# MAGNETIC BEARING USING ACTIVE AND PASSIVE FIELDS

**J. VITNER, J. PAVELKA, J. LETTL**

Department of Electric Drives and Traction, Faculty of Electrical Engineering,
Czech Technical University in Prague
Technicka 2, 166 27 Prague 6, Czech Republic,
vitner@ujf.cas.cz, pavelka@fel.cvut.cz, lettl@fel.cvut.cz

***Abstract:*** *This paper discusses development and rotor stabilization process of the combined magnetic bearing for high speed bearing-less motors. In the first part the paper deals with the various types of magnetic bearings, their characteristics, properties, and principles. The second part presents a detailed view of the combined magnetic bearing placed in the laboratory of the Department of Electric Drives and Traction FEE CTU in Prague. This part includes mathematical concept of the combined magnetic bearing, calculation of the magnetic circuit parameters, and design of the 3-phase winding, determination of the force effects of the passive and active magnetic field. In the last part the paper deals with driving methods of the active magnetic field to stabilize the rotor. The computer simulation results and results of the measurements on the real stabilized combined magnetic bearing are presented.*

***Key words:*** *Magnetic bearing, positional stabilization, magnetic levitation, power electronics.*

## 1. Introduction

Magnetic bearings are becoming more and more an object of interest to designers, constructors, and producers of rotating machines for various applications. Their advantages, as ability to work in vacuum, in weightlessness, in chemical aggressive environment and alike are demonstrable. Next advantage is the possibility to change their stiffness and damping by changing the controller parameters. It allows adjusting the proper frequency of rotating system oscillation [1], [2].

Magnetic bearings are particularly bounded with magnetic levitation systems. From this point of view, we can mention systems with permanent magnets using only passive magnetic field with its repulsive and attractive forces without any feedback [2], [5].

The other are systems with diamagnetic materials where the diamagnetic material is placed into the magnetic field so there is a repulsive force acting to the diamagnetic material and the material defends invading of magnetic field. The opposite situation occurs when using paramagnetic or ferromagnetic material [3], [4].

Another systems use so called transformational levitation when an electrically conducting solid is put into the variable magnetic field. Transformational voltage is induced into the component to be stabilized and it produces in it turbulent currents. The magnetic field of turbulent currents interacts with the main field and this interaction produces a repulsive force.

Systems based on an electromagnetic levitation use an attracting force between a ferromagnetic object and an electromagnet. The object position feedback determination is necessary to reach the stable state in the current axes. The current in the electromagnet coil is controlled according to the object position [7], [9].

Systems using the electrodynamic levitation are based on application of repulsive force produced by affecting between the electromagnet and moving conductive belt. Such system consists of a coil powered by direct current that is moving above the metal belt. The movement causes the turbulent currents inside the metal belt and they give rise a magnetic field affecting the basic magnetic field of the coil. The interaction of magnetic fields produces two forces, one repulses the coil and the second acts against the motion [8], [10], [6].á

From technical point of view, magnetic bearings can be divided into passive bearings and active bearings. Passive magnetic bearing utilizes repelling resp. attracting of permanent magnets to create a force between its stator and rotor. As is known, it is not possible to obtain a stable equilibrium using passive magnetic bearings only and therefore at least one direction has to be stabilized by means of mechanical bearing or active magnetic bearing. Passive magnetic bearing operates without electric energy consumption but its small stiffness and damping constitute large disadvantages [6].

Classical active magnetic bearing exploits attractive force of magnetic flux in the air gap acting between its stator and rotor. This force can be controlled by excitation current in the stator winding. The force is only attractive and therefore two opposite located electromagnets have to be used for one axis. The resulting force is determined as the difference between these two forces. A disadvantage is that some “bias” currents in both winding are needed to reach zero resulting force and they represent losses in windings.

Combined magnetic bearing eliminates bias currents and therefore the losses are reduced. The advantage and main benefit of the described project is the possibility to use classical three-phase winding for the stator and inverter, which is typical for AC machines. According to the controlling system, the contribution lies in linearization of the relation between the active and passive magnetic fields.

