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Design Aspects of AMBs for High-Speed Permanent Magnet Synchronous Machine

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Abstract
Distributed power generation is nowadays one of the global trends. Compared with the centralized power generation there is no need to transmit and regulate electricity network in the case of distributed generation. These advantages can be critical for many electricity consumers. Distributed power generation using microturbines is an alternative to the commonly used combustion engines. These installations increase total system efficiency and enable operation at the low partial loads. In this paper the design aspects of a high-speed permanent magnet synchronous machine (PMSM) equipped with active magnetic bearings (AMBs) are considered. The structure of the permanent magnet generator is explained and its parameters are presented and discussed. This paper concentrates on the additional magnetic pull created by the PMSM at standstill. This situation creates extra forces and set extra requirements to AMBs. The method to avoid unnecessary magnetic bearing overdimensioning using electrical machine control system is described. An influence of the unbalanced magnetic pull on the active magnetic bearing control is presented. The uneven distribution of the force leads to additional complexity for the controller synthesis. The rotating reference frame for the control problem formulation is discussed.

Key words : magnetic bearings, permanent magnet synchronous machine, magnetic pull, control system

1. Introduction

For the latest years there is a global tendency to more distributed power generation. In the total amount of installations on average 45 % are relatively small installations from 0.5 MW to 3.5 MW. Traditionally, in that scale the most common solution is a combustion engine (Malkamäki et al., 2015). In power production the combustion engine has a good efficiency and for this reason it has been used in these applications instead of microturbines. However, reciprocating engines do have other technical disadvantages such as fuel allowance, noise, emissions. Also their partial load area is typically only from 100 % to 50 %. In the mentioned power level a high efficiency gas turbine has a real and high demand on the market. The new gas turbines can reach electrical efficiency of 45.8 % (Malkamäki et al., 2015).

Very high system efficiency in microturbines besides fluid and heat transfer issues is achieved by efficient high-speed electrical generator. The speed range is given by the process itself, therefore for such frequency 553 Hz a suitable electrical machine solutions is necessary. Both good efficiency and high power factor can be provided by rotor surface mounted permanent magnet synchronous machine (PMSM) (Pyrhönen et al., 2008; Binder and Schneider, 2007).

A special attention in microturbine applications or distributed power generation is devoted to the reliability and maintenance issues. The Active Magnetic Bearings (AMBs) seem to be the most advantageous solution in that case because of the friction free operation, reduced maintenance, and absence of oil (Schweitzer and Maslen, 2009). In addition for combined heat and power (CHP) applications magnetic bearings allow withstanding back pressure on turbine exhaust pipe.

To design and implement an efficient electrical machine on AMBs for the microturbine a multidisciplinary analysis is necessary (Boglietti et al., 2014; Huang et al., 2016). In most cases the design leads to a trade-off between electromagnetic performance and mechanical feasibility. This also affects the dimensioning of the bearing to provide enough supporting force with a wide enough bandwidth. The problem gets one more dimension with the synthesis of stabilizing controller, because in that case the locations of external forces and their frequencies are needed.

This article discusses the aspects of constraints imposed by a PMSM on an AMB-rotor system performance. The limitations of the different types of the high-speed machines can be found in (Moghaddam, 2014; Kolondzovski et al., 2011). At the mentioned nominal speed it is common for the electrical machines to have one pole pair because of the high iron losses and converter limitations (Lim et al., 2015; Bianchi et al., 2004). Such number of poles provides rather uneven flux distribution leading to problems for AMBs at the startup. Another issue is the unbalanced magnetic pull (UMP) at the nominal conditions. These issues were already considered for induction machines with AMBs by (Amati and Brusa, 2001) and the pull for PMSM is discussed by Dorrell et al. (2014).

The methods of the electrical machine unbalanced pull calculation at the standstill and at the nominal operating point are presented. Finite Element Method (FEM) analysis is utilized to compute the magnetic pull. The influence of the above-mentioned and other effects of PMSM on magnetic bearing design and controller synthesis is discussed. Suggestions to minimize the AMB dimensions using the control of the electrical machine are drawn.

