FLUXES AND DISPERSION REACTANCES OF THE ASYNCRONOUS MACHINE

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ABSTRACT. Fluxes and dispersion reactance of the frontal sides of asynchronous machine windings were determined by applying the finite element method. The obtained results had been compared with the application of FEMM program and the results obtained by calculating using analytic expressions for special sources of electrical machine design.

Keywords: stator, frontal sides, winding, inductance, reactance.

ABSTRACT. Cu aplicaţia metodei elementului finit sau determinat fluxurile şi reactanţa de dispersie a părţilor frontale a înfăşurării maşinii asincrone. Sau comparat rezultatele obţinute cu aplicarea programului FEMM şi rezultatele obţinute prin calcul cu expresii analitice folosite în sursele speciale de proiectare a maşinilor electrice.

Cuvinte cheie: stator, părţi frontale, înfăşurare, inductivitate, reactanţă

1. INTRODUCTION

The parameters of the electric machines' windings play an important role in the exploitation process, as in stationary regime as in transitory regime. The dispersion reactances of stator and rotor windings of electric machines have relatively low values in comparison with mutual and cyclic reactances, this is why the fix determination of these parameters is difficult.

This difficulty is determined by the complexity of closing paths of the dispersion fluxes. The dispersion fluxes produced by the currents of the stator and rotor are closing through many paths, for example, stator and rotor notches of the alternative current machines, through the crown teeth, through the frontal sides of windings. Dispersion fluxes that correspond to the superior level harmonics, named as differential dispersion fluxes, do also exist.

All these components of the dispersion fluxes, which correspond to the respective reactances, are usually calculated using the approximate graphical or analytic methods. The dispersion fluxes of the frontal sides of the stator and rotor windings are especially difficult to be calculated. The magnetic field produced by the closed currents that flux through these windings' parts is three-dimensional and the mathematical interpretation of these dispersion fluxes is complicated.

The electrical machines have the frontal sides of the windings localized in geometrical spaces, which are surrounded with ferromagnetic and not ferromagnetic bodies. Different calculation methods are exposed in technical literature of specialty and of electric machines design [1, 2, 3], which use analytical expressions for determining dispersion magnetic fluxes and the reactances that correspond to the frontal sides. The complexity of determining these fields impose significant neglecting [4, 5] in order to obtain approximate analytical expressions. Empiric expressions, obtained basing on experimental data and design experience of electric machines, are usually used.

The implementation of computers in description and electric machines design gave the possibility to elaborate new methods of determining the magnetic field of an electric machine, the geometric and electromagnetic parameters of electric machines being specified for study.

2. FLUXES AND DETERMINATION OF DISPERSION REACTANCE

One of the modern methods of calculating the magnetic field present at electric machines is the finite element method. Despite the complex geometric configuration of closing surfaces of main and dispersion fluxes, the magnetic fields' image realized using this method is appropriate to the existent one.

The paper is devoted to the calculation of dispersion magnetic fluxes and, respectively, to the dispersion reactance, which corresponds to the frontal sides of the stator and rotor windings. The transversal section shown in figure 1 represents the simplified constructive scheme, because some constructive pieces like bandage and support consoles of the frontal sides are excluded, being obligatorily present in the construction of high power machines.

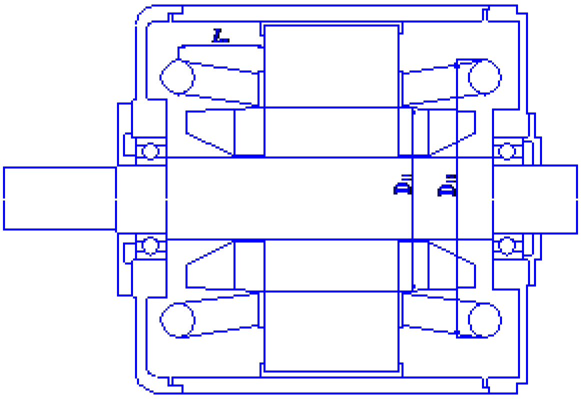


Fig.1. Longitudinal section of the asynchronous machine

The frontal sides of the three-phase stator winding in one layer represent the extensions l_{za} of the sections out of notches in axial direction, but the lateral ends of the sections form a belt consisted of 2pτ segments with the average arch length $\tau=\pi\frac{D_m}{2p}$, here $D_m=\frac{D_{l1}+D_{l2}}{2}$.

