Calculation of Leakage Flux in Stator and Rotor Windings and Reactances of Solid Salient Poles Synchronous Motor by Finite Element

Mirka Popnikolova Radevska[1]

Abstract – **In this paper is presented a methodology for numerical determination and complex analysis of a Solid Salient Poles Synchronous Motor (SSPSM), product of MAWDSLEY with rated data: 3.52 kW, 240 V, exitation current I_f =5.5 A, and 1500 r. p. m. Programe package FEM 3D, for calculation in magnetostatic case is applied in order leakage fluxes in active parts of stator and rotor windings and the part of the winding overhangs to be calculated. Leakage fluxes are determined from the value of magnetic vector potential A. For that purpose a cross section on each local coordinate systems for five layer of the active length and the rotor und stator overhangs are presentation.**

Keywords – **Solid Salient Poles Synchronous Motor, programme package FEM-3D, Calculation of leakage flux, Motor reactances.**

I. Introduction

FEM 3D is proven numerical tool for analyzing electromagnetic phenomena in electrical machines and devices. This method enables to enter “inside the machine” and to evaluate exactly magnetic quantities such as air gap flux or leakage flux in any part (layer) of the motor. Using numerical calculation performed by FEM. 3D, they can be calculated more precisely which improves overall accuracy of motor reactances. Mathematical model is generated by dividing motor domain per z-axis in five layers and is presentation in Fig.1.

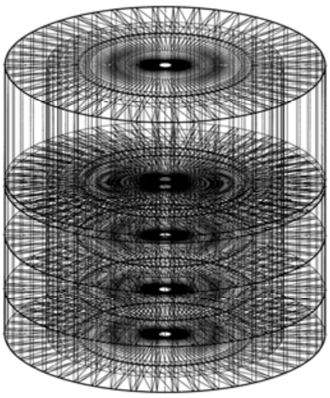
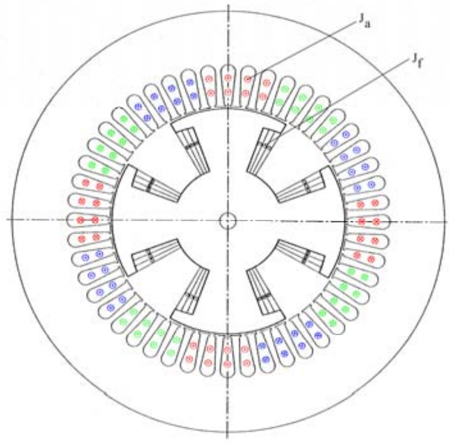


Fig. 1. 3 D view of the mesh.

[1]Mirka Popnikolova Radevska is with Technical Faculty, Ivo Lola Ribar b.b., 7000 Bitola, Macedonia, E-mail: mirkare@mt.net.mk

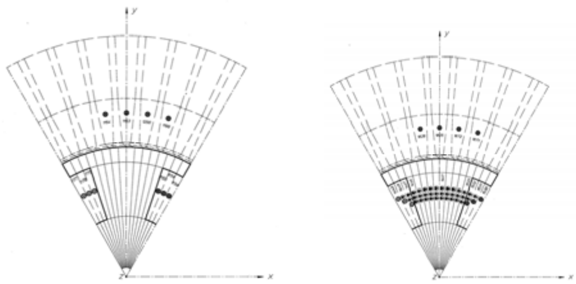
In first layer are placed active parts of stator and rotor winding while winding overhangs are placed in second, third and fourth axial layer. Each layer is divided into sub-domains wit local coordinate system. FEM 3D automatically generates mesh of finite elements and calculated the values **A** in each node of the 3D mesh.
The cross section of first layer and currents density is presentation in Fig. 2.

Fig. 2. Cross section of first axial layer with current densities.



A part of cross section of second and third axial layer and currents density is presentation in Fig. 3.

Fig. 3. A part of cross section of second and third axial layer and



currents density.

