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Impact of equalizing currents on losses and torque ripples in electrical machines with fractional slot concentrated windings

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Abstract. The implementation of parallel branches is a commonly used manufacturing method of the realizing of fractional slot concentrated windings in electrical machines. If the rotor eccentricity is enabled in a machine with parallel branches, the equalizing currents can arise. The simulation approach of the equalizing currents in parallel branches of an electrical machine winding based on magnetic field calculation by using Finite Elements Method is discussed in the paper. The high accuracy of the model is provided by the dynamic improvement of the inductances in the differential equation system describing a machine. The pre-computed table flux linkage functions are used for that. The functions are the dependences of the flux linkage of parallel branches on the branches currents and rotor position angle. The functions permit to calculate self-inductances and mutual inductances by partial derivative. The calculated results obtained for the electric machine specimen are presented.

The results received show that the adverse combination of design solutions and the rotor eccentricity leads to a high value of the equalizing currents and windings heating. Additional torque ripples also arise. The additional ripples harmonic content is not similar to the cogging torque or ripples caused by the rotor eccentricity.

1. Introduction

Windings of electrical machines are often implemented with parallel branches because of some technological reasons. For example, it is widely used in low-voltage machines with large rated currents having a large cross-section of armature winding wires. The usage of parallel branches reduces current in the elementary coil. Moreover, the wire cross-section decreases and technological problems associated with large section wires laying can be solved. Similar difficulties arise during the manufacture process of large machines having the cross-section of a wire equal to 8-12 mm² or more, as well as in low-power machines, especially if automated winding machines limiting cross section of a wire are used.

The main disadvantage of parallel branches winding is the risk of equalizing currents appearance. Equalizing currents occur when EMFs in divers parallel branches are different. The problem of equalizing currents occurs frequently in direct current machines. Equalizing currents of such machines are passed through the commutator and affects directly the quality of commutation. To combat that phenomenon in the windings of DC machines, special equalizing connections are implemented creating paths for equalization currents flowing without brushes.

A similar problem occurs in permanent magnet synchronous machines which includes machines with fractional slot concentrated windings. Such machines are widely used in the automotive industry, for example, in the electric power steering drive. In machines of this type, asymmetry of branches



EMFs arises because of the various poles magnetization or rotor eccentricity, resulting in a difference between magnetic fluxes under the poles.

The equalizing current leads to additional heating of a winding. It induces magnetic flux and the machine magnetic field becomes asymmetrical. This asymmetry deforms the shape of the MMF curve and creates the torque fluctuations. Equalizing current is not controlled and response characteristics vary leading to disturbing of a correct system running in high precision drives. Manufacturing of a totally symmetric machine without the eccentricity is impossible in practice.

One of the way calculating the equalization currents in the PMSM with fractional slot concentrated windings is discussed and the results of investigation of the equalization currents and caused by them torque fluctuations are presented in the paper. The approach proposed takes into account most of factors: the objective air-gap structure, magnets disposition, winding scheme and core saturation level.

2. Subject

The motor for electric power steering developed for LADA Granta is considered as an example. The motor parameters are presented in Tab. 1.

It is convenient to study the machine in the no-load generator mode. In this case there are only equalizing currents in the winding, no current is caused by supplying.

Table 1. Technical information of the machine.

Parameter	Value
Torque, N·m	3.2
Number of slot per pole per phase	2/5
Number of poles	10
Voltage, V	12
Current, A	60
External diameter, mm	76
Frame length, mm	35
Inner diameter, mm	45

3. Methods

The equalizing current in the circuit of one phase parallel branches can be estimated basing on Kirchhoff's law system under the no-load mode:

$$\begin{cases} 0 = i_{p1}r_{p1} + \frac{d\psi_{p1}}{dt} , \\ 0 = i_{p2}r_{p2} + \frac{d\psi_{p2}}{dt} \\ 0 = i_{p1} + i_{p2} \end{cases} \quad (1)$$

where the flux linkage of each parallel branch ψ_n is a complex function of the phase currents, angle of the rotor, magnetic circuit geometry, properties of electrical steel and many other factors:

$$\psi_n = f(i_{n1}, i_{n2}, i_{n3} \dots \alpha).$$

Figure 1 shows the cross section of the machine. In such machine, one of the higher harmonics of the magnetic field participates in the torque production process. It is a conventional way for traditional machines to calculate only one pole pitch assuming every pole magnetic conditions is equal. It is

evident from Fig. 1 that the magnetic conditions of poles can differ significantly. Moreover the permeance of the any pole depends on the rotor position.