2. Permanent Magnet Synchronous Generator

In this case the designed gas turbine includes two identical electrical machines, one for low pressure and one for high pressure units. Each generator provides 250 kW electrical power at 33 200 rpm. The rotor of the electrical machine has 2 poles with the relative width of the permanent magnet about 0.9. Fig. 1 illustrates the machine rotor structure. In the middle of the rotor there is a yoke made of a ferromagnetic material with cooling ducts under the magnets. Magnets are divided into segments both radially and axially and installed around the yoke. Permanent magnet segments are separated with a metal cage between them. This structure is supported by a carbon fiber retaining sleeve around the magnets.

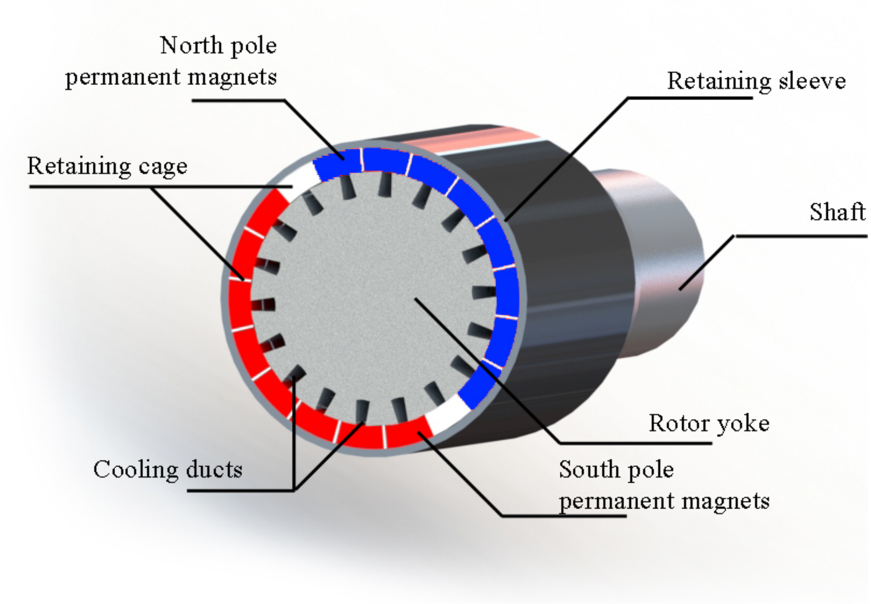

Fig. 1: High-Speed two-pole PMSG rotor model cross-section

Fig. 2 shows the structure of the electrical machine stator. The generator stator has 24 semi-closed slots. There are axial cooling ducts above each slot. The distributed windings are made as a double-layer winding with the number of slots per pole and phase $q = 4$. The winding short pitching influences the air gap flux density harmonic content and rotor losses. A lower value of the winding step allows reducing the end winding axial protrusion length. The winding short pitching was optimized to be 4/6 to keep low air gap flux density harmonic content and reduce the end winding axial protrusion length. Magnetic wedges were installed between the tooth tips. Stator yoke is made exceptionally thick to reduce total iron losses.

The electrical machine main parameters are shown in Table 1. NdFeB permanent magnets were selected for this high-speed permanent magnet synchronous generator. The remanent flux density of the selected magnet grade is 1.03 T. The magnets are highly resistant to irreversible demagnetization at the temperatures about 200 °C. At the rated operating

