

Calculation of rotor losses in permanent magnet machine with fractional slot concentrated windings

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Abstract. In the article, questions of calculation losses in the rotor of the permanent magnet machine with fractional slot concentrated windings of the stator are considered. The losses calculation is based on E-H equivalent circuits and analysis of eddy currents distribution in a finite dimensions conducting plate. The comparison of calculated and experimental data is presented.

1. Introduction

The synchronous permanent magnet machine with stator windings with a number of slots per pole and a phase smaller than the unity (fractional slot concentrated windings) are increasingly used in various types of electric drives [2,3]. On the one hand, the increasing popularity of these machines is due to the advantages of magnetolectric excitation systems. On the other hand, advantages of fractional slot concentrated windings allow us to realize a high pole of the machine, to reduce axial dimensions and improve workability and reliability.

2. Fractional slot concentrated windings

During several years there has been the work on developing and studying electrical machines with fractional slot concentrated windings [3] in NSTU (Novosibirsk State Technical University) at the department of electromechanics. Conducted research has shown that an important feature of this type of winding is a wide range of space excitation harmonics of the magnetic field. This spectrum of harmonics is created in the air gap of the electrical machine. Moreover, unlike traditional distribution windings, fractional slot concentrated windings form both space excitation harmonics of higher order (relative to the working one) and lower order (subharmonics) in the air gap of the machine [1,8]. When the machine is operating, the space excitation harmonics rotate asynchronously with the rotor. They can become a source of stray losses caused by eddy currents induced in the elements of the rotor design.

Traditionally fractional slot concentrated windings were used for creating low-speed electrical machines. These windings make it relatively easy to create multipolar machines with the comparatively small number of stator teeth. However, the technological advantages of this type of windings predetermined attempts to use them in high-speed machines, which are characterized by an increased frequency of supply of the stator winding and an increased rotor speed. For high-speed machines, the non-working MMF harmonics of the armature reaction rotate asynchronously with the rotor. They can cause an unacceptably high level of stray losses in the elements of the rotor design.



3. The study of the level of stray losses

The research of the level of stray losses at load operation are performed on a special 50 kW synchronous motor. The motor has fractional slot concentrated windings with the number of slots per pole and phase $q = \frac{2}{5}$, rotation frequency 6000-r/min, power frequency 500 Hz. Figure 1 shows the rotor of the motor design. A characteristic feature of the rotor is the presence of conductive elements in construction, located on the armature reaction flux return paths. Such structural elements are: a bandage cylinder made of non-magnetic stainless steel; permanent magnets (SmCo), whose material has a relatively high electrical conductivity; a massive rotor yoke made of low-carbon steel, which is electrically conductive.

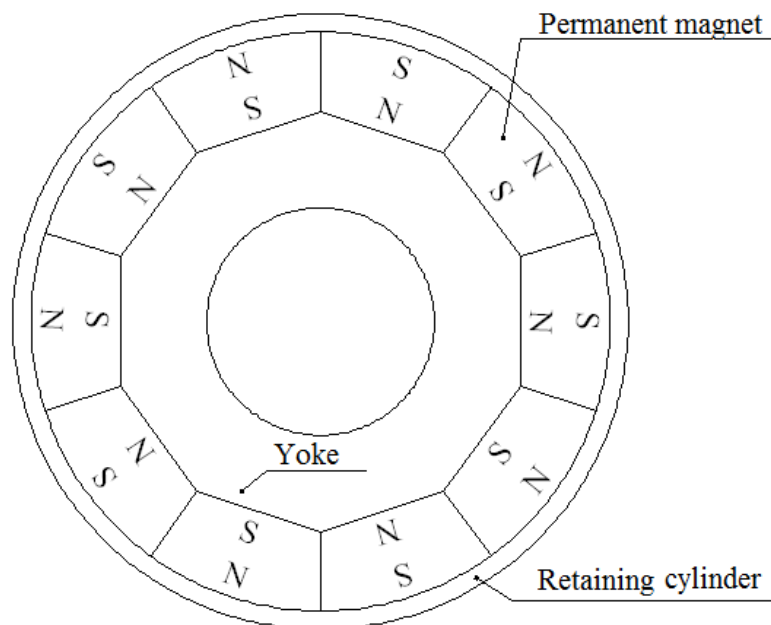


Figure 1. A construction diagram of the investigated motor rotor.

Space excitation MMF harmonics of the armature winding rotate asynchronously with the rotor and induce eddy currents in the elements of rotor design, which cause an increased level of stray losses during the load operation of the machine. The relative amplitude of space excitation MMF harmonics of the armature winding and corresponding current frequencies in elements of the rotor design are presented in the table.

