Calculation of leakage Fluxes in Solid Salient Poles Synchronous Motor by Finite Element Method

Mirka Popnikolova Radevska[1]

Abstract – **Solid Salient Poles Synchronous Motor (SSPSM) is well known for its simple construction as well as for its operational reliability due to absence of short circuit cage. Object of investigation in this paper is SSPSM, product of MAWDSLEY with rated data: P_1=3.520 kW, U_n=240 V, I_f=5.5 A, cosφ=0.97 and 2p=4. Software package FEM for 3D calculation in magnetostatic case is applied in order leakage fluxes of stator and rotor windings as well as leakage reactances to be calculated.**

Keywords – **SSPSM, FEM 3D, leakage fluxes, leakage reactances**

I. Introduction

Numerous classical methods exist for analytic calculation of motor parameters through empirical equations by simplifying electromagnetic processes inside the machine. In this paper is used completely different approach for motor parameters calculation using software package FEM 3D which calculates magnetic field in 3D motor domain, as well as leakage fluxes and consequently enables calculation of leakage reactances in stator and excitation winding of SSPSM.

II. Calculation of Leakage Fluxes in Stator Winding

Calculation of leakage fluxes of stator winding is made in active parts of stator winding, part of the winding placed in stator channel or part of the winding placed in first axial layer of motor mathematical model Fig. 1 and winding overhangs – second, third and fourth axial layer of motor mathematical model. Mathematical model is generated by dividing motor domain per z axis in five layers.

In first layer are placed active parts of stator and excitation winding while winding overhangs are placed in second third and fourth axial layer. Each layer is divided into sub domains with local coordinate system. FEM 3D automatically generates mesh of finite elements and calculates the values A in each node of finite element mesh.

Local coordinate system is placed regarding winding sub domains as it is shown on Figs 2 and 3.

- Leakage flux in first axial layer

Leakage flux in active part of motor windings is determined from the value of magnetic vector potential **A** which includes active parts of stator and rotor windings (first axial layer per z coordinate of motor model).

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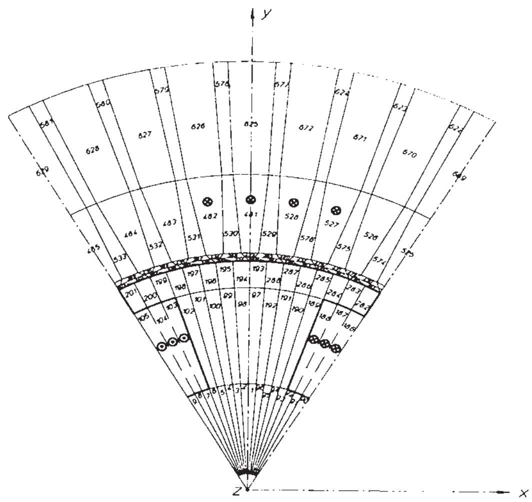

Fig. 1. Cross section of first axial layer with current densities

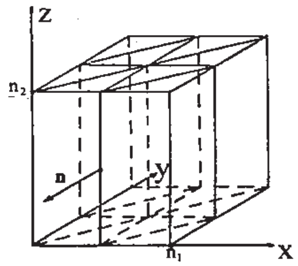

Fig. 2. Local coordinate system per z coordinate

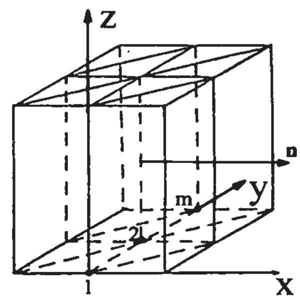

Fig. 3. Local coordinate system per y coordinate

Leakage flux is calculated when current is in direction of z-axis, thus normal vector of magnetic induction which creates leakage flux is in the direction of x-axes.

