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Selected technical-design parameters of a synchronous motor with permanent magnets and sine waveform control

***Abstract**. In the paper the calculations of technical-design parameters of a synchronous motor with permanent magnets in rotor, three-phase stator winding and with trapeze waveform control are given. The dependencies of self and mutual inductances, associated fluxes on stator current are presented.. The dependencies make it possible to analyze physical processes occurring inside the motor. Flux Ψ is a nonlinear vector function, whose values are calculated on the basis of magnetic field distribution determined with the use of specialized software. Analytical calculation of partial derivatives is endowed with certain problems and the necessity to carry out a large number of additional calculations. The simulations and calculations have been carried out for the motor IPMSg132 S4 PMSM. The results have been presented in the graphical form*

***Streszczenie.** W referacie zawarto obliczenia parametrów techniczno-konstrukcyjnych silnika synchronicznego z magnesami trwałymi w wirniku i z trójfazowym uzwojeniem stojana o sterowaniu trapezoidalnym. Przedstawiono zależności indukcyjności własnych i wzajemnych, strumieni skojarzonych od prądu stojana. Przebiegi te pozwalają analizować procesy fizyczne zachodzące wewnątrz silnika. Strumien Ψ jest nieliniową funkcją wektorową, ktorej wartości są obliczane na podstawie określenia pola magnetycznego przy użyciu specjalistycznego oprogramowania. Analityczne obliczenie pochodnych cząstkowych zwiazane jest z pewnymi trudnościami i koniecznością wykonania dużej ilości dodatkowych obliczeń. Obliczenia symulacyjne wykonano dla silnika typu IPMSg132 S4 PMSM. Wyniki przedstawiono w formie graficznej. (**Obliczenia parametrów techniczno-konstrukcyjnych silnika synchronicznego z magnesami trwałymi w wirniku i z trójfazowym uzwojeniem stojana o sterowaniu trapezoidalnym**)*

Keywords: differential parameters, permanent magnet synchronous motor PMSM.
Słowa kluczowe: parametry dynamiczne silnika, silnik bezszczotkowy z magnesami trwałymi.

Introduction

Electric motors excited with permanent magnets gain more and more popularity due to their advantages. Most important ones are: high ration of the obtained moment and power to the volume and mass of the machine, what results in lower dimensions and unit mass, thus to better control and dynamic properties. These machines usually have low inertia moment and quickly react to stimuli, may obtain high angular accelerations in a wide range of rotational velocities, they obtain high efficieny in the whole range of rotational velocities. Due to the lack of the commutator they exhibit high reliability.

Calculation-based analysis

Magnetic coupling of the stator circuit is defined as the algebraic sum of the magnetic coupling due to tooth-end face dissipation and the magnetic coupling due to working flux in the slot part of the stator.

Magnetic coupling due to tooth-end face dissipation depends linearly on currents of all electric circuits and is defined as a product of appropriate dissipation inductances and these currents.

The part of magnetic circuit due to flux in the slot part of the stator is calculated as the product of elementary magnetic fluxes, which couple with a part of the inductor multiplied by the number of coils included in that part of the inductor. Adding magnetic couplings for the whole region of the inductor, we obtain the magnetic coupling of the inductor due to flux in the slot part of the motor.

Total magnetic coupling for the whole circuit $\psi_{\delta k}\ (k=\overline{1,K})$, where K – number of electric circuits, is obtained as an algebraic sum of magnetic couplings of the inductors. Taking the abovegiven into account magnetic couplings in the stator are given with the relationship,

$$\begin{aligned}\psi_1 &= L_{\sigma11}i_1 + L_{\sigma12}i_2 + L_{\sigma13}i_3 + \sum_{k=1}^{K}\psi_{\delta k1}\\ \psi_2 &= L_{\sigma21}i_1 + L_{\sigma22}i_2 + L_{\sigma23}i_3 + \sum_{k=1}^{K}\psi_{\delta k2}\\ \psi_3 &= L_{\sigma31}i_1 + L_{\sigma32}i_2 + L_{\sigma33}i_3 + \sum_{k=1}^{K}\psi_{\delta k3}\end{aligned} \quad (1)$$

written in the matrix form:

$$\vec{\psi} = L_\sigma \vec{i} + \vec{\psi}_\delta \quad (2)$$

where: $\vec{\psi} = [\psi_1\ \psi_2\ \psi_3]$ – column vector of magnetic couplings of electric circuits in the stator,

$\vec{i} = [i_1\ i_2\ i_3]$ – column vector of currents in the electric circuits of the stator,

$L_\sigma = \begin{bmatrix} L_{\sigma11} & L_{\sigma12} & L_{\sigma13}\\ L_{\sigma21} & L_{\sigma22} & L_{\sigma23}\\ L_{\sigma31} & L_{\sigma32} & L_{\sigma33}\end{bmatrix}$ – matrix of inductances of tooth-end face dissipation,

$\vec{\psi}_\delta = [\psi_{\delta1}\ \psi_{\delta2}\ \psi_{\delta3}]$ – column vector of magnetic couplings of electric circuits, due to couplings in the slot part of the machine.

