Magnetic vibrations in synchronous machines with permanent magnets and fractional slot concentrated winding

D M Toporkov¹, M A Kovtun¹, I L Popov¹

¹Novosibirsk State Technical University / Department of Electromechanics, 20, Karla Markska ave., Novosibirsk, 630073, Russia

E-mail: kovtynaga96@gmail.com

Abstract. Nowadays synchronous machines with permanent magnets are widely used in motor manufacturing due to output parameters. The paper aims to analyse the radial magnetic forces that cause the stator vibration of a synchronous machine with permanent magnets and a fractional slot concentrated winding. The method to assess the vibration parameters of synchronous machine is proposed.

1. Introduction

Vibration is a type of mechanical movement in which each of the points of the body makes a periodically repetitive movement near a relatively fixed position. The scale and nature of the vibration change over time for each case are individual, the analysis of the vibration state of an electric machine is of the greatest interest, the study of which makes it possible to diagnose the technical condition of mechanisms and machines, identify sources of vibration excitation and eliminate many defects that improve the vibration state of an electric machine.

Vibration control solves several problems:
- The prevention of the increased vibration and the intensive wear of the mechanism by vibration
- Diagnosis of dangerous developing defects that can lead to serious damage, and sometimes to the complete destruction of the mechanism.
- Evaluation of the noise level, in order to reduce the impact of the noise level on the person.

Nowadays, permanent-magnet synchronous motors with fractional cog windings with a wide range of advantages are gaining more and more popularity as compared to classical synchronous machines:
- The use of high-coercivity rare-earth magnets based on NdFeB and SmCo with high specific magnetic energy, which makes it possible to manufacture machines with the best mass-dimensional parameters.
- Fraction slot concentrated winding allow in the dimensions of conventional classic low and medium power machines to perform electrical machines with the number of poles reaching 50 or more, resulting in the rejection of the use of the gearbox, cheapening and reducing the weight of the electric drive.
- The use of fractional slot concentrated winding windings reduces copper consumption and axial length of the motor by reducing the length of the end parts, and also simplifies the installation technology, since each coil covers one stator tooth, which reduces the manufacturing costs.

However, in spite of the listed advantages of SMPM (synchronous machines with permanent magnet) with fractional slot concentrated winding, their implementation and widespread use in some areas is
limited. This is especially true of high precision drives and those areas where stringent requirements are imposed on vibrations, noise and oscillations of the moment.

Due to the increasing relevance of synchronous motors with fractional slot concentrated winding (SMPM FSCW), due to the advantages described above, there is a need to analyze the vibration state of the electric machine. As the literature review [1-5] showed, the vibration state analysis is provided for machines with classical windings (with the number of slots per pole per phase greater than one), which causes certain difficulties for estimating the vibration level of the PDMS FSCW and designing an electrical machine that satisfies the technical requirements.

2. Problem statement
The literature [2-5], [8] contains a detailed description of the method for analyzing the vibration of electric machines due to the action of mechanical and aerodynamic forces, which is the same for most types of machines. The calculation of the magnetic forces that cause vibration for each type of machine is calculated individually, as a result, the need has arisen to develop a technique for analyzing the vibration state for SMPM FSCW, due to the action of radial magnetic forces.

3. Theory
A. General assessment of the cause of the vibration of a magnetic nature
The cause of vibration is magnetic radial forces acting between the stator and the rotor, which vary in space and time. According to Maxwell, at any point of the air gap a radial force acts, the value of which per unit area can be expressed by the equality:

$$p_r = \frac{B^2(\alpha, \theta)}{2 \cdot \mu_0} \quad (1)$$

Where $B(\alpha, \theta)$ - the instantaneous value of the magnetic flux density at the point of the air gap, shifted relative to the origin of coordinates by angle $\alpha$, now of time $\theta$ and $\mu_0$ is magnetic permittivity of vacuum.