Calculation of leakage flux in active part of motor winding is done according to Eq. (1).

$$\Delta\Psi_n = 2\cdot\left(\Delta\Psi_{1n} + \sum_{i=1}^{m}\Delta\Psi_{in}\right) \tag{1}$$

Calculation of leakage flux of stator winding in first axial layer is done for excitation current $I_f = 0$ and rated current I_{an} in phase A of stator winding. Leakage flux per pole for one channel is calculated according to:

$$\Delta\Psi_{Iki} = l_s\frac{N_k}{4}\frac{\Delta A_i}{\Delta y} \tag{2}$$

I - denotes first axial layer, k - channel leakage, i - channel number, Δy - radial channel length, N_k - number of conductors.

Total leakage flux in first axial layer or in active part of stator winding per pole is read out from the output file POT3D.DAT of FEM 3D and its value is:

$$\sum \Delta\Psi_{Iki} = \sum_{i=481}^{482} \Delta\Psi_{Iki} + \sum_{i=527}^{528} \Delta\Psi_{Iki} \tag{3}$$

$\sum \Psi_{Iki} = 0.02248$ Vs

- Leakage flux in second and third axial layer

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 equation 1 only lengths of stator winding overhangs in second and third layer are replaced and following results are gained respectively:

$$\sum \Delta\Psi_{IIki} = \Delta\Psi_{IIk1153} + \Delta\Psi_{IIk1154} + \Delta\Psi_{IIk1199} + \Delta\Psi_{IIk1200} \tag{4}$$

$\sum \Psi_{IIki} = 7.676 \cdot 10^{-5}$ Vs

$$\sum \Delta\Psi_{IIIki} = \Delta\Psi_{IIIk1825} + \Delta\Psi_{IIIk1826} + \Delta\Psi_{IIIk1871} + \Delta\Psi_{IIIk1872} \tag{5}$$

$\sum \Psi_{IIIki} = 3.449 \cdot 10^{-5}$ Vs

- Leakage flux in fourth axial layer

Now, local coordinate system is placed as it is shown on Fig. 4.

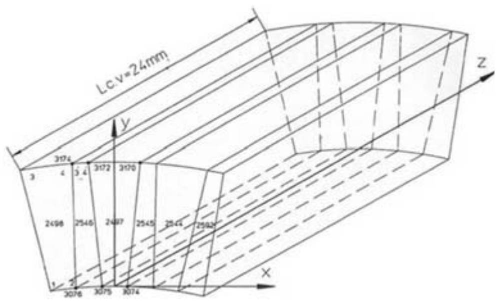

Fig. 4. Local coordinate system in fourth axial layer. l_{SIVcv}=24 mm – axial length of fourth layer; b_k=55.9 mm – channel width; t_1=99.7 mm pitch channel-tooth; b_z=43.8 mm – width of stator tooth; N_k – number of conductors per channel

Leakage flux is determined from equation **B**=rot **A**.

a) Leakage flux per **k** ort

1. For y=const, $l_{SIVc.v}$=24 mm

$$\sum \Delta\Psi_{IVay} = l_{sIVc.v}\frac{N_k}{4}(\Delta A_{2497} + 3\Delta A_{2498} + + 3\Delta A_{2543} + +\Delta A_{2544} + 2\Delta A_{2546} + \Delta A_{2592}) \tag{6}$$

$\sum \Psi_{IVay} = 0.236 \cdot 10^{-3}$ Vs

2. For x=const

Following the same logic calculated value of leakage flux is:

$\sum \Psi_{IVax} = 0.222 \cdot 10^{-3}$ 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:

$\sum \Psi_{IVa} = 0.324 \cdot 10^{-3}$ Vs.

b) Leakage flux per **i** ort

1. For y=const Δx=b$_k$

$$\sum \Delta\Psi_{IVbky} = b_k \cdot \frac{N_k}{4}(\Delta A_{2497} + 3\Delta A_{2498} + 3\Delta A_{2543} + \Delta A_{2544}) \tag{7}$$

$\sum \Delta\Psi_{IVbky} = 0.00596$ Vs

2. For y=const Δx=b$_z$

$$\sum \Delta\Psi_{IVbzy} = b_z \cdot \frac{N_k}{4}(\Delta A_{2546} + \Delta A_{2544}) \tag{8}$$

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

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

$$\Sigma\Delta\Psi_{IVby} = \Sigma\Delta\Psi_{IVbky} + \Sigma\Delta\Psi_{IVbzy} = 0.0096 \text{ Vs}\,. \tag{9}$$

Total leakage flux in winding overhangs for z =const per **i** ort is:

$\Sigma\Delta\Psi_{IVb} = 0.0102$ Vs.