Table 1. MMF harmonic composition of the fractional slot concentrated winding with $q = \frac{2}{5}$

№ of MMF harmonic	Relative MMF amplitude	Frequency of rotor currents	Direction
1	0.359	600	backward
5	1.0	0	operating, forward
7	0.714	1200	backward
11	0.0327	600	forward
13	0.0278	1800	backward
17	0.294	1200	forward
19	0.263	2400	backward

23	0.0159	1800	forward
25	0.0139	3000	backward
29	0.173	2400	forward
31	0.162	3600	backward

4. E-H equivalent circuits

A method based on cascade replacement schemes of motors can be used to calculate the losses in the rotor caused by the space excitation MMF harmonics of the armature [5, 6].

The use of E-H equivalent circuits makes it possible to obtain a simple model of electromechanical energy conversion processes. Such equivalent circuits take into account the accompanying processes of the ferromagnetic elements saturation of the magnetic circuit and the current displacement in the conducting elements of the structure, eliminating the need for obtaining a large number of integration constants.

The rotor E-H equivalent circuit for the v -th space excitation MMF harmonic of the stator winding in the investigated motor is shown in Figure 2. It was obtained in accordance with the principles of synthesizing such equivalent circuits [5, 6].

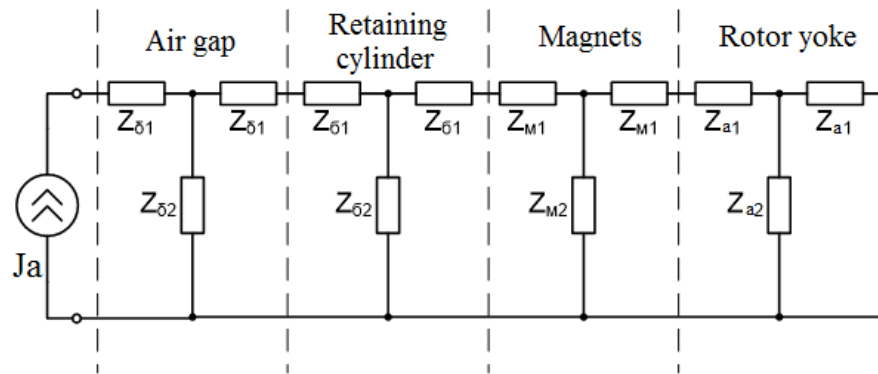


Figure 2. The rotor E-H equivalent circuit of the investigated motor.

The parameters of the E-H equivalent circuit, shown in Figure 2, are determined on the basis of the following relations [6]:

- Resistance with index 1

$$Z_1 = \frac{j\omega\mu_x}{n} \operatorname{th}\left(\frac{nh}{2}\right).$$

- Resistance with index 2

$$Z_2 = \frac{j\omega\mu_x}{n \operatorname{sh}(nh)}.$$

- Current source J_a

$$J_a = F_{mv} \alpha_v.$$

- Auxiliary coefficients

$$n = \sqrt{j\omega\mu_x \gamma + \frac{\mu_x}{\mu_y} \alpha^2}.$$

$$\alpha_v = \frac{\pi}{\tau_v}.$$

In the relations given above: μ_x, μ_y - averaged magnetic permeabilities along the x and y axes, respectively; γ - averaged electrical conductance of the corresponding structural zone; τ_y - pole pitch for v -th space excitation MMF harmonic; ω - angular currents frequency from v -th space excitation harmonic.

The equivalent circuit shown in Figure 2 allows us to determine components of E_z and H_x vectors at the source terminals (the rotor surface) with the known geometry and material properties. The obtained values of the components of the electric and magnetic intensity vectors can be used to calculate the stray losses from the considered space excitation MMF harmonic, by calculating the integral of the Poynting vector over the rotor surface. The sum of losses due to the armature MMF harmonics makes it possible to determine the amount of the stray losses from the armature reaction field in the elements of the rotor design.

Calculations of losses using the E-H equivalent circuit showed that the obtained results allow a qualitative estimation of the stray losses level in the rotor machine and the influence of material properties, geometry and operating conditions on them. However, in comparison with the experimental data, these calculations give a loss value that is too high by 30-40%. The analysis showed that this significant error is due to the fact that in the synthesis of E-H equivalent circuits [6], the assumption about the plane-parallel nature of the magnetic field in the active volume of the motor is made. This assumption basically does not allow us to take into account the influence of such factors as the limited length of the elements of the rotor design, for example, of magnets along the axis of the machine. The influence of the finite length of the rotor structural elements along the axis of the machine on the value of the eddy currents can be considered by solving a separate problem for calculating the eddy currents in the conducting elements of the rotor structure. Calculation of losses from eddy currents in thin conducting plates penetrated by a stationary alternating magnetic field was considered in [7].

