Active Magnetic Bearing and Induction Bearingless Machine – A Comparison

José Andrés Santisteban[1], Domingos F. B. David[2] and Richard M. Stephan[3]

Universidade Federal Fluminense – UFF
Rua Passo da Pátria 156 - Niterói - RJ - 24210-240
Dept. of Electrical Engineering[1] – jasl@mec.uff.br
Dept. of Mechanical Engineering[2] – domdavid@netfly.com.br
Universidade Federal do Rio de Janeiro – COPPE/UFRJ
C. P. 68504 – 21945-970 – Rio de Janeiro - RJ - Brazil
Dept. of Electrical Engineering[3] – richard@coe.ufrj.br

***Abstract* – The substitution of mechanical bearings by magnetic bearings has as advantage the frictionless operation, which is desired in high-speed motors or even in slow speed applications where the absence of impurities is necessary. The magnetic bearing technology includes different mechanical and electrical engineering subjects like dynamics, electromagnetism, electric machines, control, analog and digital systems and power electronics. In this work, the conventional radial magnetic bearings are analytically compared with the induction bearingless machine. Some interesting aspects as the effect of misalignment of the rotor in the positioning radial forces will be shown.**

Keywords: Electromagnetic bearing, Bearingless motor.

I. INTRODUCTION

Magnetic Bearings use the levitation principles in order to substitute the mechanical bearings of electric machines. In the last decades different approaches have been designed to attend some particular industrial applications. In all of them, frictionless operation is an important advantage. In high-speed applications, for example, the supervising time interval can be largely extended. On the other hand, although nowadays the initial investment is high, in comparison with other technologies, the future benefit can be compensatory [1]. One of the successful experiences with magnetic bearings is reported in Japan, where two hydro turbines use these devices [2]. It must be said that, in this case, an additional advantage is the absence of oil pollution. Such advantage is also appreciated in medical applications.

I.1 Magnetic Levitation.

To hold a body in the air is an old fascinating idea which means to compensate the gravity force. Among other methods, the use of magnetism has shown feasible but also new challenges have been established [23]. Magnetic levitation can be passive or active. In the first one, permanent magnets, diamagnetic materials or even superconductors are used [3], [4]. In the second one, the electromagnetic principles are used instead. In this case, electromagnets are the base of the operation [5]. Additionally, two approaches can be distinguished. In a case, levitation is obtained after a critical speed of a moving electromagnet (induced currents approach), as used in the Japanese MAGLEV trains [5], and in the other case, the current of a static electromagnet is controlled, as used in the German TRANSRAPID. This work will refer to this last approach.

I.2. The Electromagnetic Bearing

Based on the principles of the magnetic levitation, magnetic bearings are constructed to substitute the mechanic ones of the conventional electrical machines. These have the function of maintain constant the relative position between the rotor and the stator. Depending of its spatial orientation, they can be divided into two types: radial magnetic bearing and axial magnetic bearing. The first one acts along perpendicular axes to the axis of the rotor meanwhile the second acts along the turn axis of the rotor [1]. Analogously to the levitation systems, these can be passives or actives, being that several control techniques are used. In this work the comparisons will be referred to this type of implementation.

The principle of operation of the active levitation when applied to a small ferromagnetic sphere is depicted in Fig. 1. In this illustration, the fixed electromagnet is responsible for the generation of the magnetic flux "ϕ". It has a winding with N turns that when supplied by an electric current of intensity "I" produces the magnetic field intensity "H" (Ampere Law) [22].

This field crosses the fixed areas (primary), the levitated sphere(secondary) and the airgap. A displacement sensor closes the control loop in such a way that the controller generates a reference signal to the current amplifier implemented with power semiconductors.

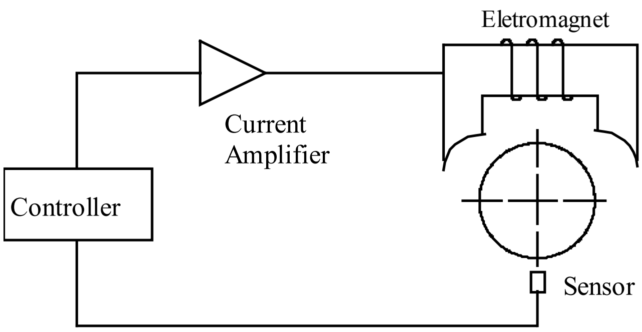

Fig. 1- Operation principle of an active magnetic bearing.

II. THE CONVENTIONAL RADIAL MAGNETIC BEARING.

This device acts along a perpendicular axis to the rotor axis of an electrical machine. Its structure is done such that there is a laminated cylindrical piece, mounted concentric with the rotor axis, where the magnetic flux will cross. Its diameter, larger than the rotor axis, is appropriately calculated. The stationary part, where windings are mounted, is also cylindrical but its internal area possesses curved form in such a way to be able to maintain a constant airgap.