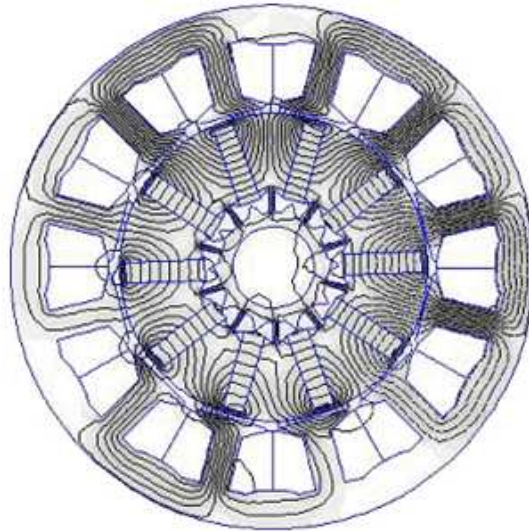


Figure 1. Justification of the caption so that it is of the same width as that of the graphic.

In order to take solution of the system (1) the dependence of the flux linkage on the current and rotor position must be determined. This dependence can be obtained analytically. But it involves some specific problems for PMSM with fractional slot concentrated windings where the flux linkage of each parallel branch ψ_p is a complex function of the current, rotor position, core geometry, materials properties and other factors.

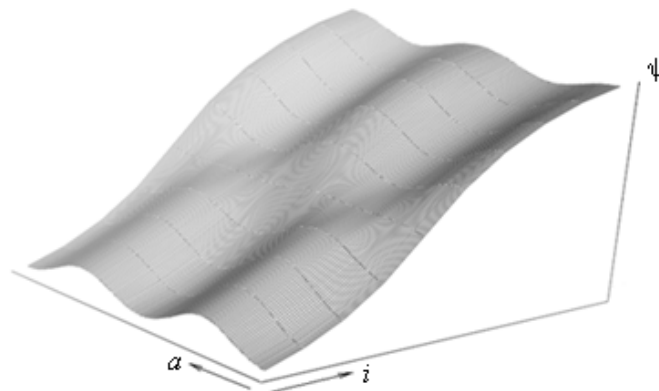


Figure 2. Example of function $\psi(i, \alpha)$.

In view of the above-mentioned, it is effectually to compute the parallel branches flux linkages by the numerical calculation of the magnetic field in the whole machine volume using the finite element method (FEM).

There are two basic approaches using the numerical calculations of the field distribution for the electromechanics tasks.

The most common method used in such software applications as ANSYS assumes that the equation system coefficients are improved by the step-by-step approach. This way takes a lot of computation time.

The work uses another method that permits to decrease the computation time significantly. The method has the following algorithm. At first, flux linkage array $\psi(i, \alpha)$ is calculated under the whole moral values of the current and rotor position (Fig. 2). It is seen from Fig. 2 that the function has no breaks and jumps. So any value of the flux linkage can be evaluated by the joint spline interpolation. The advantage of the method is absence of necessity to use FEM for magnetic field calculation at every integrating step after the limited number of points numerical estimation. So the field calculation carries out one time and other computations based on the results of the field distributions that can be completed as the fast infinite number of times.

Function $\psi(i, \alpha)$ is unique for every electrical machine and can be considered as a "portrait" of this machine. In the work, functions $\psi(i, \alpha)$ are fixed in a table form. Desirable points are determined by the joint spline interpolation. Such way permits a decrease of the computation time significantly during the multiplex calculating using one response region.

The equation system (1) is evaluated according the following procedure. A flux linkage under the given time estimated by usage of the function $\psi(i, \alpha)$ portrait if the current i_0 and rotor position angle α_0 is known. The rotor position becomes equal to α in a small time duration. So the equation $ir = (\psi(i', \alpha) - \psi_0) / \Delta t$ can be solved assuming that current becomes equal to i' . If the value obtained $i \approx i'$ has an acceptable error, the current is computed faithfully. In other case, the i' value varies and the method of successive iterations can be used.

The following assumptions are accepted for the study:

- 1) the mutual inductance fluxes between any two phases are negligibly small and processes can be researched in one phase only;
- 2) the rotor speed is constant.

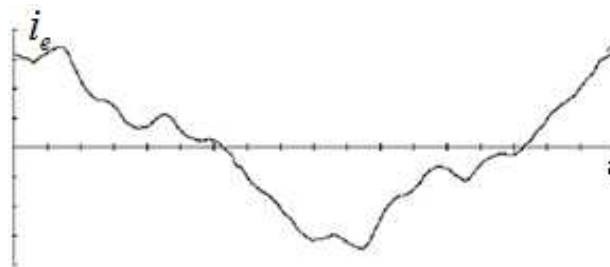


Figure 3. Single phase AC equalizing current

Fig. 3 shows the example of the current equalizing curve. A shape and amplitude of an equalizing current curve are responsible for the level of a magnetic system asymmetry. Seven various rotor eccentricities described in Tab. 2 are investigated.