II. Calculation of Leakage Fluxes in Stator and Rotor Windings

Computation of leakage fluxes of stator winding is made in active parts of stator winding and the parts of the windings placed in channel or second, third and fourth axial layer of mathematical model Fig. 1. and Fig. 2 and Fig. 3. Leakage flux in active part of the motor windings is determined from the value of magnetic vector potential **A**. Leakage flux is calculated when current is in direction z-axis, and normal vector of magnetic induction **B** which creates leakage flux is in the direction of x-axes. The Leakage flux in active part of motor winding, when the excitation current $I_f = 0$, and rated stator current I_{an} in phase A is calculated according to Eq.1 :

$$\Delta\Psi_{Iki} = l_s \frac{N_k}{4}\frac{\Delta A_i}{\Delta y} \tag{1}$$

I-denotes first axial layer, *k*-channel leakage, *i*-number of channel, Δy-radial channel length, N_k-number of conductors. Total leakage flux in first axial layer or in active part of stator winding per poles is read out from the output file POT. DAT of FEM 3D and its value is:

$$\sum\Delta\Psi_{Iki} = \sum_{i=481}^{482}\Delta\Psi_{Iki} + \sum_{i=527}^{528}\Delta\Psi_{Iki} \tag{2}$$

$$\sum\Delta\Psi_{Iki} = 0.004034\ \text{Vs}$$

Calculation of leakage flux in second and third layer of stator winding represents the leakage flux in winding overhangs. Method of calculation is identical as in the first layer. Now local coordinate system is placed in sub-domains which approximately represent winding overhangs. In Eq. 1, only lengths of stator winding overhangs in second and third layer are replaced and following results are gained respectively:

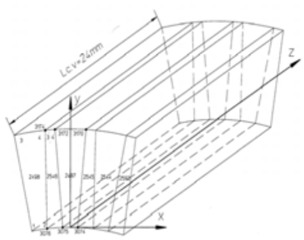


Fig. 4. Local coordinate system in winding overhangs of stator winding, where is:

$$\sum\Psi_{IIki} = 7.676\times10^{-5}\ \text{Vs}$$

$$\sum\Psi_{IIIki} = 3.449\times10^{-2}\ \text{Vs}$$

Leakage flux in fourth axial layer is determined from Eq. $\mathbf{B} = rot\mathbf{A}$. Now, local coordinate system is placed as it is shown on Fig. 4.

l_{SIVcv} – axial length of fourth layer, $b_k = 55.9$mm- channel width, $t_I = 99.7$mm- pitch channel-tooth, b_z – width of stator tooth, N_k – number of conductors per channel.

A. Leakage flux per **k** –ort

1. For y=const, $ls_{c.v.}$=24mm

According to Eq.1., leakage flux in overhangs over channels has value:

$$\sum\Psi_{IVay} = 0.236\ \text{Vs}$$

2. For x=const. following the same Eq. calculated value of leakage flux is:

$$\sum\Psi_{IVax} = 0.222\cdot10^{-3}\ \text{Vs}$$

Total leakage flux in stator winding per **k** ort is calculated froom root square of $\sum\Psi_{IVay}$ and $\sum\Psi_{IVax}$ and its value is:

$$\sum\Psi_{IVa} = 0.324\cdot10^{-3}\ \text{Vs.}$$

B. Leakage flux per **i** ort

1. For $y = const, \quad \Delta x = b_k$

$$\sum\Delta\Psi_{bky} = 0.00596\ \text{Vs}$$

2. For $y = const., \quad \Delta x = b_z$

$$\sum\Delta\Psi_{IVbzy} == 0.00399\ \text{Vs}$$

Total Leakage flux in winding overhangs for $y = const.$ per **i** ort is calculated as:

$$\sum\Delta\Psi_{IVby} = \Delta\Psi_{IVbky} + \Delta\Psi_{IVbzy} = 0.0096\ \text{Vs}$$

Total Leakage flux in winding overhangs $z = const.$ per **i** ort is:

$$\sum\Delta\Psi_{IVb} 0.0102\ \text{Vs}$$

Total Leakage flux in stator winding overhangs per pair of poles is found from:

$$\sum\Delta\Psi_{IV\,c.v.} = 2\cdot\sum\Delta\Psi_{IV\,a} + \sum\Delta\Psi_{IV\,b}$$

Computation of leakage fluxes of rotor winding is made in active parts of rotor winding and the parts of the windings placed in channel or second, and third axial layer of mathematical model Fig. 1. and Fig. 2 and Fig. 3. It is assumed that rated current flows trough rotor winding $I_f = I_{fn} = 5.5\text{A}$, and the current in the stator winding is $I_a = 0$. Local coordinate system is placed it is shown in Fig. 5. and Fig. 6. Normal vector of **B** is in direction of x-axis. Leakage flux is also in the direction x-axis. Calculation is made according to Eq. 1. Value of leakage flux per pair poles is:

$$\sum\Delta\Psi_{If} = \sum_{i=103}^{105}\Delta\Psi_{Ifi} + \sum_{i=186}^{188}\Delta\Psi_{Ifi} \tag{3}$$

$$2\sum\Delta\Psi_{If} = 0.0143\ \text{Vs}$$

Leakage flux in second and third layer is calculated regarding sub-domains which define winding overhangs of rotor winding in second layer Fig. 5.