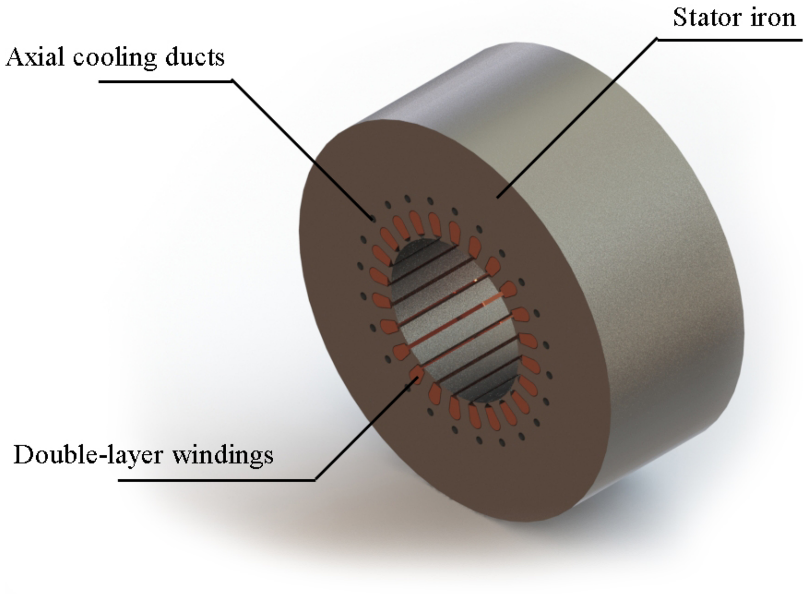

Fig. 2: High-Speed PMSG stator model cross-section

Table 1: Designed Machine Main Parameters

Machine parameter	Value
Rated speed n_n, min^{-1}	33 200
Number of poles p	2
Number of stator slots Q_s	24
Rated torque T_n, Nm	72
Rotor outer diameter D_o, mm	116
Physical air-gap length δ, mm	2
External diameter D_e, mm	294
Active length l, mm	260
Permanent magnet material	NdFeB
Permanent magnet remanence B_r, T	1.0
Retaining sleeve material	Carbon fiber
Stator stack lamination material	NO20

conditions they can tolerate a 3-phase short-circuit at temperatures up to 150 °C. This magnet grade was selected for the prototype to ensure stable operation during the first runs and reduce the risk of the magnet irreversible demagnetization.

The retaining sleeve is made of carbon fiber because of the high stresses between the sleeve and the permanent magnets. This material has exceptional mechanical properties and in addition there are almost no eddy current losses in it. The drawback of the carbon fiber is its low thermal conductivity. Therefore, it is necessary to provide another path for the heat generated in the magnets, retaining cage, and rotor yoke. For this purpose the rotor axial cooling ducts are used. According to the thermal calculations these ducts with a sufficient cooling flow can effectively dissipate the heat from the rotor.

In high-speed machinery low number of poles is preferred to keep fundamental frequency as low as possible. When, for example, a 2-pole rotor is not located in the geometrical center of the machine permanent magnets will create a force even at no-load and zero speed. These forces may set additional requirements to the AMB characteristics during the start up.

When an AMB supported machine is at rest the rotor is laying on safety bearings. In this situation the rotor is displaced from the geometrical center in the direction of the gravity force. This displacement is the same for the active part of the electrical machine and the shaft and it is defined by the clearances of the safety bearings. In this situation permanent magnets create a magnetic pull force in addition to the gravity force.

Fig. 3 shows the forces created by the electrical machine permanent magnets with the various rotor position angles.

The forces are calculated using FEM model of the electrical machine. The rotor is displaced from the geometrical center by 250 μm, which is the clearance of the safety bearings in the designed PMSM. It is seen in Fig. 3 that there is 180° periodicity related to the 2-pole rotor structure. The minimum value of the force is 87 N and the maximum value is 208 N, which lead to the force difference of 121 N between 0° and 90° rotor positions. At standstill the rotor is tending to hold a position with the minimum potential energy, which means that it will hold a position with maximum force created by the permanent magnets.

