Considerations on magnetic levitation realized with superconductive materials

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***Abstract* – In this paper are discussed the particularities of the magnetic levitation made with superconducting materials; the operating principle is specified and possibilities for making this levitation are presented. It highlights the structure, properties and applications of passive and active magnetic bearings.**

Keywords* – *magnetic levitation, magnetic bearing superconducting materials,

I. INTRODUCTION

In electrical engineering, there is a tendency to develop new techniques and use of new materials, such as superconducting materials [1]. The storage of electric power as well as the improvement of its transport by introducing limiters is based on the phenomenon of superconductivity [4], [5]; magnetic levitation has been possible to achieve by using superconducting materials (inertia flywheels).

No complete levitation (with control of 5 degrees of freedom) can be achieved from conventional passive magnetic bearings. According to the Earnshaw theorem, levitation cannot be stable if, on the whole system, the relative permeability fulfills the condition: $\mu_r \geq 1$; Superconductors allow the design of a fully stable passive magnetic levitation. Interaction of type II superconductors (high critical temperature) with permanent magnets results in better levitation and superior amortization when returning to the equilibrium position; the force of levitation between magnets and the superconductor has the expression:

$$F_z = \int_{V'} \mu_0 M(H) \frac{\mathrm{d}H}{\mathrm{d}Z} \mathrm{d}V = \mu_0 M(H) \frac{\mathrm{d}H}{\mathrm{d}Z} \mathrm{d}V \quad (1)$$

where *V'* is volume of magnetized superconducting *M(H)* is the magnetization of the superconductor material (depends on the magnitude of the field generated by the magnets, *H*) and *V* is the volume of the superconducting material.

The force of levitation has high values if the superconducting material is characterized by high critical current density; Permanent magnets have to generate a magnetic field of polarization in the whole volume of superconducting material for magnetization and high magnetized volume. Cooling conditions influence the value of levitation force: if the superconductor is cooled in contact with the magnet, there are forces of attraction that hold the magnet attached to the superconductor (so the magnet will not levitate); if the cooling is achieved with the permanent magnet sufficiently outlying, the levitation becomes possible.

II. METHOD

The magnetic bearings can be passive and active and have the advantage of operating without mechanical contact, requires no lubrication, no wear, and friction due to magnetic losses is reduced. The passive magnetic bearing is made with permanent magnets or electromagnets (excitation current is constant) operating on the basis of repulsion forces or on the basis of alignment forces. Two permanent magnets in repulsion can develop a force that exceeds their weight. The alignment force occurs if a radially magnetized permanent magnet fixed on the rotor is placed between two radially magnetized permanent magnets fixed on the machine stator, in this case the magnetic fields are in complete attraction and the structure is radially stable but not axial, Fig. 1. In order for the levitation to be complete, an active magnetic counterpart (control system) must be inserted axially.

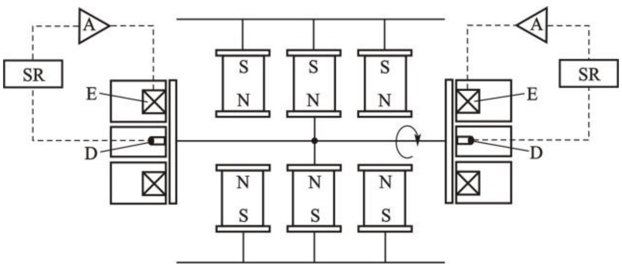

Fig. 1. Bearings with magnets attraction:
Amplifier, Detector, System Control, Electromagnet

The passive magnetic levitation is used in the inertia flywheel in the hybrid configuration Fig. 2, realized by two magnetized external rings, between which a central superconducting core (cooled in the field, in contact or from a certain distance). The central core is consists of alternately magnetized concentric rings, which interact with 7 superconducting pads of YBaCuO inserted into an isolated liquid nitrogen enclosure. Radial core stiffness ensures annihilation of destabilizing effects due to magnet-magnet outer counterparts (unless the pads are cooled out of range from the core magnets).

The active magnetic bearing it works due to the attraction force developed by electromagnets with variable excitation; Electromagnets are controlled by motion detectors via an electronic control system. Permanent rare-earth magnets [2] develop significant magnetic energy and do not require complex electronic assemblies for active bearings. These bearings have reasonable load capacity, relatively low rigidity and virtually zero amortization (for radial bearing are used shock absorbers with Foucault currents). The radial plate consists of a cylindrical ferromagnetic rotor located in the magnetic fields generated by electromagnets mounted two by two in opposition, Fig. 3. The currents which pass through the electromagnetic windings are provided via amplifiers. The rotor equilibrium state is due to electromagnetic forces, and the rotor position is evaluated by four inductive sensors that sense potential displacements.