Magnetic flux density, changing in space and time, corresponds to the radial force arising between the stator and the rotor, which also varies in space and time in a certain way. These forces cause vibrations of individual parts of the machine, and the radial force has the greatest effect on the stator yoke, which is a thin-wall hollow cylinder with the lowest rigidity compared to other parts of the electric machine.

To express the distribution of the radial magnetic forces arising between the stator and the rotor, it is necessary in formula (2) to substitute the magnetic induction in the air gap, which can be found as the product of the sum of the magnetomotive force stator winding and the magnetomotive force of the rotor magnets multiplied by the magnetic permeance of the air gap:

$$B_\delta(\alpha, \theta) = \left[ F_S(\alpha, \theta) + F_R(\alpha, \theta) \right] \cdot \Lambda(\alpha, \theta) \quad (2)$$

Therefore, to determine the magnetic flux density in the air gap, and then find the radial magnetic force, it is necessary to determine the magnetomotive force distribution of the stator and rotor fields, as well as the magnetic permeance of the air gap of the electric machine.

Magnetomotive force definition of stator SMPM FSCW described in detail in [6-7], in where the amplitudes and orders of harmonics are calculated for windings with $q=\frac{1}{2}, \frac{2}{5}, \frac{3}{8}, \frac{4}{11}$. Magnetomotive force of each stator harmonics is an infinite series:

$$F_S(\alpha, \theta) = \sum_{v=1}^{\infty} F_{mv} \sin(v\alpha - \theta) \quad (3)$$

The amplitude of the stator magnetomotive force is calculated by the expression:
The order of magnetomotive force harmonics is calculated by the ratio:

\[ v = 3k \pm 1 \]  

From the figure in Figure 1 it can be seen that the teeth have a wide range of higher harmonics.

The sum of stator magnetomotive force harmonics creates a resultant magnetomotive force, which determines the occurrence of radial magnetic forces.

The winding coefficient \( k_w \) show the reduction of the electromotive force of the distributed winding in comparison with the electromotive force of the winding with the same number of turns. Figure 3 shows a graph of the distribution of a winding coefficient for each harmonic number of magnetomotive force for winding with \( q = \frac{3}{8} \).

**Figure 1.** Relative magnitudes of three-phase winding harmonics with \( q = \frac{3}{8} \).

Winding scheme with \( q = \frac{3}{8} \) shown in Figure 2.

**Figure 2.** Winding diagram with \( q = \frac{3}{8} \).
Figure 3. Winding coefficient for winding with $q = \frac{3}{8}$.

B. Determination of the rotor magnetomotive force

The design of the rotor with a surface mounted permanent magnets presented in Figure 3.

Figure 4. Machine design with radial magnets.

In paper [8], the distribution of rotor magnetomotive force, which in general form represents an infinite harmonic series

$$F_R(\alpha, \theta) = \sum_{\mu=1}^{\infty} F_{m\mu} \sin(\mu\alpha - \theta)$$

(6)

Where $p$ - the number of rotor pole pairs

In addition, the distribution of magnetomotive force shown in Figure 4.

Figure 5. Distribution of magnets magnetomotive force.
C. Determination of air gap magnetic conductivity

If the air gap between the stator and the rotor varies along the inner surface of the stator core of the machine in an arbitrary periodic relationship, then the magnetic conductivity of the air gap, assuming that the rotor around the circumference is smooth, can be represented by an infinite harmonic series:

\[ \Lambda(\alpha) = \Lambda_0 + \sum_{v=1}^{\infty} \Lambda_{mv} \cos vz_1 \alpha \]  

(7)

Where \( z_1 \) - number of stator slots

By multiplying the terms of equation (2) and substituting them into equation (1), one can obtain expressions for the harmonics of radial magnetic forces varying in time and space and having different orders. Among which the following can be taken into account from the point of view of creating vibration:

Force waves created by the main field:

\[ p_{r1}(\alpha, \theta) = P_1 \cos(2p\alpha - 2\theta) \]  

(8)