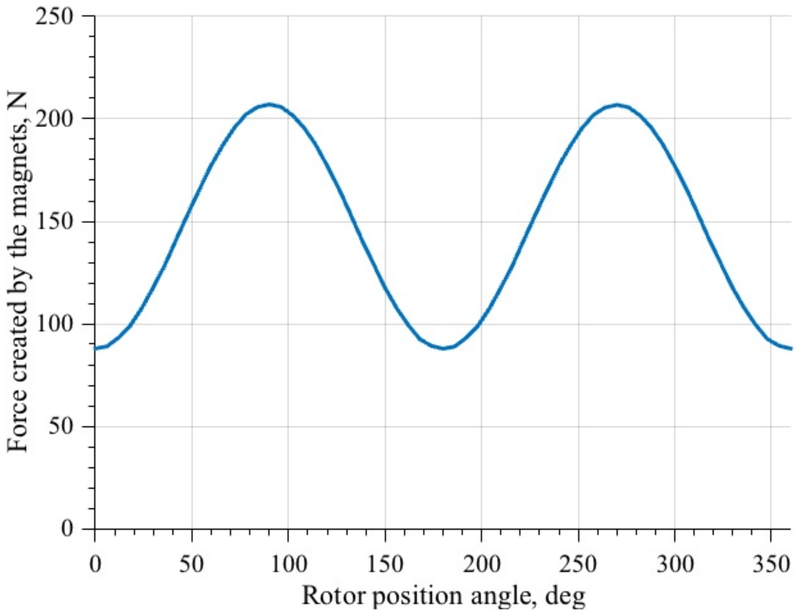

Fig. 3: Forces created by the permanent magnets at rest versus the position angle of the resting rotor

3. Magnetic Bearings

The force provided by a pair of symmetrical electromagnets is defined by the following equation

$$f = k_b \left(\frac{(I_b + i_c)^2}{(g_0 - x)^2} - \frac{(I_b - i_c)^2}{(g_0 + x)^2} \right), \tag{1}$$

where I_b is a bias current, control current is denoted as i_c, g_0 is the nominal airgap, x is the rotor displacement, and k_b is bearing force coefficient which is defined by surface of actuators, number of turns and geometrical orientation. For the control purpose the equation (1) is linearized near the operating point under assumption that control current is less than bias current and rotor displacement is significantly smaller than nominal airgap. The linearization is done by approximating the force equation into Taylor series and omitting all terms except first ones. Thus the force can be written as

$$f = k_x x + k_i i_c, \tag{2}$$

where k_x and k_i are position and current stiffness. These terms are defined as follows

$$k_x = 4k_b \frac{I_b^2}{g_0^3}, \tag{3}$$

$$k_i = 4k_b \frac{I_b}{g_0^2}. \tag{4}$$

In general the force provided by the magnet is defined by the flux in the airgap. Thus for the electrical machine where flux is provided by permanent magnets the similar approximation can be done. At the standstill case the flux does not depend on the current and thus only position stiffness k_{em} term is left.

3.1. Initial Levitation

According to the general rule the bearing force is dimensioned to be $3mg$, where m is the rotor mass and g is the gravitational constant. For the permanent magnet machine the bearings should also overcome the magnetic pull during the initial levitation and in the designed machine this value is 208 N. The mass of the active rotor part is around 17.5 kg, thus the bearing force devoted for the levitation of this part is around 515 N. When accounting the magnetic pull this should be increased at least by 208 N or by 40 %.

The addition of 40 % is quite significant. In contrast, with another rotor position angle the force addition is just 87 N or 17 %. The way to solve this issue is to utilize modern inverters. In practical cases high-speed machines are already equipped with a variable frequency converter. These converters are capable to provide a current vector in a certain direction creating flux that will stabilize the rotor in a certain position angle. In addition, it is not necessary to know the rotor angle only a current vector direction. Thus, the rotor will take the required position by aligning the rotor flux vector to the stator flux vector in a way to minimize the torque.

Taking into account the above mentioned consideration the start up procedure for the permanent magnet machine with magnetic bearing should be done in the following steps:

(1) Align the rotor angle to the beneficial position by applying predefined current pattern to the coils of the electrical machine,

(2) Levitate the rotor by turning on the magnetic bearings,

(3) Continue operation of the machine by accelerating to the nominal speed.

This procedure can be implemented in the PLC that operates the plant. The start up procedure does not require special hardware changes. For the machine under study it allows to save 23 % of bearing force devoted to the electrical machine part levitation.