## 2. Detailed description of the used combined magnetic bearing

The magnetic bearing at the Faculty of Electrical Engineering CTU in Prague is a kind of hybrid magnetic bearing. It consists of two mutually perpendicular magnetic circuits, one excited by permanent magnets, the second one by three-phase winding. The active part of the magnetic bearing is similar to the stator of an asynchronous motor. The 3-phase two pole double-layer winding is located in 12 slots of the stator from a solid magnetic material (Fig. 2-1). The magnetic circuit is assembled from two identical parts with above mentioned winding in each part. Eighteen permanent magnets are located in perimeter between both parts, which is shown in Fig. 2-2.

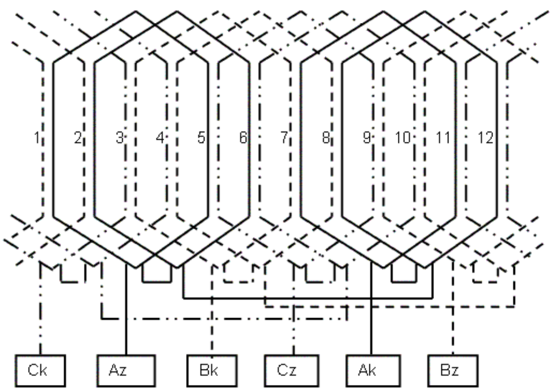

Fig. 2-1 Three-phase stator winding

The 3-phase winding is the source for one of magnetic circuits (dashed line in Fig. 2-2) and produces controlled magnetic field in this circuit. This active magnetic field is closing up in radial plane. The path of this active magnetic field is going from the stator exciting winding to the air gap. It continues through the shaft to the opposite air gap and opposite pole of exciting winding and closing itself in the magnetic circuit in the radial plane. Magnetic resistivity of the magnetic circuit for this active magnetic field is independent on a rotor shaft motion. The active magnetic field flows through both horizontally opposite air gaps and therefore the sum of both air gap lengths is constant. The magnetic resistivity is primarily determined by air gap size.

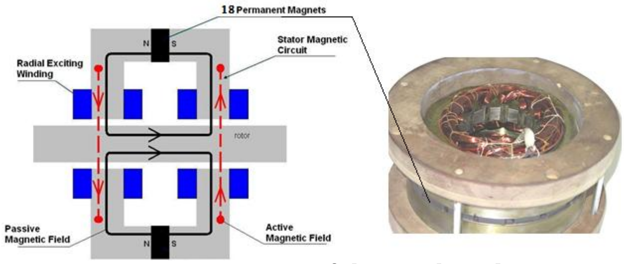

Fig. 2-2 Magnetic circuit of the combined magnetic bearing

…The source for the second magnetic circuit is formed by 18 permanent magnets in perimeter between both parts. This second magnetic source is passive without any possibility to control its magnetic force. All magnets are polarized along the whole stator circumference in the same direction. The path of the passive magnetic field leads from the north pole of permanent magnet in the axial plane to the stator teeth, then through the air gap to the rotor and continues along the axis of the rotor to the vertically opposite stator teeth through the air gap to the south pole of the permanent magnet (solid line in Fig. 2-2). Magnetic resistivity of the magnetic circuit of the passive magnetic field is depending on the rotor position in the air gap. If the rotor moves closer to the stator part in any direction, the air gap decreases its size and therefore the magnetic resistivity decreases, too. The magnetic flux in this direction increases and therefore the attractive force acting on the rotor in this direction increases. According to that, the permanent magnets are continuously attracting the rotor in any direction and the attracting force is the higher the closer the rotor is to stator. Thus the passive magnetic field is not able to reach any stable position of rotor. To control its position, we need to sum these two magnetic fields, the passive magnetic field and the active magnetic field. The active magnetic field has to have the opposite direction in each of radial planes of the magnetic circuit because the passive magnetic flux is changing its direction along the vertically opposite air gap. Our effort to control the position of the rotor is to influence the passive magnetic field by the active magnetic field so that we choose the polarity of the active magnetic field to increase or to decrease the passive magnetic field in the air gap. Thus both fields could be added or subtracted in the air gap.

It is known from the theory of electrical AC machines that a three phase winding produces one magneto-motoric force and its direction and magnitude in air gap is given by values of currents in phases. These three currents can be transformed to two orthogonal axes ($\alpha,\beta$). The position of the rotor in air gap is possible to be described in the same axes. It is the basic idea of the rotor position control.