The structural elements in rotating motors are under the influence of a traveling magnetic field. The problem of calculating losses in such structural elements is reduced to calculating the distribution of eddy currents in a finite-size conducting plate made of a material with electrical conductivity γ and under the influence of a traveling magnetic field (Figure 3).

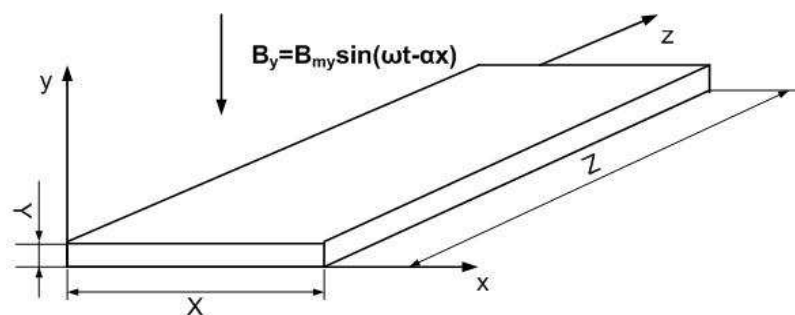


Figure 3. A finite-size conducting plate in the travelling magnetic field.

If we assume that the magnetic induction acting on the conducting plate and the eddy currents in it vary sinusoidally with time, then we can write the following equations describing the field of eddy currents:

$$\begin{cases} \text{rot } \hat{\delta} = -j\omega\gamma\hat{B}_y e^{-j\alpha x} \\ \text{div } \hat{\delta} = 0 \end{cases}.$$

The solution of the system of equations by the Greenberg method made it possible to obtain the correlations for calculating the components of the current density vector in the conducting plate. To do this, as boundary conditions, the equality to zero of normal current component to all the boundaries of the current density was used.

$$\dot{\delta}_{xv} = \sum_{k=1}^{\infty} \beta_k \frac{j\omega\gamma\dot{B}_{zk}}{\alpha_v^2 + \beta_k^2} \left[\operatorname{th}\left(\frac{\beta_k X}{2}\right) \operatorname{sh}(\beta_k x) - \operatorname{ch}(\beta_k x) + e^{-j\alpha_v x} \right] \cos(\beta_k z)$$

$$\dot{\delta}_{zv} = -\sum_{k=1}^{\infty} \frac{j\omega\gamma\dot{B}_{zk}}{\alpha_v^2 + \beta_k^2} \left[\beta_k \operatorname{th}\left(\frac{\beta_k X}{2}\right) \operatorname{ch}(\beta_k x) - \beta_k \operatorname{sh}(\beta_k x) - j\alpha_v e^{-j\alpha_v x} \right] \sin(\beta_k z).$$

In the relations above:

$$\beta_k = \frac{k\pi}{Y}, \quad \alpha_v = \frac{\pi}{\tau_v}, \quad \dot{B}_{yk} = \frac{2}{k\pi} \dot{B}_{my} [1 - \cos(k\pi)],$$

τ_v - pole pitch for v-th space excitation MMF harmonic.

The obtained relations for the density of eddy currents make it possible to determine the losses in the conducting plate under consideration, by calculating the integral over the volume of the corresponding structural element of the rotor:

$$P = \sum_{v=1}^{\infty} Z \int_0^X \int_0^H \frac{\delta^2}{\gamma} dx dy.$$

5. Conclusion

Thus, both the estimated and refined approach to the calculation of stray losses from the armature reaction field in the elements of the rotor design can be realized on the basis of the research carried out. In the estimated approach, it suffices to use the E-H equivalent circuit and determine the components of the H_x and E_y vectors on the rotor surface, and then, after calculating the integral of the Poynting vector along the rotor surface, obtain the estimated value of the losses in the rotor. With a refined approach, the E-H equivalent circuit allows us to determine the values of the magnetic induction in separate layers of the rotor design, and then to obtain the specified value of the stray losses in the rotor, using the obtained relations for eddy currents taking into account the edge effects along the machine axis.

The results of calculating the losses in the rotor of the 50 kW motor using the proposed approach and comparing them with the experimental data were shown in Table 2.

Table 2. Comparison of calculated and experimental values of the stray losses in the rotor

E-H equivalent circuit	Calculating by proposed approach	Experiment
3280 W	2130 W	2510 W

The data presented in Table 2 show that the proposed approach for determining stray losses in the rotor design elements from the non-working space excitation harmonics of the armature reaction field provides sufficient calculation accuracy for practice and can be recommended for practical use.

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