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

$$\Sigma\Delta\Psi_{IVc.v} = 2\,(\Sigma\Delta\Psi_{IVa} + \Sigma\Delta\Psi_{IVb}) = 0.021046 \text{ Vs}. \tag{10}$$

III. Calculation of Leakage Fluxes in Excitation Winding

Similar to the calculation of leakage fluxes in stator winding, calculation of leakage fluxes in excitation winding is made in winding active part-first axial layer of mathematical model and winding overhangs- second, third and fourth axial layer of mathematical model.

- Leakage flux in first axial layer

It is assumed that that rated current flows through excitation winding $I_f = I_{fn} = 5.5A$ and no current flows through stator winding $I_{an} = 0$. Local coordinate system is placed as it is shown on Figs. 2 and 3. Again using software FEM 3D calculation of magnetic vector potential in complete motor domain is made and data are read out from output file.

Normal vector of **B** is in direction of x-axis. Leakage flux is also in the direction of x-axis. Calculation is made according to Eq. 1. Value of leakage flux per pair of poles is:

$$\sum \Delta\Psi_{If} = \sum_{i=103}^{105} \Delta\Psi_{Ifi} + \sum_{i=186}^{188} \Delta\Psi_{Ifi} \tag{11}$$

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

- Leakage flux in second axial layer

Leakage flux is calculated regarding sub domains which define winding overhangs of excitation winding in second axial layer Fig. 5. Again local coordinate system is placed regarding this sub domain. Values of **A** in each node of this sub domain are calculated.

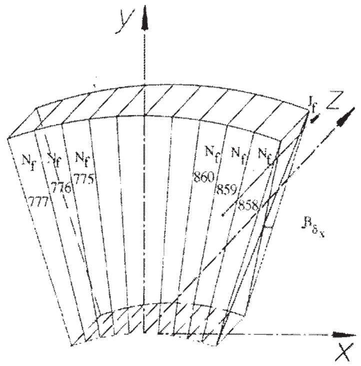

Fig. 5. Local coordinate system in second axial layer of excitation winding overhangs

Sum of all leakage fluxes in second layer of excitation winding is:

$$\sum \Delta\Psi_{IIf} = \sum_{i=775}^{777} \Delta\Psi_{IIfi} + \sum_{i=858}^{860} \Delta\Psi_{IIfi} = 0.01456$$
$$\sum \Delta\Psi_{IIf} = 0.01456 \text{ Vs} \tag{12}$$

- Leakage flux in third axial layer

Mathematical model of excitation winding overhangs in third axial layer is presented on Fig. 6

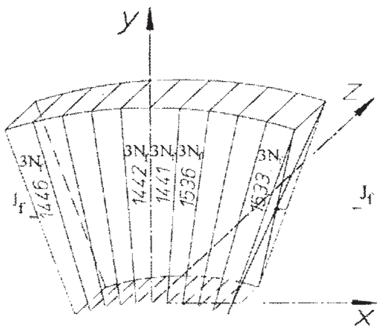

Fig. 6. Local coordinate system in third axial layer of excitation winding overhangs

Leakage flux is calculated from:

$$\sum \Delta\Psi_{IIIc.v.} = \frac{N_f}{4} l_{III} \Big(\sum_{i=1441}^{i=1446} \Delta\Psi_{IIIi} + \sum_{i=1533}^{i=1536} \Delta\Psi_{IIIi} \Big) \tag{13}$$

and its value per pair of poles is:

$$2 \cdot \sum \Delta\Psi_{IIIc.v.} = 0.02442 \text{ Vs}$$

IV. Calculation of Leakage Reactances in Stator Winding

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 determine leakage reactances of SSPSM.