## 3. Passive and Active Magnetic Fields

In order to create a right mathematical model, it is necessary to verify, numerically determine and to gauge parameters of the stator magnetic circuit and the used permanent magnets. Via such mathematical model it is possible to calculate the force effects of the passive magnetic field on the rotor for any deviation.

The magnetic resistance of each part of the magnetic circuit is given by:

$$R_{mi} = \frac{1}{\mu_0} \times \frac{l_i}{\mu_i \times S_i} \left[At / Wb\right] \qquad (1)$$

### 3.1 Passive Magnetic Field

According to the calculation of magnetic resistance for each part of magnetic circuit, it is clear that the magnetic resistance of iron is approximately 13% ampere-turns for the air gap. It will be considered in the coefficient of the next equation. The relation between the magnetic flux and the magneto-motoric force for the whole magnetic circuit for the various $\boldsymbol{R_{m\delta}}$ is given by:

$$F_m = \left(0.13 \times R_{m\delta 0} + R_{m\delta}\right) \times \Phi \quad \left[N\right] \qquad (2)$$

The magnetic induction under any stator pole is given by the total magnetic flux and the total area of all the stator teeth:

$$B_{\delta 1z} = \frac{\Phi}{S_\delta} \quad \left[T\right] \qquad (3)$$

The force, excited by the magnetic induction $\boldsymbol{B_\delta}$ under one tooth, is given by:

$$F_\delta = \frac{1}{2} \times \frac{B_\delta^2}{\mu_0} \times S_\delta \quad \left[N\right] \qquad (4)$$

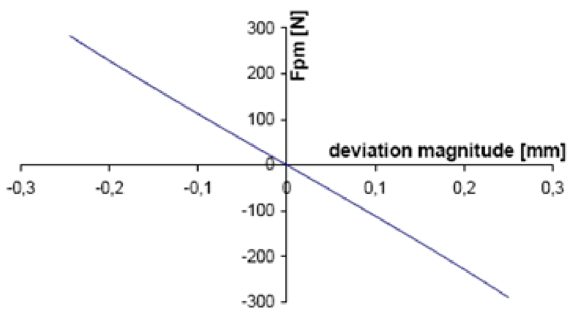


Fig. 3-1 Dependence of the force of the permanent magnets on the air gap size

### 3.2 Active Magnetic Field

The magnetic resistance of the air gap for the active magnetic field is constant for any rotor position. According to the calculation of magnetic resistance for each part of magnetic circuit, it is clear that the magnetic resistance of iron is approximately 22% ampere-turns for the air gap. It will be considered in the coefficient of the next equation. The relation between the magnetic flux and the magneto-motoric force for the whole magnetic circuit for the constant $\boldsymbol{R_{m\delta}}$ is given by:

$$F_{mw} = 1.22 \times R_{m\delta} \times \Phi \quad \left[At, mWb\right] \qquad (5)$$

According to the modified relation for the magneto-motoric force of the multi-phase winding we can calculate the corresponding current:

$$F_{mw} = \frac{m \times N \times k_v}{\pi \times p} \times I \quad \left[N\right] \qquad (6)$$

The force of the exciting winding is dependent on the magnetic induction for 24 teeth on the stator according to:

$$F_w = \frac{1}{2} \times \frac{B_\delta^2}{\mu_0} \times 2 \times 12 \times S_\delta \qquad \left[N\right] \qquad (7)$$

Hence with the help of few transformations we are able to determine the required value of the required stator current in dependence on the required force.