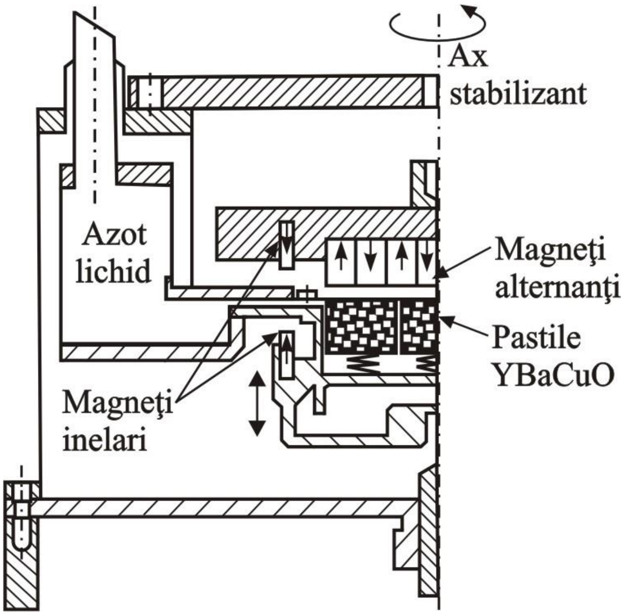

Fig. 2. Inertia flywheel

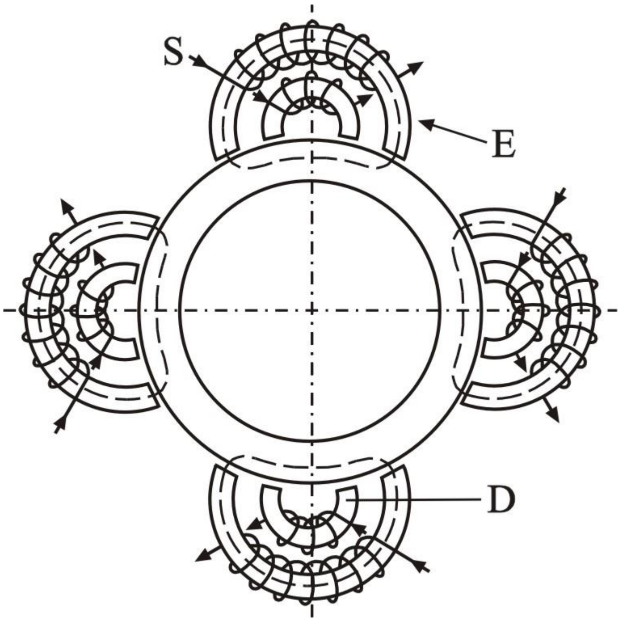

Fig. 3. Radial bearing:
Stator, Rotor, Detector, Electromagnet

The detectors provide electrical voltage (proportional to the variations of the magnetic field due to displacements) which is an error signal and, through an electronic control system, causes the current to change through the electromagnetic windings (and thus magnetic fields that tend to bring the rotor to nominal position). The axial bearing is made on the same principle as the radial bearing, the rotor being formed by a disc in a plane perpendicular to the axis of rotation, in front of which electromagnets are placed (this level acts as an axial counterweight), Fig.4.

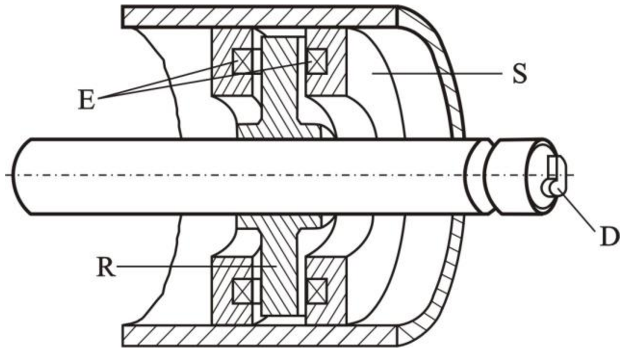

Fig. 3. Axial bearing:
Stator, Rotor, Detector, Electromagnet

Active magnetic bearings are used for both small rotary machines (a few kilograms rotor) and very large machines (several tons of rotors). The range of electrical equipment in which these levels are found is very broad (satellite equipment, high-performance vacuum pumps, machine tools, compressors, fans, turbines, crushers, etc.), being recommended by the following advantages: high operating speed, significant loss reduction, improved yield and energy savings, pollution, since it does not require oil or grease; automatic compensation by rotation around the inertia axis, amortization of aerodynamic instability, simplifying the design and structure of the electric machine, numerical control or adaptive control of machine operation.

III. DISCUSSIONS

The electronic control system controls the position of the rotor by correlating the current in electromagnets with the information provided by the position detectors. The position detector signal is compared to the reference signal, which defines the nominal position of the rotor; if the reference signal is null, the normal position is in the center of the stator. The error signal is proportional to the difference between the nominal and instantaneous positions of the rotor. This signal is processed by an computer that outputs the power amplifier command signal; The transfer function [3] is defined by the ratio of the control and error signals and must ensure that the rotor is maintained in its nominal position and, (when appear a displacement caused by a disturbing force), to put in initial position soon as possible. The control system defines both the rigidity and the amortization of the magnetic levitation.

The power amplifier provides the magnetic field energy to the electromagnets which, through the developed forces, act on the rotor. The power of the amplifier is correlated with the maximum force of the electromagnet and the response rate of the electronic control system to the occurrence of preferences due to a variable load.

