FE analysis of electromagnetic circuit of a written pole motor

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The structure and working principle of a written pole motor are presented. To the analysis of the motor, a field-circuit model of electromagnetic phenomena that takes into account magnetic hysteresis of magnetically hard materials is applied. The motion of the rotor, non-linear properties of magnetically soft materials, and eddy currents induced in the conductive massive materials are taken into account. To solve the equations of the proposed model, the finite edge element method and step-by-step algorithm are used. The elaborated method and software are applied to the analysis of the written pole motor.

KEYWORDS: written pole motors, magnetic hysteresis, coupled phenomena.

1. Introduction

Written pole motors were designed in the USA in the last decade of the 20th century. In the steady state, they behave like synchronous motors excited by permanent magnets. They are adapted to direct start-up by applying supply voltage to the stator windings. After turn on the supply voltage, an electromagnetic hysteresis moment and asynchronous moment arise in the motor. The advantage of written pole motors over synchronous magnetoelectrical motors with asynchronous start-up is the lack in the characteristics of start-up electromagnetic moment of varying component produced by permanent magnets. This component makes it more difficult to start-up motors with permanent magnets. The motors with written poles are characterized by very good start-up properties. They are designed in the way that the relative start-up current is not larger than 2 and that the excess of the electromagnetic moment over the anti-torque, in the range of speed change between zero and synchronous speed, is small [2, 3, 4]. This leads to rise of a small dynamic moment in the power transmission system and to increase of start-up time. Comparing inductive motors and written pole motors from the view point of catalogue values of efficiency and power coefficients, one can conclude that for the same power and the same rotational speed greater values can be achieved for the written pole motors [2, 4]. Currently, the written pole motors that are produced worldwide are adapted to be supplied from one-phase net. They are applied in power transmission systems of non-regulated rotational speed, e.g., in pump and fan systems.

The literature concerning written pole motors is scarce, particularly when it comes to three-phase motors [5]. Papers present the structure, working principle
and functional parameters of one-phase motors [3, 4, 6]. Research on written pole motors is in its initial stage. For these motors, the methods of complex analysis of coupled electromagnetic, thermal and mechanical phenomena have not been elaborated yet. Moreover, there is no commercial software to analysis and design of such motors that would take into account the phenomenon of magnetic hysteresis. For these reasons, we have elaborated an algorithm and software basing on the field model of electromagnetic phenomena that takes into account the phenomenon of magnetic hysteresis. This software is applied to the analysis of electromagnetic circuit of the written pole motor.

2. Written pole motors

Opposite to classical synchronous machines, in written pole motors both the number and the position of poles along rotor circumference can change. In the literature, most attention is paid to written pole motors supplied from one-phase net [2, 6, 7]. During research on such type of motors, authors have designed the three-phase written pole motor shown in Fig. 1 [1]. The scheme of connections of windings is presented in Fig. 2. The main winding producing rotating field and an additional winding are located in the slots of the stator. The phase windings 1A, 1B, 1C of the main winding and the coils 2A, 2B, 2C of the additional winding are connected star-wise. The additional winding, due to its specific mode of operation, is called writing winding. It is used to form desired distribution of magnetization vector along rotor circuit in a layer of a magnetic material having a wide hysteresis loop. This layer is located on the surface of the rotor. The number and angle span of the poles formed by the writing winding depend on the speed of rotation of the rotor relative to the stator. The cores of the stator and the rotor are assembled from impressions made from electromagnetic steel sheet. In the rotor, apart from the layer made from magnetic material having wide hysteresis loop, there is also a squirrel-cage winding. To limit the start-up current, this winding is made from material of large resistivity.

