$$\times \sin\left(\omega_2 t + \frac{2\pi}{3}\right) + \left[к'_{ркn}(f_г + 1)\cos n\left(\varphi + \frac{\pi}{p} - \frac{2\pi}{3p}\right) + к''_{ркn} f_г \cos n\left(\varphi - \frac{2\pi}{3p}\right)\right] \times$$

$$\times \sin\left(\omega_2 t - \frac{2\pi}{3}\right) + \left[к'_{ркn}(f_г + 1)\cos n\left(\varphi + \frac{\pi}{p} - \frac{4\pi}{3p}\right) + к''_{ркn} f_г \cos n\left(\varphi - \frac{4\pi}{3p}\right)\right] \times$$

$$\times \sin\omega_2 t. \quad (5)$$

Expressions (3), (4) and (5) make it possible to calculate, at one point or another in the air gap, the radial component of the magnetic field strength created by the three-phase symmetric rotor winding, taking into account the effect on the field of the structural dimensions of the core, as well as the finiteness of the values of the equivalent magnetic permeabilities of bodies stator and rotor of an induction machine. When calculating the field in the air gap, created by one or another rotor winding, taking into account the finiteness of the values μ1 and μ2, similarly to when the magnetic field in the air gap created by the stator winding was calculated [4], it is convenient to consider it consists of three components:

1. Fundamental harmonic with order n = p;
2. The field of scattering along the crowns of the teeth, which is the sum of all spatial harmonic fields in the air gap, created by the rotor winding with orders from subdental and higher, and;
3. Belt scattering field, which is the sum of all spatial harmonic fields of the air gap up to the subdental order, except for the main one.

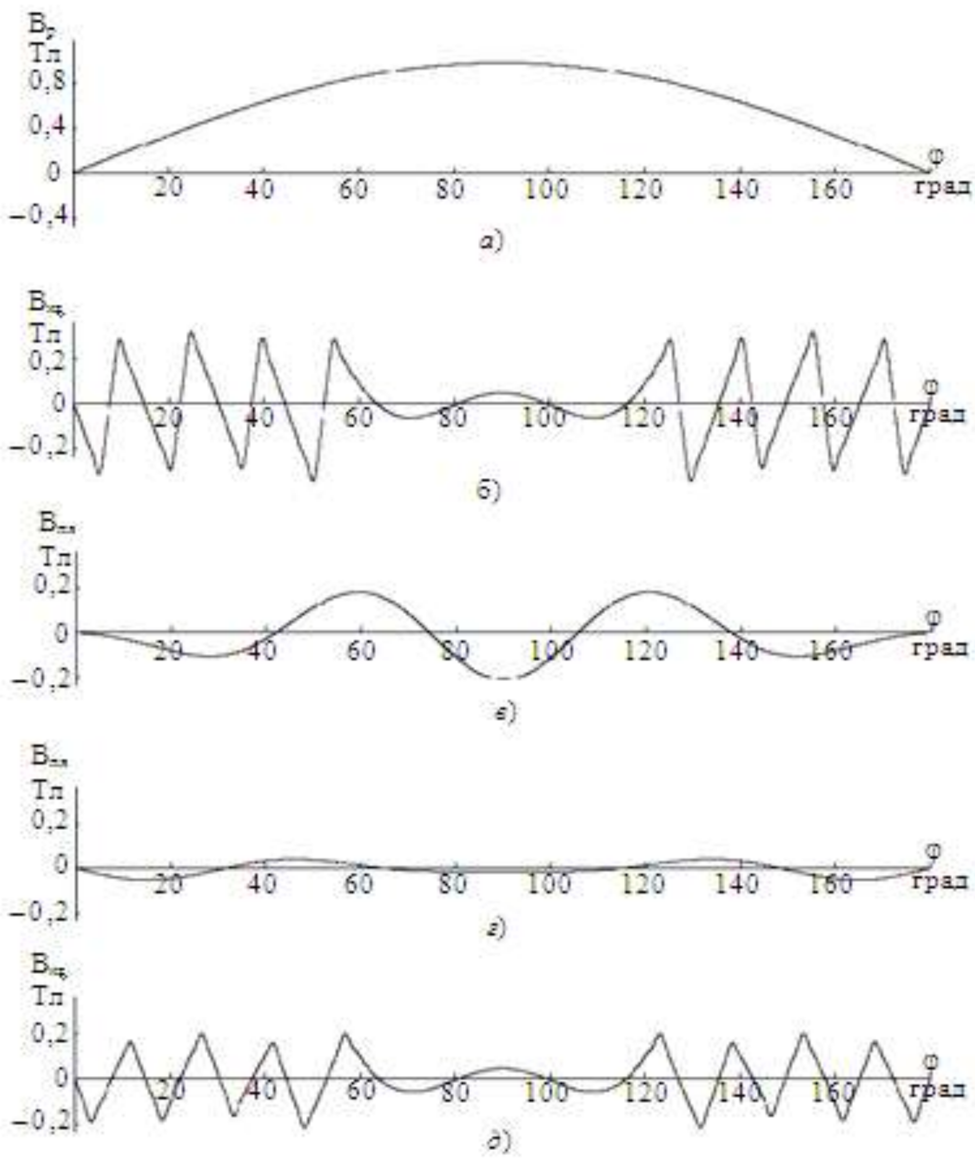

Рис. 1.

