THE COMPUTATION OF REACTION AND HOMOPOLAR INDUCTANCES OF A SYNCHRONOUS MACHINE, WITH 2D NUMERICAL ANALYSIS SOFTWARE

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***Abstract* – The aim of this paper is to present in which way is determined the reaction and homopolar inductances of a three-phase synchronous machine with electromagnetic excitation, using a numerical analysis software.**

Keywords: *reaction, homopolar inductances, synchronous machine, numerical analysis software.*

1. INTRODUCTION

Reaction and homopolar inductance determination for synchronous machine is realized even in the design stage, as well as the other parameters, when these are analytically determined. These inductances can also be determined in the design phase using numerical analysis methods of the electromagnetic field for the designed machine; from these methods probably the most used being the finite elements method (FEM).

In this paper will be realized a comparative analysis between analytically obtained results and those obtained using software specialized in computation of the electromagnetic field, software based on FEM.

Because 2D software is used, only corresponding part to the stator length of homopolar inductance is computed and this part is compared with that analytically determinate.

2. METHODS USED

2.1. Analytical computation

In order to determine these inductances in analytical way, already consecrated formulas have been used, formulas which were employed by some authors [3] in their design work for electrical machines, and these formulas are:

$$L_{ad,q} = \frac{X_{ad,q}}{\omega} \tag{1}$$

$$X_{ad,q} = x_{ad,q} \cdot \frac{U_N}{I_N} \tag{2}$$

$$x_{ad} = \frac{k_{ad} \cdot F_a}{k' \cdot U_{m\delta 0}} \tag{3}$$

$$x_{aq} = \frac{k_{aq} \cdot F_a}{k' \cdot U_{m\delta 0}} \frac{1+k_c}{2} \tag{4}$$

$$F_a = 0.9 \frac{m \cdot N_1 k_{w1}}{p} I_N \tag{5}$$

$$U_{m\delta 0} = 2 \frac{B_\delta k_c}{k_E \mu_0} \delta \tag{6}$$

In the previous formulas: L_{ad} – longitudinal reaction inductance, L_{aq} – transverse reaction inductance, ω – angular frequency of stator currents, U_N – line voltage, I_N –winding current, k_{ad} =0.875, k_{aq}=0.4, k'=1.07, k_c – Carter's coefficient, F_a – total reaction current, m – phase number, N_1 – turns number of stator phase, k_{w1} – winding factor, p – poles pair number, $U_{m\delta 0}$ – magnetic tension, B_δ – air-gap flux density , μ_0 – air magnetic permeability, δ – air-gap width.

The homopolar inductance has been determinate in according with [3].

2.2. Numerical analysis based on FEM

Numerical analyses of electromagnetic field in case of an electrical machine consist in solving Maxwell's equations with imposed boundary conditions. For stationary magnetic fields or assimilable, these equations lead to the following differential equation:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times \overline{A} \right) = \overline{J} \tag{7}$$

where: μ - magnetic permeability in terms of magnetic flux density, $\overline{A}$ - magnetic vector potential, $\overline{J}$ - current density. The solving of equation (7) using FEM can be made with Rayleigh-Ritz method, which consist in minimalizing function (8) associated with it, and in dividing the domain in finite elements that doesn't necessarily have the same shape.

$$F\left(\overline{A}\right) = \frac{1}{2}\iiint_V \frac{1}{\mu_r}\left(\nabla \times \overline{A}\right)\left(\nabla \times \overline{A}\right)dV - \\ - \mu_0 \iiint_V \overline{J}\,\overline{A}dV \quad (8)$$

In case of a 2D analysis in Cartesian coordinates formula (8) becomes:

$$F = \frac{1}{2}\iiint_V \frac{1}{\mu_r}\left[\left(\frac{\partial A_z}{\partial y}\right)^2 + \left(\frac{\partial A_z}{\partial x}\right)^2\right]dV - \\ - \mu_0 \iiint_V A_z J_z dV \quad (9)$$

Because the way of obtaining the minimalized equation system is widely shown in specific literature, e.g. [2], this paper will not approach it, being specified only that the system is solved in a single iterative cycle for linear materials, and in two iterative cycles for nonlinear materials, when magnetic permeability is permanently updated in terms of magnetic flux density.

In order to compute the transverse and longitudinal reaction inductance, and homopolar inductance, a numerical analysis has been realized – with MagNet 6.21.1 software – for a synchronous machine.

2.2.1. Longitudinal reaction inductance L_{ad}

In order to determine this inductance, the numerical analysis of a synchronous machine has been realized in the following conditions:

- the rotor poles aligned with magnetic field axis of stator;

- balanced three-phase current has been established through stator phases winding: $\frac{i_a}{2} = -i_b = -i_c$;

- current doesn't go through excitation winding.