After switching on supply voltage, the motor accelerates under the influence of rotational asynchronous moment and hysteresis moment. The hysteresis moment rises as a result of re-magnetization by rotating field of the rotor surface layer made from material of wide hysteresis loop. When the rotor reaches 0.7-0.9 of the synchronous speed, the writing winding is switched on. The field produced by this winding cooperates with the rotating field created by the main winding. As the result, one gets larger values of the magnetization vector in the magnetically hard material than the values obtained for the sole rotating field. This leads to the increase of electromagnetic moment, acceleration of the rotor, and pulling into synchronism. Then, the layer of material with wide hysteresis loop gets magnetized in such a way, that the number of rotor poles is the same as the number of poles of the stator winding.
A while after entering synchronism, the writing winding is disconnected from net, and the motor works as a magnetoelectrical synchronous motor. After restart of the motor, directly after switching on supply voltage, a surge of magnetomotive force produced by the main winding destroys previous distribution of magnetization vector and re-magnetizes the rotor.

The course of electromagnetic and mechanical phenomena in written pole motors is very complex. The analysis of these phenomena is complicated by non-linear properties of magnetically soft materials, magnetic hysteresis of the material layer located on the rotor surface, induced eddy currents, and motion of environments [1, 8]. Thus, these phenomena are hard to model using equivalent circuit diagram of the electrical motor [4]. Therefore, to the analysis of the written pole motor authors apply field-circuit model of coupled phenomena. In this model, it is assumed that the magnetic field in the electromagnetically active part of the motor is constant along shaft axis while three-dimensionality in the domain of coil outhangs is taken into account in a simplified way by considering their resistances and inductances [1, 8].
3. Algorithm of analysis of coupled phenomena

A field-circuit model of transient coupled phenomena in a written pole motor is presented in [1]. To formulate equations of a discrete model of coupled phenomena, a finite edge element method is applied [8]. The three-dimensional problem is reduced to a two-dimensional one. To describe electromagnetic field, vector magnetic potential \( A \) and scalar electric potential \( V \) are used [1, 8]. Discretizing space and time, the following system of matrix equations describing edge values \( \phi \) of vector magnetic potential \( A \) and currents in windings are obtained

\[
\begin{bmatrix}
S^n + G(I - C_k)\Delta t^{-1} & -z \\
-z^T & -(R\Delta t + L)
\end{bmatrix}
\begin{bmatrix}
\phi^n \\
i^n
\end{bmatrix}
=
\begin{bmatrix}
M^n \\
-G(I - C_k)\Delta t^{-1} & 0
\end{bmatrix}
\begin{bmatrix}
\phi^{n-1} \\
i^{n-1}
\end{bmatrix}
\]  

(1)

Angular position \( \alpha \) and angular velocity \( \omega \) of the rotor are given by

\[
\alpha^{n+1} = (\Delta t)^2(T^n - T_0^n - T_t^n)J_b^{-1} + 2\alpha^n - \alpha^{n-1}
\]  

(2)

\[
\omega(t_n + 0.5\Delta t) = \frac{d\alpha}{dt}igg|_{t_n+0.5\Delta t} = \frac{(\alpha^{n+1} - \alpha^n)}{\Delta t}
\]  

(3)

where: \( S \) – reluctance matrix, \( \phi \) – vector of potentials of grid edges, \( z \) – matrix defining the number of coils assigned to edges, \( G \) – matrix of substitute conductances, \( M \) – vector of magnetomotive forces that represents magnetization of hysteresis layer, \( U \) – vector of supply voltages, \( i \) – vector of currents in the windings, \( R \) – matrix of resistances of the windings, \( L \) – matrix of inductances of coil outhangs, \( C_k \) – matrix of coefficients, \( \Delta t = t_n - t_{n-1} \) – length of a time step, \( n \) and \( n-1 \) – indices discriminating magnitudes for time moments \( t = t_n \) and \( t = t_{n-1} \), respectively. For instance, \( S_n = S(t_n), \phi_n = \phi(t_n) \).