The last two field components in the air gap together form the differential scattering magnetic field of the rotor winding. Such a separate consideration of the field in the air gap created by one or another winding is due to the fact that the values of the equivalent magnetic permeabilities of the stator $\mu 1$ and rotor $\mu 2$ for each component of the field, calculated for a particular mode of operation of the AC machine, can differ significantly from each other from - because the magnetic circuit of each of these components is different, although they have a common magnetic circuit. As an example, Fig. 1 shows the dependences of the distribution of the magnetic inductions of the main working harmonic Bp, the stray field along the crowns of the teeth Bkz and the belt stray field Bpw along the circumference of the outer surface of the rotor, created by a three-phase two-layer winding of the phase rotor of an induction motor of the AK-62/4 type(14 kW; 220/380 V; 50.5 / 29.3 A; 1400 rpm; Z2 = 48; q2 = 4; y2 = 12; a = 0.03 m; b = 0.0996 m; s = 0.1 m; d = 0.1635 m; δ = 0.0004 m; bp2 = 0.0037 m) within one pole division of the machine, calculated according to (3) for time t = 7/300 s and rotor current i2 = 36.5 A. The position of the investigated point in space along the circumference of the air gap is characterized by the polar angle φ. The magnetic induction B was found by the value of the field strength H using the expression $B = \mu 0$ N. For greater clarity, the angle φ is expressed in electrical degrees.

When calculating the field of the fundamental spatial harmonic, the relative values of the equivalent magnetic permeabilities were taken $\mu 1 = 620$, $\mu 2 = 440$, calculated according to [3] for the nominal operating mode of the machine. For the belt scattering field of the air gap, in view of the fact that its spatial period is closer to that for the main field, the equivalent

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magnetic permeabilities for their calculation were taken equal to the corresponding values for the main field, i.e. $\mu_{пя1} = \mu_1$, $\mu_{пя2} = \mu_2$. To calculate the stray field along the crowns of the teeth, the values of the relative equivalent magnetic permeabilities determined according to [3] for the same nominal operating mode of the machine were equal to $\mu_{kz1} = 890$ and $\mu_{kz2} = 820$.

The belt component of the differential scattering field was determined as the sum of the spatial harmonic fields in the air gap with orders n = 10 and 14, and the scattering field along the crown of the teeth was the sum of harmonic fields in the range n from 22 to 298. The curves in Fig. 1 a, b and c correspond to diametric pitch of the rotor winding y2 = 12, and the dependence $B_{кz} = f(\varphi)$, shown in Fig. 1 d, to the value y2 = 10, i.e. shortening the pitch of the rotor winding by 1/6 of the pole division of the machine. Such a shortening of the pitch of the rotor winding led to a small, almost proportional coefficient of shortening the pitch of the winding for the fundamental harmonic, a change in the magnetic inductions Bp and Bkz. However, as can be seen from the comparison of the curves in Fig. 1c and 1d, such a shortening of the step significantly reduced the belt component of the differential scattering field. The root-mean-square value of the magnetic induction of the stray zone field at y2 = 12 was 0.1095 T, and at y2 = 10 it was 0.0283 T. The opening width of the rotor slot has a significant effect on the magnetic induction of the stray field along the crowns of the teeth of the rotor winding. The change in the width of the opening of the rotor slot bp2 has an insignificant effect on the main and belt fields of the air gap, i.e. in practice, they change in inverse proportion to the machine's air gap ratio. The curve of dependence $B_{кz} = f(\varphi)$ shown in Fig. 1 e corresponds to bp2 = 0.0074 m the values of the magnetic induction of the stray field along the crowns of the teeth of the rotor winding with 0.1529 T at bp2 = 0.0037 m by 0.0808 T at bp2 = 0.0074 m. Thus, the width of the open groove of the rotor has a significant effect on the magnitude of the stray field along the crowns of the teeth of the rotor winding. All three components of the air gap field created by the rotor winding vary significantly with the air gap δ.