In these conditions, magnetic flux lines and magnetic flux density are shown in the following figure (Fig.1).

After the numerical analysis we have obtained the magnetic flux produced by the stator winding that flows along the poles, Ψ_{ad}, and using this, with relation (10) the inductance L_{ad} has been computed.

$$L_{ad} = \frac{2}{3}\frac{\psi_{ad}}{i_a} \quad (10)$$

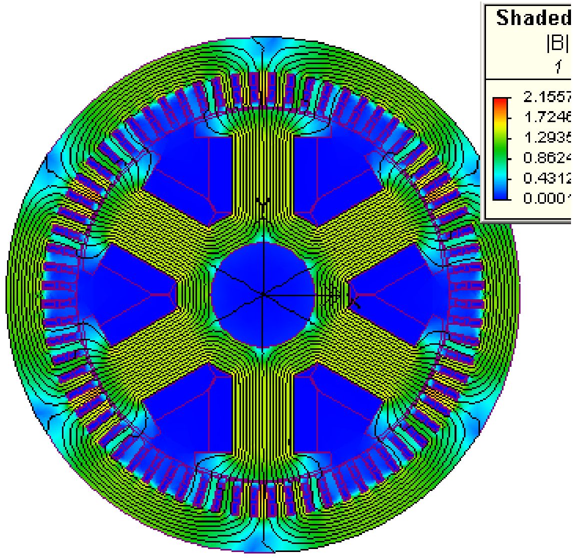

Figure 1: Magnetic flux lines and magnetic flux density distribution, when determining L_{ad}

This inductance is computed for a one phase.

2.2.2. Transverse reaction inductance

This inductance has been determined after the numerical analysis of the synchronous machine under conditions presented in the previous paragraph (2.2.1), but the position of the rotor has been chosen so that the magnetic field axis of stator coincides with the transverse axis of the rotor.

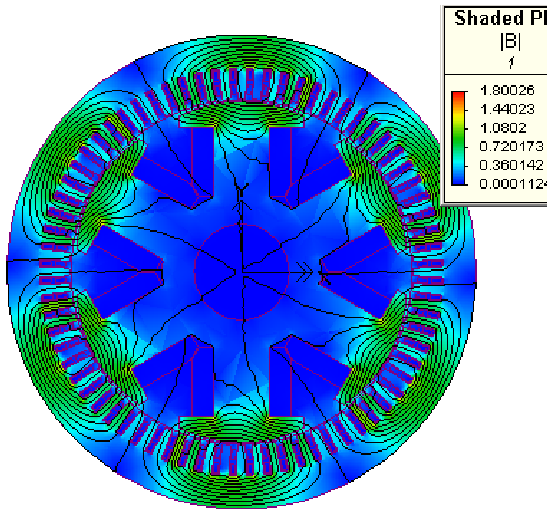

Figure 2: Magnetic flux lines and magnetic flux density distribution, when determining L_{aq}

For this position of stator magnetic field axis, magnetic flux lines and magnetic flux density are shown in the previous figure (Fig.2).

Since in this case the magnetic flux doesn't cross longitudinally the rotor poles and doesn't link the rotor winding, consequently the flux Ψ_{aq} couldn't be obtained directly as in the previous case. The computation of this flux has been realized in terms of magnetic vector potential distribution on outer diameter of the rotor, shown in figure 3.

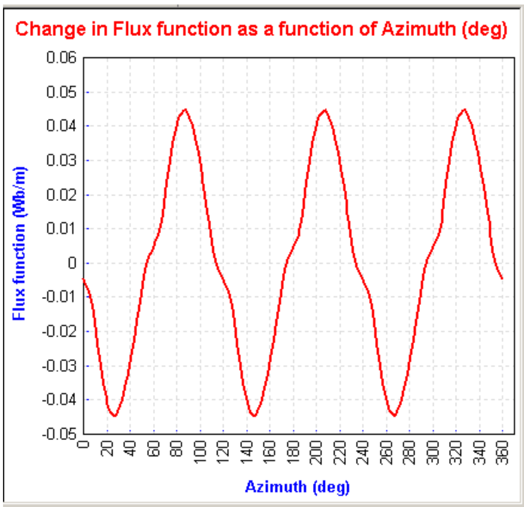

Figure 3: Magnetic vector potential distribution A on outer diameter of the rotor

The flux that crosses the poles shoes Ψ_{aq} can be determined in terms of fundamental component of the magnetic vector potential with formula 11 [1], and the corresponding inductance can also be determined with formula 10, where: l_i – ideal stator length.

$$\Psi_{aq} = \frac{2Al_i k_{w1} N_1}{\sqrt{2}} \tag{11}$$

2.2.3. Homopolar inductance L_0

Homopolar inductance has been determined by supplying the stator winding as shown in figure 4, the current being at nominal value [4].