3.2. Bearing Control

Because of the thick nonmagnetic retaining sleeve the resulting magnetic air gap equals to 5 mm. For such a long air gap the variation of force with relation to the displacement in the safety bearing limits, which is 250 µm can be assumed linear. Therefore, the position stiffness coefficients in d and q rotating coordinates k_q, k_d are 832 N/mm and 348 N/mm respectively.

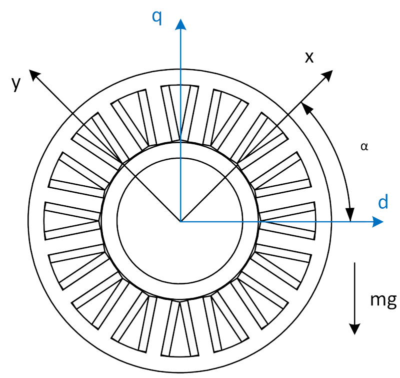

Fig. 4: Rotating and stationary coordinates for the bearing system

For the stand still operation the worst case scenario is assumed when q axis is parallel to gravitational force vector. The magnetic bearings are manufactured and installed in a way that the gravitational force is separated between two quadrants as it is presented in Fig. 4. The general transformation to bearing coordinates with transformation matrix is as follows:

$$\begin{bmatrix} d \\ q \end{bmatrix} = T \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}. \quad (5)$$

The inverse transformation is done as:

$$\begin{bmatrix} x \\ y \end{bmatrix} = T^{\mathrm{T}} \begin{bmatrix} d \\ q \end{bmatrix}. \quad (6)$$

The two pole permanent magnet machine provides flux with the period of π. This flux provides only attractive force and thus can be approximated for the control purpose as position stiffness. The node of attachment is the center of active part of an electrical machine. The stiffness can be translated to bearing coordinates as follows:

$$\begin{bmatrix} k_{\mathrm{em,x}} \\ k_{\mathrm{em,y}} \end{bmatrix} = |T| \begin{bmatrix} k_{\mathrm{d}} \\ k_{\mathrm{q}} \end{bmatrix}. \tag{7}$$

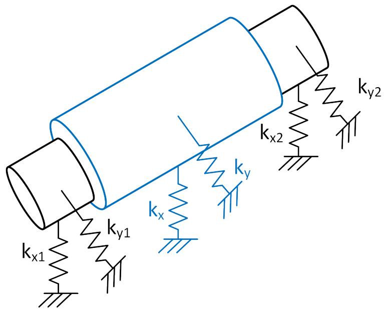

Fig. 5: Simplified model of the rotor-bearing system

For the arrangement presented in Fig. 4 the stiffness distribution is even with the following transformation:

$$k_{\mathrm{em,x}} = k_{\mathrm{d}} \cos\left(\frac{\pi}{4}\right) + k_{\mathrm{q}} \sin\left(\frac{\pi}{4}\right) = \sqrt{2}\frac{k_{\mathrm{d}} + k_{\mathrm{q}}}{2}, \tag{8}$$

$$k_{\mathrm{em,y}} = k_{\mathrm{d}} \sin\left(\frac{\pi}{4}\right) + k_{\mathrm{q}} \cos\left(\frac{\pi}{4}\right) = \sqrt{2}\frac{k_{\mathrm{d}} + k_{\mathrm{q}}}{2}. \tag{9}$$

In case the control system has information about the rotor angle it is straightforward to implement the control in the rotational coordinate frame. The construction of the bearing allows to provide the force in any direction. Therefore, measurements and forces of radial bearings are converted using equations (5) and (6). It is also beneficial to fix the angle between two coordinate systems at 45° to provide a symmetrical support.