The dimensions of the active and constructive parts of the asynchronous machine (figure 1) are equivalent with the ones of the real synchronous machine.

The calculus was made for the nominal functioning regime of the studied asynchronous engine. Meanwhile, some assumptions and neglects had been adopted, like:

- frontal segments l_{za} of the stator winding are considered being parallel with the arbor's axis;
- circular parts of the stator winding form a band of conductors that triggers the nominal current;
- the stator pack is assembled from electrotechnical steel laminated at high temperatures, this is why the magnetic permeability in the axial direction is $\mu_{Fea}=k_{Fe}\mu_{Fe}$ (k_{Fe} – fill factor of the sheet package);
- the magnetic permeability of the housings and shields made of aluminum is accepted being equal to $\mu_{Al}\approx\mu_0$;
- the magnetic and electric system of the asynchronous machine is symmetric in study;
- the magnetic dispersion flux of the frontal sides varies by a sinusoid in space and time.

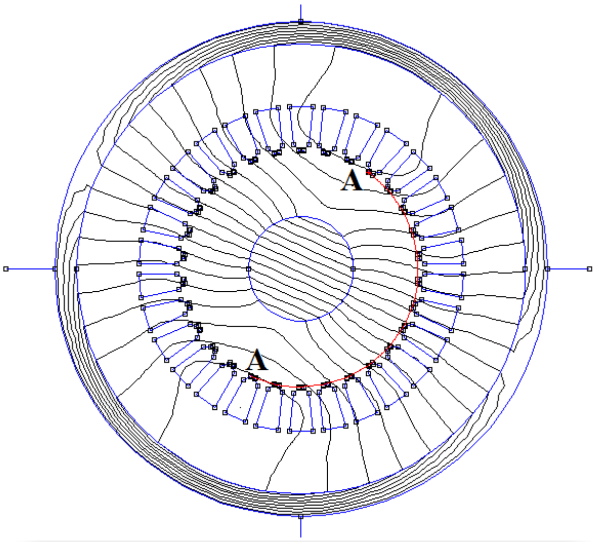
The allowed assumptions do not influence essentially on calculus and the image of the magnetic field is not deformed, being appropriate as for the real machine (figure 2).

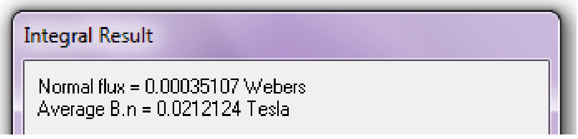
The dispersion magnetic field of the frontal sides is divided in two components, which do not influence each other: the first axial component of the dispersion flux is produced by the magnetization force

$$F_{\sigma 1a}=\frac{m_1\sqrt{2}\cdot w_1\cdot k_{w1}}{\pi p}I_1 \qquad (1)$$

and corresponds to the sections' extensions l_{z1} exited from the notches in axial direction.

The value of the magnetic dispersion flux $\Phi_{\sigma 1a}$ produced by the magnetization force according to expression (1) corresponds to the magnetic flux's value, which intersects the transversal section A-A (figure 2).




Integral Result

Normal flux = 0.00035107 Webers
Average B.n = 0.0212124 Tesla

Fig.2. Dispersion magnetic field in the transversal section of axial parts of the stator winding

It is evident from figure that the lines of the magnetic flux are concentrated into the arbor's housing, a fact that demonstrates that the magnetic induction is not uniformly distributed in this section. The dispersion flux's values and of magnetic induction from A-A section are shown in the window of figure 2.