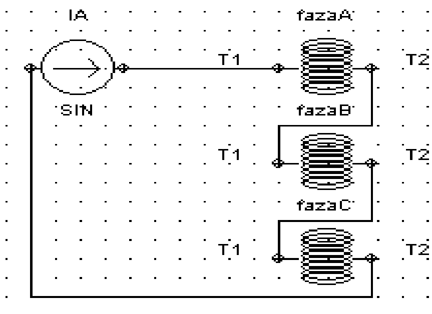

Figure 4: Stator winding supply when determining L_0

Homopolar inductance doesn't depending on rotor position.

In figure 5 are shown the magnetic flux lines and magnetic flux density distribution.

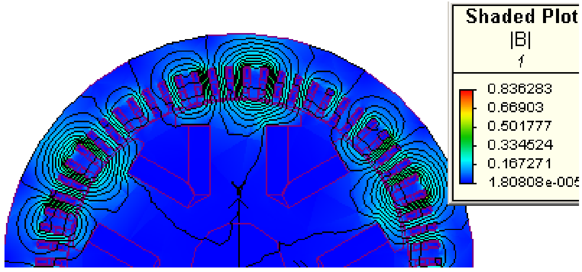

Figure 5: Magnetic flux lines and magnetic flux density distribution, when determining L_0

Taking into consideration that a numerical analysis has been realized, only that part of homopolar inductance corresponding to stator length (without the part corresponding to end winding) will be determined.

With this end in view, the average flux corresponding to one phase – Ψ_0 – will be determined in terms of the total flux of each phase (Ψ_A, Ψ_B, Ψ_C) with the following formula:

$$\Psi_0 = \frac{\Psi_A + \Psi_B + \Psi_C}{3} \tag{12}$$

Inductance L_0 has been computed with the following formula:

$$L_0 = \frac{\Psi_0}{i_0} \tag{13}$$

The same value for the homopolar inductance L_0, can be obtained if it is determined in terms of the magnetic field energy stored in the whole model – W_m, with formula:

$$L_0 = \frac{1}{3}\frac{W_m}{\frac{i_0^2}{2}} \tag{14}$$

3. RESULTS

The analyzed model is a three phase synchronous machine with salient pole with nominal power 400kW, voltage 6kV, frequency 50Hz, 1000 r.p.m., outer diameter of the stator 740mm, inner diameter 540mm, 240 turns per phase, two layers winding with shortened pitch.

For this machine the notches, parts of notches respectively corresponding to one stator phase are shown in figure 6, where can be seen that there are notches which contain coils that belong to different phases.

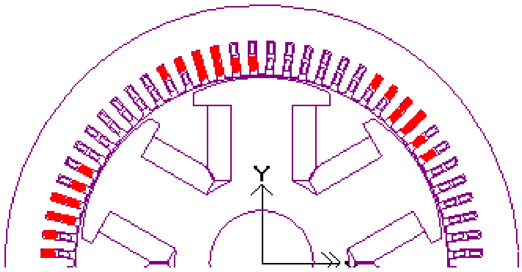

Figure 6: The notches corresponding to one phase

The obtained results for this model are presented in table 1, in which ε represents the error between analytic and FEM results.

Values [m.u.]	Analytical	FEM	ε [%]
L_{ad} [mH]	309.5	291	5.9
L_{aq} [mH]	166.84	164.2	1.6
L_0 [mH]	17.96	21	14.4

Table 1: Compared values

The error is larger for the homopolar inductance where is compared only the part which doesn't include that corresponding to the end winding.

4. CONCLUSIONS

In conclusion this paper shows how a 2D finite element program may be used to compute the reaction inductance for a synchronous machine and partially the homopolar inductance. In order to determine reaction inductances it has to take into consideration the rotor position in terms of stator magnetic field axis.

References

[1] D. Ban, D. Zarko, I. Mandic, *Turbogenerator End Winding Leakage Inductance Calculation Using a 3-D Analytical Approach Based on the Solution of Neumann Integrals*, Research Report,2003-07.

[2] M.V.K. Chari., P.P. Silvester, *Finite elements in electrical and magnetic field problems*, Mc Graw-Hill, London, 1980.

[3] I.Cioc, C. Nica, *Proiectarea maşinilor electrice,* Ed.D.P, Bucureşti, 1994.

[4] Gh. Ovidiu Drăgănescu, *Încercările maşinilor electrice rotative*, Ed. Tehnică, Bucureşti, 1987.