On the basis of relationship (2) the magnetic coupling in the windings is a function of currents flowing in individual phases and the rotation angle of the rotor with respect to the stator:

$$\begin{aligned}\psi_1 &= \psi_1(i_1, i_2, i_3, \gamma),\\ \psi_2 &= \psi_2(i_1, i_2, i_3, \gamma),\\ \psi_3 &= \psi_3(i_1, i_2, i_3, \gamma),\end{aligned} \quad (3)$$

where: ψ_1, ψ_2, ψ_3 - magnetic coupling of the stator circuits, i_1, i_2, i_3 - currents in these circuits, γ - rotation angle of the rotor,

In order to calculate the derivatives $\frac{\partial\psi_1}{\partial i_1}, \frac{\partial\psi_1}{\partial i_2}, \frac{\partial\psi_1}{\partial i_3}, \frac{\partial\psi_1}{\partial\gamma}$ at the point with coordinates i_1, i_2, i_3, γ it is necessary to:

- determine the Taylor matrix for the scaled set of nodes and to calculate the inverse matix to the determine one

$$T=\begin{bmatrix}1 & 1/2 & -1/2 & -1/2 & -1/2\\ 1 & -1/2 & 1/2 & -1/2 & -1/2\\ 1 & -1/2 & -1/2 & 1/2 & -1/2\\ 1 & -1/2 & -1/2 & -1/2 & 1/2\\ 1 & 1/2 & 1/2 & 1/2 & 1/2\end{bmatrix}$$

(4)

$$T^{-1}=\begin{bmatrix}1/6 & 1/6 & 1/6 & 1/6 & 1/3\\ 2/3 & -1/3 & -1/3 & -1/3 & 1/3\\ -1/3 & 2/3 & -1/3 & -1/3 & 1/3\\ -1/3 & -1/3 & 2/3 & -1/3 & 1/3\\ -1/3 & -1/3 & -1/3 & 2/3 & 1/3\end{bmatrix}$$

- transform the origin of the coordinate system into the point, where the derivative is calculated,
- calculate the values of node coordinates in the coordinate system of physical coordinates related to the geometry of the scaled set, so that the n-th node has the coordinates:

(5) $$\begin{bmatrix}i_{1,n}\\ i_{2,n}\\ i_{3,n}\\ \gamma_n\end{bmatrix}=\begin{bmatrix}m_{i_1} & & & \\ & m_{i_2} & & \\ & & m_{i_3} & \\ & & & m_\gamma\end{bmatrix}\cdot\begin{bmatrix}x_{1,n}\\ x_{2,n}\\ x_{3,n}\\ x_{4,n}\end{bmatrix}+\begin{bmatrix}i_{1,\xi}\\ i_{2,\xi}\\ i_{3,\xi}\\ \gamma_\xi\end{bmatrix}$$

where: $diag(m_{i_1}, m_{i_2}, m_{i_3}, m_\gamma)$ - matrix of scaling coefficients,

$\begin{bmatrix}x_{1,n}\\ x_{2,n}\\ x_{3,n}\\ x_{4,n}\end{bmatrix}$ – column of coordinates of the n-th node in the scaled system,

$\begin{bmatrix}i_{1,\xi}\\ i_{2,\xi}\\ i_{3,\xi}\\ \gamma_\xi\end{bmatrix}$ – column with coordinates, which determine the location of the origin of the coordinate system (point ξ) of the scaled set in the linear space,

- calculate discrete values of function ψ_1, for all nodes of the system,
- find the column of (scaled) derivatives

(6) $$\vec{c}=T^{-1}\cdot\vec{\psi}_1=\begin{bmatrix}c_0\\ c_1\\ c_2\\ c_3\\ c_4\end{bmatrix}$$

- determine partial derivatives in physical units:

(7) $$\frac{\partial\psi_1}{\partial i_1}=\frac{c_1}{m_{i_1}}\quad \frac{\partial\psi_1}{\partial i_2}=\frac{c_2}{m_{i_2}}\quad \frac{\partial\psi_1}{\partial i_3}=\frac{c_3}{m_{i_3}}\quad \frac{\partial\psi}{\partial\gamma}=\frac{c_4}{m_\gamma}$$

- repeat all calculations except for determination of the Taylor function for scalar functions ψ_2, ψ_3.

After performing all calculations the results may be given in the form:

(8) $$L=\frac{\partial\vec{\psi}}{\partial\vec{i}}=\begin{bmatrix}\frac{\partial\psi_1}{\partial i_1} & \frac{\partial\psi_1}{\partial i_2} & \frac{\partial\psi_1}{\partial i_3}\\ \frac{\partial\psi_2}{\partial i_1} & \frac{\partial\psi_2}{\partial i_2} & \frac{\partial\psi_2}{\partial i_3}\\ \frac{\partial\psi_3}{\partial i_1} & \frac{\partial\psi_3}{\partial i_2} & \frac{\partial\psi_3}{\partial i_3}\end{bmatrix}$$

Numerical calculations of differential parameters

The area being considered is presented in Fig. 1.