The total magnetic dispersion axial flux, which corresponds to both parts of the stator winding for a phase disposed on lateral sides of the stator package, is given by the expression

$$\Psi_{\sigma 1a}=2\Phi_{\sigma 1a}w_1k_{w1} \qquad (2)$$

The dispersion inductance for a phase which corresponds to the axial frontal sides

$$L_{\sigma 1a} = \frac{\Psi_{\sigma 1a}}{\sqrt{2} \cdot I_1} \tag{3}$$

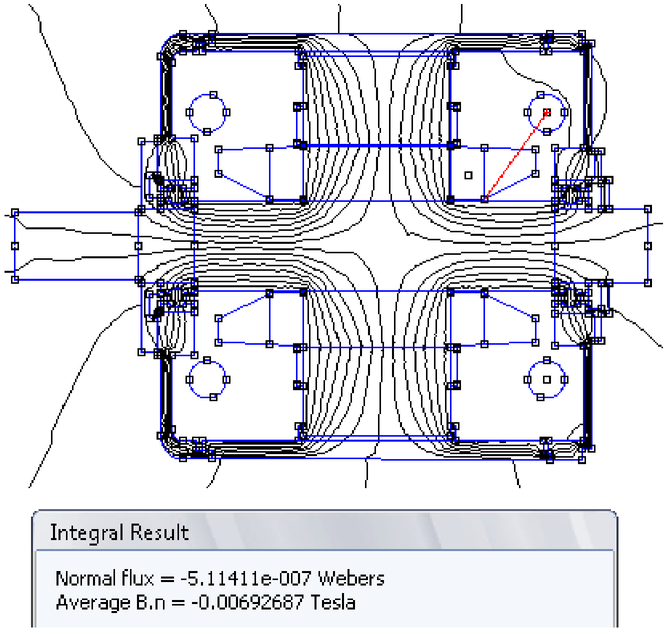
The component of the dispersion reactance for a phase by the axial length of frontal sides

$$x_{\sigma 1a} = \omega_1 L_{\sigma 1a} \tag{4}$$

The second component of the magnetic dispersion flux, which corresponds to the lateral side of stator winding, is produced by the magnetizing force corresponding to the following current:

$$F_{\sigma 1l} = \frac{m_1 \sqrt{2} \cdot w_1 \cdot k_{s1} \cdot I_1}{\pi \cdot p} \tag{5}$$

The magnetic dispersion flux's value $\Phi_{\sigma 1l}$ produced by the magnetizing force, which corresponds to expression (5), corresponds to the value of the magnetic flux, which intersects the transversal section B-B (figure 3).



Integral Result

Normal flux = -5.11411e-007 Webers
Average B.n = -0.00692687 Tesla

Fig.3. Dispersion magnetic field of the frontal sides of stator winding in the longitudinal section of the asynchronous machines

The total flux for the both lateral sides will be

$$\Psi_{\sigma 1l} = 2\omega_1 \Phi_{\sigma 1l} \tag{6}$$

The dispersion inductance corresponds to a following phase

$$L_{\sigma 1l} = \frac{\Psi_{\sigma 1l}}{\sqrt{2} \cdot I_1} \tag{7}$$

The reactance which corresponds to lateral sides of the stator winding equals

$$x_{\sigma 1l} = \omega_1 L_{\sigma 1l}$$

Finally, the reactance of frontal sides of the stator winding is

$$x_{\sigma 1f} = x_{\sigma 1a} + x_{\sigma 1l} \tag{8}$$

Paper number [4] presents two calculation methods of the dispersion reactance of frontal sides of stator winding for the alternative current machine.

The first method refers to the precise determination of the indicated reactance, taking into account the Poisson equations.

The expression for the dispersion reactance of frontal sides is obtained basing on the presented equations, with the assumption of some simplifying assumptions [6]:

$$X_{\sigma 1f} = 4\pi f \mu_0 \frac{w_1}{p} m_1 k_q^2 \frac{\tau}{\pi} k_l \tag{9}$$