The auxiliary bearings support the rotor while the machine is in repose, or if it appears an event at the magnetic suspension problem. These bearings prevent contact between the rotor and the stator, and, implicitly, damage to the magnetic circuits (laminated layers).

The load capacity of the electromagnet is proportional to the inductance and active surface squares. For typical tolerances (3% Fe-Si composition) the induction is limited to 1.5 T, which corresponds to a load force of 90 N / cm3.

The force of an electromagnet has the expression [2]:

$$F = \frac{B^2 S_u}{2\mu_0} \tag{2}$$

where B [T] is the magnetic induction in the air gap, S_u [m^2] - the active surface, and μ_0-magnetic permeability of the vacuum.

In the radial bearing, four electromagnets stabilize the rotor in four orthogonal directions, Fig. 3, each electromagnet being responsible for an area consisting of 90 ° of the active surface:

$$S = \frac{1}{\sqrt{2}} D \cdot \gamma \tag{3}$$

where D is the diameter of the rotor at the air gap and γ is the broad of the magnetic field. The winding of the electromagnet is placed in the stator's ankles, reducing the useful active surface:

$$S = \frac{\sqrt{2}}{3} D \cdot \gamma \tag{4}$$

For the axial magnetic field, Fig. 4, the active bearing surface represents half of the surface area of the disc corresponding to the outer diameter, and the magnetic induction has a value of no more than 1.5 T.

Most of the magnetizing energy is located in the air gap, the rest being in the useful magnetic circuits but also a small part in the leakages [2]. To reduce the power of the amplifier, the air gap should be as small as possible. To determining the size of the air gap, the following aspects are considered: proper operation of the auxiliary bearings requires a minimum play, imposed by rigidity and mounting tolerance and the linearity of converting the power amplifier control signal into force at the magnetic bearing.

Ampère's law applied to the electromagnet circuit has the expression [2]:

$$\sum NI = \sum Hl \tag{5}$$

where N is the number of windings of the electromagnet, I [A] the electric current in winding, H [A/m], the magnetic field strength, l [m] the length of the flow lines.

If the leakage flow is neglected:

$$NI = \frac{B}{\mu_0}\left(2\delta + \frac{L_s}{\mu_{rs}} + \frac{L_s}{\mu_{rr}}\right) \tag{6}$$

where the size of the air gap (0,2 ÷ 1 mm), Lr [m] and Ls [m] - the lengths of the flow lines in the rotor and the stator, respectively, μ_{rr} and μ_{rs} the relative magnetic permeability's for rotor and stator tolerances respectively.

With a small displacement of the rotor in the stator the variation in force is even greater as the air gap is smaller:

$$NI \approx \frac{2B\delta}{\mu_0} \tag{7}$$

With these specifications, the force of the electromagnet gives the expression:

$$F = K\frac{I^2}{\delta^2} \tag{8}$$

where K is a constant.

Derivate $\frac{\mathrm{d}F}{\mathrm{d}\delta} = -\frac{2KI^2}{\delta^3} = -\frac{2F}{\delta}$ defines the negative stiffness (or unstable) of the bearing and causes the control system to be less rigid. The negative stiffness increases with decreasing air gap bearing.

The air gap can be measured with c.a. Wheatstone deck, to which the inductive elements with variable air gap are fixed to the stator. On the machine spindle, at least two opposing elements are required at 180°. The sensing sensors can be individually fixed, or they are part of magnetic laminated layers. On the rotor there is fixed a laminated layers ring, called a reference ring, whose production technology is very pretentious.

The excitation winding is made of a copper conductor whose section is adopted so that excessive heating does not occur with Joule effect.

Stator losses have two components: joule losses in winding and very low losses by switching the magnetic field from one pole to another.

The rotor losses due to the magnetic field switch under each pole include, for a radial bearing, the losses through magnetic hysteresis and the losses caused by the Foucault currents (which have a higher weight); these losses depend on the speed of rotation, the number of poles, the thickness and the quality of the magnetic loops used.

IV. CONCLUSIONS

On a superconducting material located near a permanent magnet exerts a rejection force (Meissner effect). When the permanent magnet is placed above the superconducting material, the magnetic field crosses the superconductor and determines the magnetic flux effect. The magnet and the superconductor are rejecting, but they also attract, the magnet floating steadily over the superconductor (magnetic levitation). The phenomenon due to which superconducting material is held suspended over the magnet is called magnetic levitation.

The magnetic levitation can be realized with passive and active magnetic bearings. Bearings has the advantage of operating without mechanical contact, requires no lubrication, no wear, and friction due to magnetic loss is reduced. Due to the magnetic forces, suspension of moving parts of rotating electric machines requires passive pitching, which combines permanent magnets acting in rejection or attraction; At least for a degree of freedom a control system is required. The complex control systems required for active suspensions can be replaced with hybrid suspensions. As a rule, the active system is used in the axial direction of the rotor.

The use of superconducting materials has enabled the development of new techniques, helping to increase the performance of satellite equipment (inertia flywheel and gyro), magnetic propulsion trains, windmills, machine tools, high performance vacuum pumps, compressors, fans, crushers, turbines etc.

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