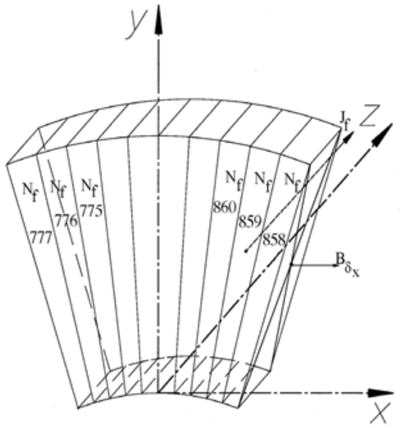


Fig. 5. Local coordinate system in second axial layer of rotor winding overhangs.

Values of **A** in each node of this sub-domain are calculated. Sum of all leakage fluxes in second layer is:

$$\sum \Delta\Psi_{II\,f} = \sum_{i=775}^{777} \Delta\Psi_{II\,fi} + \sum_{i=858}^{860} \Delta\Psi_{II\,fi} \qquad (4)$$

$$\sum \Delta\Psi_{II\,f} = 0.01456 \text{ Vs}$$

Leakage flux in third layer is calculated:

$$\sum \Delta\Psi_{III\,fc.v.} = \frac{N_f}{4} \cdot l_{III} \left(\sum_{i=1441}^{1446} \Delta\Psi_{IIIi} + \sum_{i=1533}^{1536} \Delta\Psi_{IIIi} \right) \qquad (5)$$

And its value per pair of poles is:

$$2 \cdot \sum \Delta\Psi_{III\,fc.v.} 0.02442 \text{ Vs}$$

III. Calculation of leakage reactances in stator and rotor windings

In above sections is explained method of calculation of leakage fluxes in active parts as well as in winding overhangs. Leakage fluxes close around the winding itself. These fluxes determined leakage reactances of the SSPSM.

Leakage reactance to be calculated value of leakage flux which closes around winding active part must be know.

Leakage reactance in first axial layer is calculated using the total leakage flux. There the inductance is calculated:

$$L_{Ik} = \frac{\sum \Delta\Psi_{ki}}{I_{an}} = 0.00446 \text{ H}, \quad I_{fn} = 0 \text{ A} \qquad (6)$$

$$X_{Ik} = \omega \cdot L_{I\,k} = 1.4005\,\Omega$$

Leakage reactances in second, third and fourth axial layer of stator winding are:

$$X_{IIk} = \omega \cdot L_{IIk} 0.0241\,\Omega$$

$$X_{IIIk} = \omega \cdot L_{IIIk} 0.108\,\Omega$$

$$X_{IVc.v.} = 0.656\,\Omega$$

Totalleakage reactance of stator winding is calculated as sum of reactances in all four layers:

$$X_{\sigma a} = X_{Ik} + X_{IIk} + X_{IIIk} + X_{IVc.v.} \qquad (7)$$

Considering the value of leakage flux in active part of rotor winding, inductance and reactance in this part of winding are calculated:

$$L_{I\,f} = \frac{\sum \Delta\Psi_{I\,f}}{I_{f\,n}} = 0.0026 \text{ H}, \quad I_{an} = 0 \text{ A} \qquad (8)$$

$$X_{I\,f} = \omega \cdot L_{I\,f} = 0.816\,\Omega$$

Leakage reactance in second and third layer are:

$$X_{II\,f} = 0.831\,\Omega$$

$$X_{IIc.v.} = 0.697\,\Omega$$

Total leakage reactance in rotor winding is:

$$X_{\sigma f} = X_{I\,f} + X_{II\,f} + X_{IIIc.v.} = 0.0491 \text{ p.u.} \qquad (9)$$

IV. Conclusion

Using contenporary numerical method for magnetic field calculation FEM. 3D leakage fluxes in SSPSM are calculated. Futher flux distribution in motor air-gap is also calculated. These values enabels us to calculate motor equivalent inductance per d and q axises, motor self inductances as well as leakage reactances in stator and rotor windings. Value of calculated leakage reactance of stator winding $X^*_{\sigma a} = 0.0431$ p.u. is compared with value gained from analytic calculation $X^*_{\sigma a} = 0.0694$ p.u. Compared result show reasonable agreement. Knowing that analytical calculation of inductances is always with cetain approximations, this proves FEM as accurate numerical method for motor parametar calculation.

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