In the known expression (11)

$$k_l = \frac{1}{\pi} k_{i\sigma} k_{gfr} \sum_{1,2,3,4} \frac{2}{T\sqrt{\frac{\pi^2}{\tau^2} + \left(\frac{n\pi}{T}\right)^2}} \cdot \frac{1}{\left(\frac{4n^2 L_{za}^2}{\beta^2 T^2} - 1\right)^2} \times$$
$$\times \left[\left(1 + \frac{16 n^2 L_{za}^4}{\beta^4 \tau^2 T^2}\right) k_{s1}^2 + \left(\frac{4 L_{za}^2}{\beta^2 \tau^2} + \frac{4 n^2 L_{za}^2}{\beta^2 T^2}\right) \sin^2 \frac{n\pi L_{za}}{T} - \right.$$
$$\left. - \frac{4 n L_{za}}{\beta T} \left(1 + \frac{4 L_{za}^2}{\beta^2 \tau^2}\right) k_{s1} \sin \frac{n\pi L_{za}}{T} \right] \tag{10}$$

the coefficient $ki_{\sigma 1} = 1 + 0.03 \sin\gamma$ takes into account the prone position of the section's frontal sides;

L_{za} – frontal sides' length in axial direction;

$k_{s1} = \sin\beta\pi/2$ – shortening rate, $\beta = y_1/\tau$;

T – distance from the stator package to shield.

The second method provides the dispersion reactance decomposition into two components. The first component is taken by the *z* axis, but the second one by the *x* axis.

The both expressions are presented by *z* axis as follows

$$X_{fz} = 4\pi f m_1 \frac{(w_1 \cdot k_{w1})^2}{p} \mu_0 \frac{L_{za}}{2\pi} \left(\frac{\pi\beta + \sin\pi\beta}{\pi\beta}\right) \tag{11}$$

And the component by *x* axis

$$X_{fz} = 4\pi f m_1 \frac{\left(w_1 \cdot k_{q1}\right)^2}{p} \mu_0 \tau \left(\frac{1 - \cos\beta \frac{\pi}{2}}{\pi} \right)^2 \times$$

$$\times \frac{1}{\pi} \left(\ln \frac{4 \mathrm{l_{cg}}}{\mathrm{D_m}} + \frac{1}{4} \right) \tag{12}$$

where

$$L_{cg} = L_{za} \frac{1 - \frac{2}{\pi\beta} \sin\beta \frac{\pi}{2}}{1 - \cos\beta \frac{\pi}{2}} \tag{13}$$

The expression for dispersion reactance of frontal sides is obtained if summing the both components

$$X_{\sigma 1 f} = 4\pi f m_1 \frac{\left(w_1 \cdot k_{q1}\right)^2}{p} \mu_0 \frac{\tau}{\pi} \mathrm{k_1} \tag{14}$$

where $k_l \cong 0.3(3\beta\text{-}1)$

As it was demonstrated, the expression obtained in the papers [1, 2] is complicated, and are not always used in the practice of alternative current machines design. Frequently, the following expression is used (16)

$$X_{\sigma 1 f} = \frac{0.158 f_1}{100} \left(\frac{w_1}{100} \right)^2 \frac{l_\delta}{p q_1} \lambda_{\mathrm{f}} \tag{15}$$

where the coefficient of specific permeance is

$$\lambda_f = 0.34 \frac{q}{l_\delta} \left(l_f - 0.64 \beta\tau \right) \cdot k_s^2$$

l_f – medium length of the half wound.

It is evident that the last expressions are approximated, but not so complicated.

Figure 4 shows the magnetic dispersion field's image produced by the closed currents inside shortcut rings of the rotor winding.

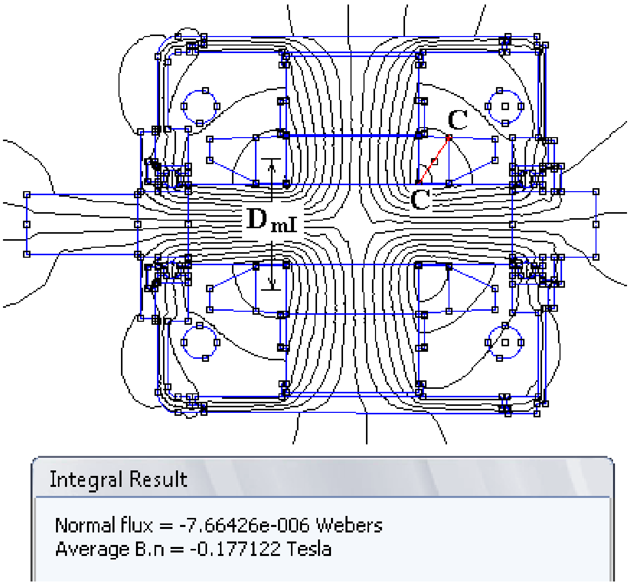
The current from rotor bar corresponds to the current density, which varies in the range (2.5-3.5)A/mm^2. The current value from the shortcut ring is