- Leakage reactance in first axial layer

In order leakage reactance to be calculated value of leakage flux which closes around winding active part must be known. Using result from Eq. 3 inductance is calculated as:

$$L_{Ik} = \frac{\sum \Delta\Psi_{Iki}}{I_{an}} = 0.00446 \text{ H},\ I_{fn} = 0 \text{ A} \tag{14}$$

Leakage reactance in first axial layer of stator winding is calculated from:

$$X_{Ik} = \omega L_{Ik} = 1.4005\ \Omega \tag{15}$$

- Leakage reactance in second and third axial layer

Considering that leakage fluxes in second and third axial layer of stator winding from Eqs. (4) and (5), inductances and reactances are calculated as:

$$L_{IIk} = \frac{\sum \Delta\Psi_{IIki}}{I_{an}} \tag{16}$$
$$X_{IIk} = \omega L_{IIk} = 0.0241\ \Omega \tag{17}$$
$$L_{IIIk} = \frac{\sum \Delta\Psi_{IIIki}}{I_{an}} \tag{18}$$
$$X_{IIIk} = \omega L_{IIIk} = 0.0108\ \Omega \tag{19}$$

- Leakage reactance in fourth axial layer

Considering the value of leakage flux from Eq. (10) inductance and reactance in fourth axial layer of stator winding are calculated as:

$$2L_{IVc.v.} = \frac{\sum \Delta\Psi_{IVc.v.}}{I_{an}} = 4.176 \cdot 10^{-3} \text{ H} \tag{20}$$
$$X_{IVc.v.} = 0.656\ \Omega$$

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

$$X_{\sigma a} = X_{Ik} + X_{IIk} + X_{IIIk} + X_{IVc.v.} \tag{21}$$

or in per units:

$$X^*_{\sigma a} = 0.0431 \text{ p.u.}$$

V. Calculation of Leakage Reactances in Excitation Winding

- Leakage reactance in first axial layer

Considering the value of leakage flux in active part of excitation winding from Eq. (11), inductance and reactance in this part of winding are calculated as:

$$L_{If} = \frac{\sum \Delta\Psi_{If}}{I_{fn}} = 0.0026 \text{ H} \tag{22}$$
$$X_{If} = \omega L_{If} = 0.816\ \Omega \tag{23}$$

- Leakage reactance in second axial layer

Leakage flux in second axial layer of excitation winding is calculated according to Eq. (12). Consequently inductance and reactance in this part are calculated:

$$L_{IIf} = \frac{\sum \Delta\Psi_{IIf}}{I_{fn}} = 2.647 \cdot 10^{-3}\ \mathrm{H} \quad (24)$$

$$X_{IIf} = \omega L_{IIf} = 0.831\ \Omega \quad (25)$$

- Leakage reactance in third axial layer

Leakage flux in third axial layer of excitation winding is calculated according to Eq. (13). Inductance and reactance in third axial layer of excitation winding are calculated:

$$L_{IIIc.v} = \frac{\sum \Delta\Psi_{IIIc.v}}{I_{fn}} = 2.22 \cdot 10^{-3}\ \mathrm{H} \quad (26)$$

$$X_{IIIc.v} = \omega L_{IIIc.v} = 0.697\ \Omega \quad (27)$$

Total leakage reactance in excitation winding is:

$$X_{\sigma f} = X_{If} + X_{IIf} + X_{IIIc.v} \quad (28)$$

or in per units:

$$X_{\sigma f} = 0.0491\ \text{p.u.} \quad (29)$$

VI. Conclusion

Using novel Finite Element Method calculation of motor leakage fluxes can be done due to what motor reactances can be calculated more accurately than by analytic methods since there is no simplification of electromagnetic processes inside the machine. 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. This proves methodology as adequate one also for calculation of excitation winding leakage reactances as well as self reactances or machine reactances per d and q axises.

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