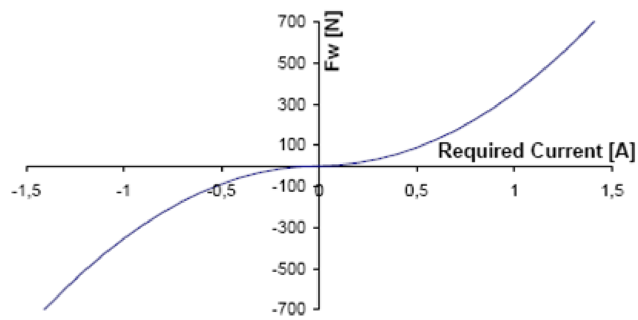


Fig. 3-2 Dependence of the winding force on the required current

## 4. Results of experimental measurements

To stabilize position of the rotor in the centre of the bore of the magnetic bearing stator is the general point and the required target of our effort. The information about the actual position of the rotor is provided by two position sensors placed in mutual perpendicular axes (α,β). The information about the actual position of the rotor from position sensors is represented by two voltage signals that are converted by A/D converters of the control unit. The digital information about the actual position of the rotor is an input for the PID controller. The output of the PID controller consists of two estimated value of stator current in axes (α,β). These two values of the stator estimated currents have to be transformed to the real currents of the 3-phase stator system. Thus we receive the estimated value of the current for each phase of the stator winding.

Stator windings are star connected and therefore the sum of all three instantaneous current values must be zero. Two from three stator phases have their own PI controllers and the third current is given from the above mentioned condition. Reliability and stiffness of the rotor stabilization is largely dependent on the achievable speed of the current PI controller. The delta connection of stator phases and the parallel connection of windings in both sides of the stator winding were tested with the target to decrease the time constant of the current loop. The steady state value of the phase current was double increased by help of the parallel connection. The achievable maximal current change in time is shown in Fig. 4-1 and its value is **0.005** A/μs.

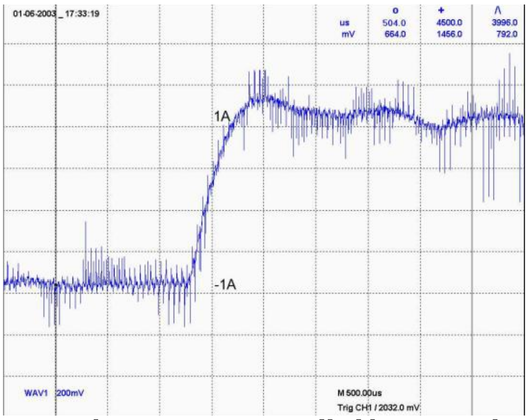

Fig. 4-1 Phase current controlled by PI regulator

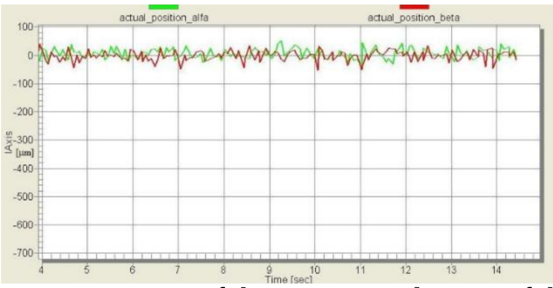

Fig. 4-2 Levitation of the rotor around centre of the stator bore

Before tuning of the stabilization process, the rotor of the magnetic bearing had to be mechanically centred in the bore of the magnetic bearing stator as precisely as possible. In the next step, the rotor was mechanically fixed in the centre of the horizontal axis and the stabilization process was tuned only for the vertical axis of the rotor motion. The system operates correctly only when the correct steady weight compensation value of the force acting the rotor was found. Without the steady weight compensation force, the special adjustment of the PID controller would have to be performed for the vertical axis. Further, the rotor was fixed in the centre position for the vertical axis and the rotor could move only in the horizontal axis. The stabilization process was successful with the similar adjustment of the PID controller as was used for the vertical axis. In the last step, the rotor was released in both axes and stabilized in the centre position of the stator bore. The levitation of the rotor is shown in Fig. 3-2. The air gap between the stator and rotor is *0.5 mm* and during the stabilization process the magnitude of the rotor oscillations around the centre position is not higher than the ±*50 μm* as it is shown in Fig. 4-2.

## 5. Conclusion

In the previous paragraphs, kinds of magnetic and electromagnetic levitation principles and basic sorting of the magnetic bearing types with the principles of their function are summarized. The detailed view on the special kind of the magnetic bearing placed in the laboratory of the Faculty of Electrical Engineering CTU in Prague called combined magnetic bearing is presented. The paper gives description of the function state of this combined magnetic bearing with its driving behaviour and characteristics and presents experimental results obtained when measuring on real system in laboratory.

It is supposed to continue in tuning of the combined magnetic bearing in shaft run and to simulate different modes of load changes.

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