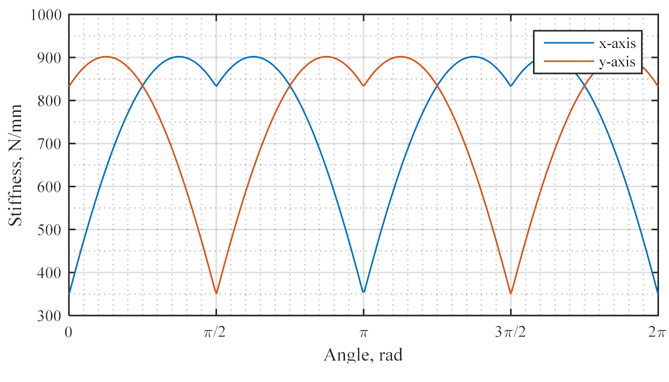

Fig. 6: Rotating and stationary coordinates for the bearing system

If angle information is not available the system tends to have asymmetry in the supporting stiffness. The total contribution for x and y stiffnesses from the electrical machine is presented in Fig. 6. The minimum added value is 348 N/mm and the maximum is 902 N/mm, on average the added stiffness is 750 N/mm. For the control purpose in the stationary frame this stiffness can be considered as an uncertain parameter with variation between minimum and maximum value.

The effect on the plant model for minimum and maximum variation of added stiffness is presented in Fig. 7. The 'Non Drive End' bearing is slightly smaller and effect of the electrical machine is more visible. The nominal plant model without added stiffness is denote with blue line. In general the additional position stiffness is not beneficial for the AMBs as it destabilizes the system by pulling the rotor from the center point. Thus, higher control gain and higher currents are necessary in the low frequency region.

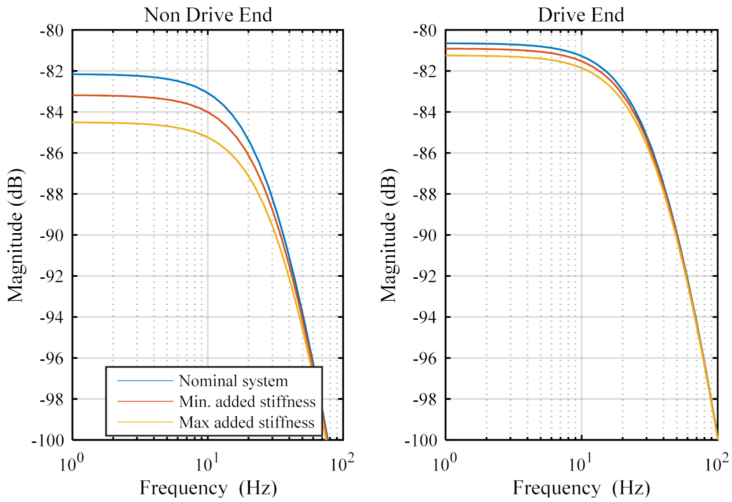

Fig. 7: Effect on bearing rotor model for minimum and maximum variation of stiffness induced by the electrical machine. Left - Non Drive End with smaller bearing. Right - Drive End with bigger bearing

The other effect for the system in stationary coordinates, which is introduced by an asymmetric bearing is the difference in flexible mode frequencies. The maximum difference possible for x and y axis from Fig. 6 is 484 N/mm. This difference appears at angle 0° and repeats by every 90°. At these points the effect is quite minor and results in 0.2 Hz and 0.1 Hz difference for the first and second flexible modes respectively.

From the bearing control perspective the rotational frame is beneficial as bearings always have equal stiffness. Thus, the plant model is constant and does not need any uncertainty consideration. The total added stiffness value is lower than the possible maximum and in addition a minor effect of difference in flexible modes is avoided.

4. Conclusions

In this paper the effect of permanent magnet synchronous machine on magnetic bearing system is demonstrated. In general, the usage of such machine requires increasing the bearing size. This must be done to provide initial levitation and to alleviate the effect of added position stiffness.

For the initial levitation a procedure is proposed that allows minimizing the force related to the active part of the electrical machine under study at standstill by 23 %. This is achieved by utilizing the features of modern variable frequency converters and turning the rotor to a favorable position.

The system is also evaluated from the control point of view. It can be concluded that by utilizing the rotational coordinates most of the issues are alleviated or completely eliminated. However, this approach requires real-time information of the rotor angle. The effect on the system in stationary coordinates is also discussed and the way to include stiffness variation as an uncertain parameter in the controller synthesis procedure is proposed.

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