Table 2. Variatings of the machines eccentricities

Model No.	Eccentricity vector module $m/\delta\%$	The deviation of the eccentricity vector from the phase axis
0	0	-
1	20%	0
2	40%	0
3	60%	0
4	20%	$0.5t_z$

5	40%	$0.5t_z$
6	20%	t_z
7	40%	t_z

4. Research results

The results of the equalizing currents calculations for the considered models under the various rotor speeds are presented in Tab. 3 and Fig. 4. The rotor speed varying is taken into account in order to estimate the influence of the saturation. The maximum, minimum and RMS current values are presented in Tab. 3 since the equalizing current curves are nonsinusoidal and have direct components. By means of that, the equalizing currents heat effect can be estimated.

Tab. 3 data are useful for the understanding of an equalizing currents influence in PMSM machines with fractional slot concentrated windings. The rated current value of the machine investigated is equal to 60A. So the equalizing currents values achieve 10% of the rated current, and electric losses increase up to 21%

Table 3. Equalizing currents level at various eccentricities and nominal rotor speeds

Motor №	I_{\min} A	I_{\min}/I_n %	I_{\max} A	I_{\max}/I_n %	I A	I/I_n %
0	-0.082	-0.137	0.104	0.173	0.03	0.05
1	-4.667	-7.778	4.665	7.775	2.756	4.593
2	-8.931	-14.885	8.787	14.645	5.408	9.013
3	-13.536	-22.56	13.292	22.153	8.237	13.728
4	-4.373	-7.288	4.356	7.26	2.612	4.353
5	-8.347	-13.912	8.224	13.707	5.131	8.552
6	-3.85	-6.417	3.831	6.385	2.316	3.86
7	-13.179	-21.965	12.271	20.452	6.23	10.383

Alongside with flux linkage calculation, the electromagnetic torques of every machine $T_E = f(i, \alpha)$ were evaluated by the FEM and Maxwell stress tensor. The torque ripples caused by the single phase equalizing current were estimated using that. The results of this analysis under the no-load rated speed mode are presented in Tab. 4 and Fig. 4.

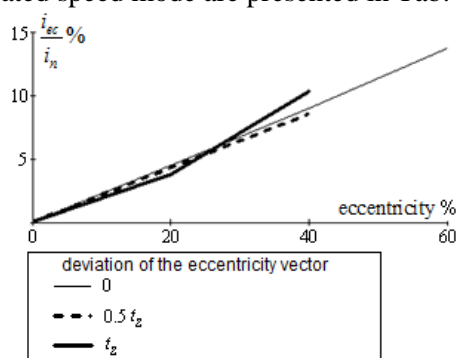


Figure 4. Dependence of equalizing currents on eccentricity under rated speed.

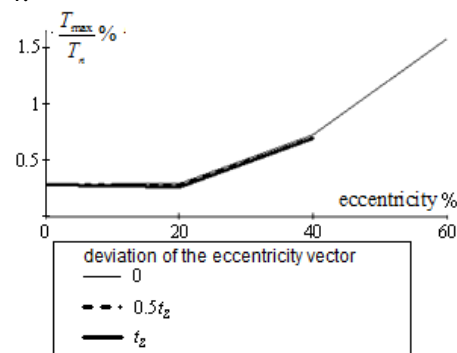


Figure 5. Dependence of torque ripple amplitude on eccentricity taking into account the impact of equalizing currents.

Table 4. The amplitude of torque ripple caused by equalizing currents under various eccentricity.

model No.	T_{\max} Nm	T_{\min} Nm	T_{RMS} Nm
0	-0.013	0.017	0.0085
1	-0.029	0.019	0.0089
2	-0.062	0.023	0.022
3	-0.115	0.028	0.048
4	-0.027	0.014	0.0087
5	-0.057	0.018	0.021
6	-0.022	0.017	0.0081
7	-0.052	0.041	0.021

5. Conclusions

The torque ripple caused by equalizing currents under the low eccentricity (models 1, 4, 6) is close to cogging torque (model 0). The eccentricity increasing leads to rising of the torque ripples to impermissible values. Fig. 5 shows that the increasing of the ripples amplitude is not linear and close to the parabolic curve. For example, the eccentricity less than 20% does not result in a significant ripples increasing. Such eccentricity can be acceptable from this point of view. On the other hand, the harmonic content of the torque ripples under the equalizing currents existing involves harmonics, which are not conventional for the cogging torque and other torque fluctuations. Therefore, constructional solutions reducing the cogging torque may be not effective for the decreasing of the ripples caused by the equalizing currents. This issue requires special consideration.

The technique described in this paper permits one to calculate the equalizing currents taking into account the real geometry and saturation of an electric machine. This calculation makes it possible to estimate the maximum permissible eccentricity of an electric machine being designed, to find the optimal geometry of slots basing on a minimum of the influence of the eccentricity on the magnetic symmetry of a machine, as well as to make conclusions about the validity of windings with two parallel branches.

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