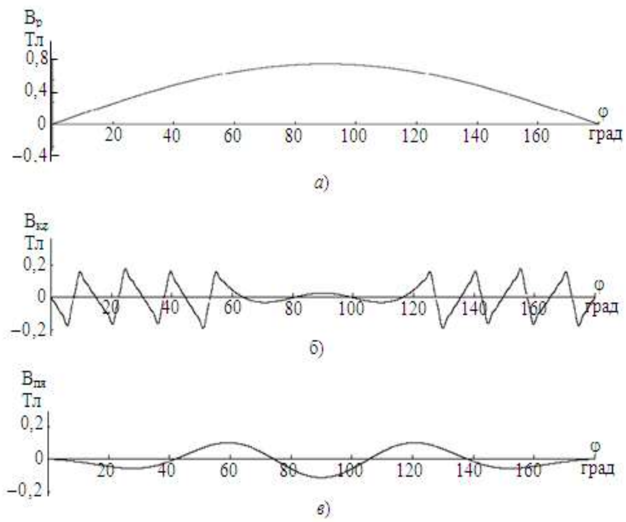

Рис. 2.

Figure 2 shows the dependences at bp2 = 0.0037 m and δ = 0.0008 m, i.e. at twice the value of in comparison with Fig. 1. A two fold increase in δ led to a decrease in the maximum value of the magnetic induction of the fundamental harmonic from 0.9968 T to 0.852 T, the rms value of the magnetic induction of the stray field along the crown of the teeth from 0.1529 T to 0.0808 T and a similar magnitude of the stray stray field from 0 , 1095 T at 0.0587 T.

Each component of the field in the air gap created by the rotor winding determines the corresponding inductive resistance of the same winding. The reactivity of the belt component of the differential scattering of the rotor winding is due to the belt scattering field in the air gap. This reactivity can be determined from the distribution pattern of the belt scattering field in the air gap by the energy method [4]. Due to the small size of the air gap in asynchronous machines, the field of the belt scattering practically does not change in the radial direction of the air gap of the machine.

Calculation of the inductive impedance component of the differential scattering of the rotor winding by the crown of the teeth was carried out by the value of the total flux linkage of the investigated phase of the rotor winding by the scattering field along the crown of the teeth, similarly to how it was carried out for the stator winding [5].

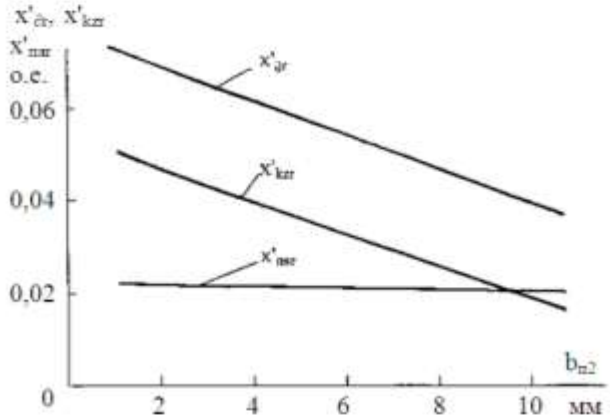

Рис. 3.

Figure 3 shows the dependences of the differential scattering inductive resistance, reduced to the stator winding and expressed in relative units, as well as along the teeth crowns and belt components for the phase rotor winding of an asynchronous motor of the AK-62/4 type, depending on the width of its rotor slot at $\delta = 0.4$ mm. As you can see, when the width of the opening of the rotor slot of the machine changes, the belt component of the differential scattering of the rotor winding practically remains unchanged, and its component along the crowns of the teeth changes in a rather wide range and as a result also changes in a wide range of the inductive resistance of differential scattering, which is the sum belt and on the crowns of the teeth of the winding dissipation reactivity. In Fig. 3, the dashed line shows the dependence of the inductive resistance of the differential dissipation of the rotor winding reduced to the stator winding on the width of the opening of its slot for a machine of the AK-62/4 type, obtained by calculation according to the method described in [1]. As you can see, a somewhat underestimated value of the inductive resistance of the differential scattering of the rotor winding is obtained in the entire range of variation of the width of the opening of its slot. The discrepancies increase as bp2 increases. If at bp2 = 2 mm these discrepancies are 18.4% of the value obtained by the proposed method, then at bp2 = 10 mm they are 50.1%. Since in the proposed calculation method the inductive resistance of differential scattering is determined from the pattern of the field distribution in the air gap, obtained taking into account the influence of design and operating factors on it, in our opinion, the results obtained by the proposed method are closer to the real one, as evidenced by the practically good coincidence of the results of calculating the differential scattering of the stator winding of a synchronous machine with the experimental data [5], where the calculation was carried out by a method similar to that described in this work.

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