$$I_{2sc} = \frac{I_2}{2 \sin \frac{\pi p}{Z_2}} \tag{16}$$

where $\quad I_2 = j \cdot q_b$

The phasor of the rotor current forms the Ψ_2 angle compared with the electromotive voltage phasor induced into rotor winding.

The reactive component I'_{2r} or I_{2r} participates at the production of dispersion magnetic field of frontal sides of the rotor winding. The value of beam magnetic flux $\Phi_{\sigma 2f}$ corresponds to the value of the magnetic flux, which intersects the transversal section C-C (figure 4).



Integral Result

Normal flux = -7.66426e-006 Webers
Average B.n = -0.177122 Tesla

Fig.4. Dispersion magnetic field of shortcut rings of the rotor winding in the longitudinal section of asynchronous machine

Figure 5 shows phasor diagram according to which, the I'_2 current has two components: one active and the other one being reactive:

$$I'_2 = I'_{2a} + jI'_{2r}$$

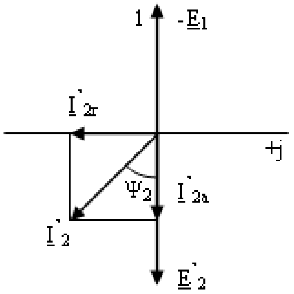


Fig.5. Simplified phasor diagram of voltages and currents

The total magnetic flux for both frontal sides is

$$\Psi_{\sigma 2f} = 2\Phi_{\sigma 2f}$$

In this case the rotor parameters are not reported to the stator parameters.

The dispersion inductivity of shortcut rings of the rotor winding is:

$$L_{\sigma 2f} = \frac{\Psi_{\sigma 2f}}{\sqrt{2} I_2}$$

Then, the dispersion reactance is $X_{\sigma 2f} = w \cdot s \cdot L_{\sigma 2f}$ and being referenced to the stator is:

$$X_{\sigma 2f} = X_{\sigma 2f} \cdot 4m_1 \cdot \frac{(w_1 \cdot k_{w1})^2}{Z_2} \qquad (17)$$

The dispersion reactance of frontal sides of the rotor windings corresponds only to the shortcut rings, because these are adjusted on the lateral sides of the rotor package.

It means that, the axial component of the dispersion flux is missing.

In design literature the dispersion reactance of shortcut rings of the rotor winding is usually calculated with the well known expression:

$$X_{\sigma 2f} = 7{,}9 \cdot f_1 \cdot l_\delta \cdot \lambda_{f2} \qquad (18)$$

where $\lambda_{f2} = \frac{2{,}3 D_{mI}}{Z_2 \cdot l'_\delta \cdot \Delta} \lg \frac{4{,}7 D_{mI}}{2a_{sc} \cdot b_{sc}}$.

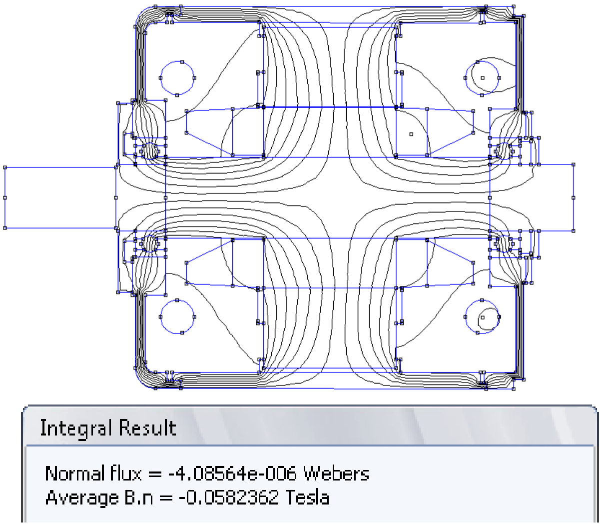
These expressions are approximated.