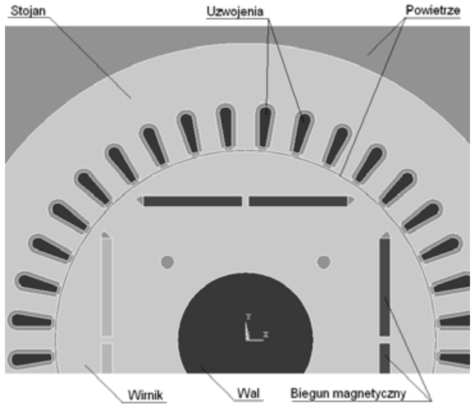

Fig. 1. The area of calculations

In order to discretize the area of calculations is divided into a number of finite elements. The division into triangular finite elements is presented in Fig. 2.

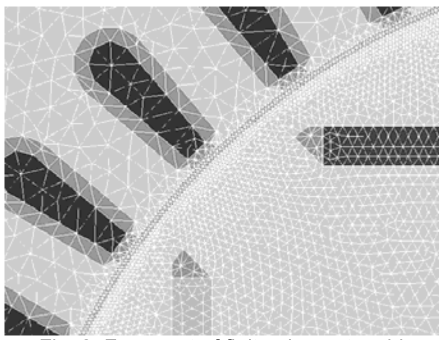

Fig. 2. Fragment of finite elements grid

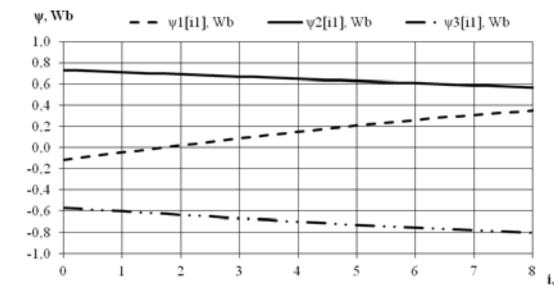

Fig. 3. Magnetic couplings for the respective windings caused by motor currents i_1=var and i_2=i_3=0 for the immovable rotor

In Figs. 5 and 6 the dependencies of self- and mutual inductances of motor windings on the stator current in the winding „1” are presented.

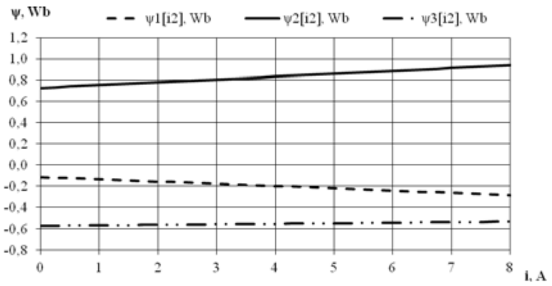

Fig. 4. Magnetic couplings for the respective windings caused by motor currents i_2=var and i_1=i_3=0 for the immovable rotor

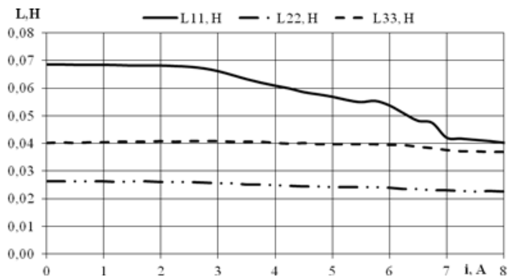

Fig. 5. Self-inductances of the windings versus stator current i_1=var and i_2=i_3=0 for the immovable rotor

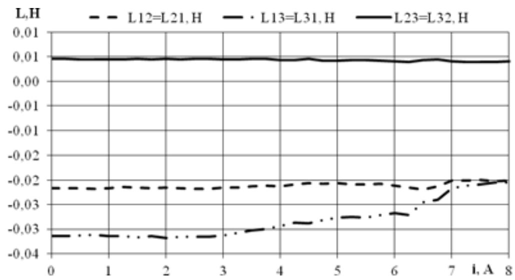

Fig. 6. Mutual inductances of the windings versus stator current i_1=var and i_2=i_3=0 for the immovable rotor

Conclusions

From the results of carried out calculations the following conclusions may be drawn:

1. As it can be seen from Figs. 1 and 2, the magnetic coupling of the winding circuit with current has an addtional component due to the current.
2. A substantial decrease in self-inductance for the conditions i_1 = 3-4 [A], i_2 = i_3 = 0 is caused by saturation of the active zone of the motor by the reaction field of the rotor.
3. For currents above 3-4 [A] the magnetic circuit of the machine enters the saturation state, what results in a decrease of self-inductance L_{11}. The absolute value of mutual inductance L_{21} in dependence on current increases for a given rotor position, current i_1 increases mutual magnetic coupling between phases.

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