For the purpose of representation of magnetic properties of magnetically soft materials it is assumed that

\[
H = \nu B
\]  

(4)

where reluctivity \( \nu \) is determined from unique material magnetization characteristic. Whereas, in order to analyze the phenomenon of re-magnetization of rotor surface layer made from magnetically hard material, it is assumed that

\[
H = \nu_0 B - H_i
\]  

(5)

where \( H_i \) is a magnetization vector and \( \nu_0 \) is vacuum reluctivity.

In the mathematical model of magnetic properties of a permanent magnet it is assumed that the magnetically hard material is characterized by rectangular anisotropy and the phenomenon of magnetic hysteresis is taken into account [8, 9].
In the elaborated discrete model, to represent the hysteresis properties of the material used to make rotor surface layer, Jiles-Atherton inverse model is used [9].

System of equations (1)-(3), depending on the density of space discretization, can contain from several up to tens of thousands non-linear algebraic equations. To solve this system of equations, Newton-Raphson method is used [8]. Based on the presented discrete model of phenomena, a computer program has been written in Delphi XE environment to analyze steady and transient work states of written pole motors.

4. Analysis of electromagnetic circuit

To test the elaborated computer program, the electromagnetic circuit of the motor whose structure is shown in Fig. 1 has been analyzed. It is assumed that a stator package of the three-phase inductive motor of type Sg 100L-4B of voltage U = 400 V and power 3kW was used to construct the motor. The hysteresis layer in the rotor was made from powder material with remanence induction 0.73 T and coercive force intensity 464 kA/m designed in the Tele- and Radiotechnical Institute in Warsaw. Squirrel-cage winding was made from aluminum. The calculations were performed on a computer with two four-core Intel XENON W5580 3,2Ghz 64bit processors. Calculation time for one time step was about 90 seconds.

The chosen working states of the motor have been analyzed. The results of the simulation of the motor start-up process have been presented. The direct start-up of the motor loaded with braking torque T_o = 10 Nm has been considered. It is assumed that the magnetically hard material was demagnetized before switching on the motor to the net. Obtained exemplary characteristics of rotational speed and electromagnetic torque are presented in Fig. 3. One can observe how these characteristics are influenced by switching on the writing winding. This winding was switch on to the net when the rotor obtained speed of 1050 rpm, at time t = t_z. Turn on of the writing winding causes a transient state. It transpires that the electromagnetic torque increases and synchronous speed is achieved faster than in case of the start-up performed without the help of the writing winding.

Switching off the writing winding also causes a transient state as indicated by the pulsations in the characteristics of rotational speed and electromagnetic torque for t > t_w. Exemplary distribution of magnetic field and exemplary distribution of magnetization vector in the layer of wide hysteresis loop, directly after motor start-up and in the steady state, are shown in Fig. 4.

The results of the analysis of the influence of the number of phase winding turns on the course of the start-up process, for active and inactive writing winding, are gathered in Fig. 5. The influence of the writing winding on re-magnetization, during motor start-up, of the wide-hysteresis-loop layer in subdomain located near the air gap and near the rotor core is presented in Fig. 6. This figure also shows a limiting hysteresis loop of the material used to make the hysteresis layer.
Fig. 3. Characteristics of a) rotational speed and b) electromagnetic torque during start-up of the written pole motor.

Fig. 4. Distribution of magnetic field in the motor and distribution of magnetization vector in the hysteresis layer a) directly after motor start-up, b) in the steady state.
Fig. 5. Influence of the number of main winding coil turns on the course of the start-up process

Fig. 6. History of magnetization of subdomains of the hysteresis layer located near the air gap (on the left) and near the surface of the rotor core (one the right) during motor start-up with active writing winding

5. Final remarks

It results from the above considerations and from the analysis of calculation results that the elaborated software can be applied to the analysis of motion-related electromagnetic phenomena in written pole motors. We plan to employ this software to design a model written pole motor. After construction of this model motor and performing its laboratory tests, it will be possible to finally verify the usefulness of the proposed method and elaborated software to the analysis of coupled phenomena, simulation of working states, and design of written pole motors.
References