These waves cause vibrations with order \( r=2p \), with frequency \( 2\Omega \) and amplitude:

\[ p_r = \frac{B_0^2(\alpha, \theta)}{4 \cdot \mu_0} \]  

(9)

Force waves created by the interaction of any pair of higher harmonic fields of the stator and rotor:

\[ p_{\nu\mu} = P_v \cos((v+\mu)\alpha - (\theta_v \pm \theta\mu)) \]  

(10)

With amplitude:

\[ P_{\nu\mu} = \frac{B_v(\alpha, \theta_v)B_\mu(\alpha, \theta\mu)}{2 \cdot \mu_0} \]  

(11)

With order \( r = v - \mu \) and angular velocity \( \frac{\theta_v - \theta\mu}{t} \).

The largest contribution to the occurrence of vibration made by the tooth harmonics of the order \( v = Z_1 \pm p \) и \( \mu = Z_2 \pm p \), what is described in the paper [8].

4. Experimental results

Vibration measurement was carried out on the motor VDM-80 with,

\[ Z = 18, p = 8, q = \frac{3}{8} \]

according to the test program in no-load mode when powered by a frequency converter, without mounting the motor, at the points shown in Figure 5.

The measurement results are shown in Table 1.

Based on the permissible vibration speeds for electric machines, with a height of the axis of rotation up to 132 mm for a category of machines without special vibration requirements, with free fastening, in accordance with the standard with GOST IEC 60034-14, that should not exceed 1.6 mm/s.
Figure 6. Measuring points of the motor vibration speed.

Table 1. The preset measured values of vibration velocity (mm / s) vdm-80

| n (rpm) | 1000 | 1500 | 3000 |
|---------|------|------|------|
| Point 1 | 1.3  | 0.76 | 0.91 |
| Point 2 | 1.0  | 1.0  | 1.25 |
| Point 3 | 0.02 | 0.07 | 0.7  |
| Point 4 | 1.35 | 0.9  | 1.7  |
| Point 5 | 1.0  | 1.17 | 2.08 |

5. Discussion of results
Estimating the vibration state for SDPM SDCs listed in Table 1, one can judge the deviation of experimental results from the permissible values required by GOST standards for vibration velocity values at 3000 rpm at points 4 and 5. This deviation is unacceptable for the operation of the electric motor and justifies the urgency of applying solutions that reduce the level of vibration velocity to acceptable values.

6. Conclusion
Exploring the expressions for the values of magnetic radial forces for SDPM FSCW, obtained by multiplying the infinite harmonic series in formulas (1) and (2), we can find the amplitudes and frequencies of the forces that cause vibrations, then with the help of constructive methods to neutralize or reduce the magnetic radial force amplitude, and thereby improve the vibration state of the electric machine.

These conclusions will help investigate the influence of vibration due to magnetic forces in SDPM FSCW for more detailed.

References
[1] Balagurov V A, Galteev F F and Larionov A N 1964 Electric machines with permanent magnets (Moscow: Energy)
[2] Goldin A S 1999 Vibration of rotary machines. (Moscow: Mashinostroenie)
[3] Kucher V Ya 2004 Vibration and noise in electric machines: written lectures (St. Petersburg: SZTU) 81
[4] Lee S K, White P R 1997 Higher-order time-frequency analysis and its application to fault detection in rotating machinery Mechanical Systems and Signal Processing 11 4, 637-650
[5] Lee S K, White P R 1998 The enhancement of impulsive noise and vibration signals for fault detection in rotating and reciprocating machinery Journal of Sound and Vibration 217 3 485-505
[6] Bukhgole U G, Komarov A V, Shevchenko A F, Shevchenko L G 1996 Multipolar synchronous machines with fractional slot windings part 2 (Novosibirsk: NGTU)
[7] Bukhgolc U G, Komarov A V, Shevchenko A F, Shevchenko L G 1996 Multipolar synchronous machines with fractional slot windings part 1 (Novosibirsk: NGTU)

[8] Heller B, Hamata V 1977 Harmonic field effects in induction machines (New York: Elsevier)