The reciprocal action of the fluxes of stator and rotor escapes is not taken into account in the majority of publications acknowledged to the calculation of fluxes and dispersion reactances of frontal sides.

The reciprocal influence degree of these fluxes can be determined with the application of finite element method. The superposition method can be applied as a result, because these fluxes are especially closing through non-ferromagnetic environments.

Figure 6 shows the image of the resulting magnetic field produced by the magnetizing forces, which correspond to the stator and rotor windings.

The values of escapes and magnetic induction flux are given in the window of figure 6.



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Normal flux = -4.08564e-006 Webers
Average B.n = -0.0582362 Tesla
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Fig.6. Superposition of dispersion magnetic fields of the frontal sides windings of stator and rotor.

This dispersion flux is common for the both lateral ring sides of the rotor and stator winding. The frontal axial side of the stator winding is not surrounded by the dispersion flux produced by the shortcut rings' currents, because these are positioned in perpendicular plane on the axial extensions of the stator winding.

The total dispersion flux of the frontal sides can be given as follows, if considering the reciprocal influence:

$$\Psi_{\sigma 1} = w_1 \Phi_{\sigma 1a} + w_1 \Phi_{12} = w_1 \Phi_{\sigma 1r} = \Psi_{\sigma 1r} \qquad (19)$$

and

$$\Psi_{\sigma 2} = \Phi_{12} = \Psi_{\sigma 2r} \qquad (20)$$

The inductances which correspond to the previously indicated total fluxes can be given by the expressions: for the frontal sides of the stator winding

$$L_{\sigma 1} = \frac{2\Psi_{\sigma 1r}}{\sqrt{2} \cdot I_1} \qquad (21)$$

and for the frontal sides of the rotor winding

$$L_{\sigma 2} = \frac{2\Psi_{\sigma 2r}}{\sqrt{2} \cdot I_2} \qquad (22)$$

Respectively, the dispersion reactance of the frontal sides of stator winding is

$$X_{\sigma 1} = \omega_1 \cdot \mathrm{L}_{\sigma 1} \qquad (23)$$

and the dispersion reactance for the frontal sides of the rotor winding is

$$X_{\sigma 2} = \omega_1 s \cdot \mathrm{L}_{\sigma 2} \qquad (24)$$

The obtained results had proved that the dispersion flux value and of the magnetic inductance of stator and rotor frontal sides are very low (figure 6). As a result, these values can be taken into consideration for making a calculus that corresponds to the theoretical values when needed. The se values can be neglected in engineering calculations.

3. OBTAINED RESULTS

Table 1 shows the calculus results of the dispersion reactance of frontal sides of a 15 kW, 2p = 2 asynchronous engine.

Table 1

Calculation expressions and the obtained results

Program FEMM	Expresii analitice
$x_{\sigma 1f} = 0{,}499$ [Ω]	$x_{\sigma 1f} = 0{,}473$ [Ω]
$x_{\sigma 2f} = 0{,}183$ [Ω]	$x_{\sigma 2f} = 0{,}18$ [Ω]

The calculations for the stator and rotor winding had been realized after the appraisal of FEMM program and analytical expressions used in electric machines design.

The deviation accounts 5,2% approx., just for the frontal sides of the stator winding. However, the phase dispersion reactance value of the stator winding is also linked with the dispersion fluxes closed through notches, through the teeth crowns and the fluxes produced by the currents of superior level harmonics.

4. CONCLUSIONS

- ✓ The calculation of dispersion magnetic flux, which corresponds to the dispersion reactance of the frontal sides of stator and rotor windings, had been made using the finite element method.
- ✓ Insignificant assumptions had been adopted for constructing the studied machine, which had not essentially deformed the determination of these magnitudes. The comparison of the results obtained with FEMM program and the results obtained by calculus using analytical expressions showed that the deviation accounts 5,2% only for dispersion reactance of the frontal sides.
- ✓ The FEMM program application excludes the approximation, simplifies by minimum the calculus volume and gives the possibility to rapidly and exactly optimize the electric machine's parameters.

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