The outline shown in Fig. 2 can be used to deduce the basic equations that describe the behavior of the conventional radial magnetic bearing. The reluctance force between the ferromagnetic pieces possesses the tendency to decrease the airgap "h".

Basic electromagnetism texts (e.g. [22]) demonstrate that the force intensity f_R in each airgap is given by:

$$f_R = \frac{\phi^2}{2\mu_0 A_a} , \tag{1}$$

and the total force f_{RR} acting in the two airgaps is:

$$f_{RR} = 2 f_R = \frac{\mu_0 A_a n^2}{4} \frac{I^2}{h^2} . \tag{2}$$

Where I is the electric current flowing through the n turns of the electromagnet, A_a is the area of the section and μ_0 is the magnetic permeability of the vacuum.

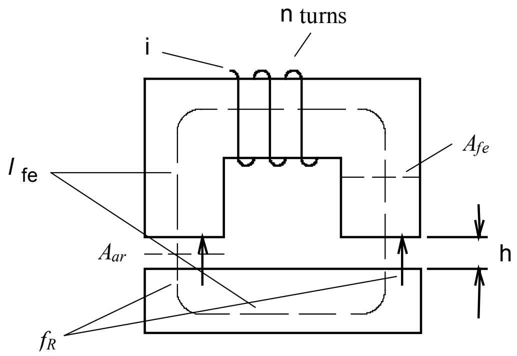

Fig. 2- Conventional Magnetic Levitator.

A real example of application of magnetic bearings is sketched in Fig. 3. It is a vertical rotor operating with three magnetic bearings, two radial and one axial type. This rotor is drived by an induction electric motor. Each magnetic bearing is composed by four electromagnets (Fig. 4), whose stationary parts are built in "U" format and the mobile parts form together a cylinder that rotates concentrically attached to the rotor axis. The electromagnets, positioned symmetrically with respect to the axis of the rotor, operate in the so called differential way, being the supply of the perpendicular radial forces acting on the rotor. The control technique of these forces is described below based in the outline of the Fig. 5.

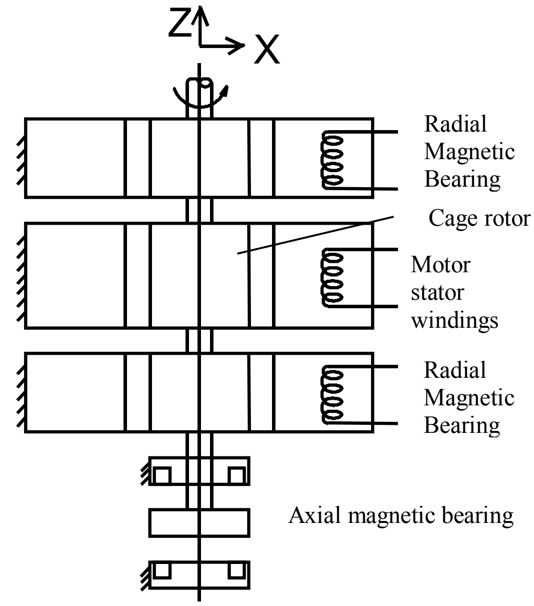

Fig. 3 - Rotor levitation with conventional magnetic bearings.

The forces generated by the electromagnets to the right f_D and the left f_E direction are:

$$f_D = \frac{\mu_0 A_a n^2}{4} \frac{{I_D}^2}{(h-x)^2} \tag{3}$$

$$f_E = -\frac{\mu_0 A_a n^2}{4} \frac{{I_E}^2}{(h+x)^2} \tag{4}$$

The differential strategy consists in supplying each of the electromagnets with a base current I_{C0} and also a differential current I_{Cx}, which is added to the electromagnet located on the side of the positive displacements and subtracted to the opposite electromagnet. So:

$$I_D = I_{C0} + I_{Cx} \tag{5}$$

$$I_E = I_{C0} - I_{Cx} \tag{6}$$

Calling f_{Cx} the net force along axis "x", with (3) and (4) in (5) and (6), then:

$$f_{Cx} = f_D + f_E = \frac{\mu_0 A_a n^2}{4} \left[\left(\frac{I_{C0} + I_{Cx}}{h-x} \right)^2 - \left(\frac{I_{C0} - I_{Cx}}{h+x} \right)^2 \right] \tag{7}$$

In (7) μ_0, A_a, n and h are constants. I_{C0} could also be made constant. If the displacement "*x*" is sufficiently smaller than the airgap "*h*", a linearized form for f_{Cx} around the equilibrium point x=0, I_{Cx}=0 can be deduced:

$$f_{Cx} \cong k_{Cp}x + k_{Ci}I_{Cx}, \quad (8)$$

where:

$$k_{Cp} = \left.\frac{\partial f_{Cx}}{\partial x}\right|_{x=I_{Cx}=0} = \frac{\mu_0 n^2 A_a I_{C0}{}^2}{h^3}, \quad (9)$$

$$k_{Ci} = \left.\frac{\partial f_{Cx}}{\partial i_x}\right|_{x=I_{Cx}=0} = \frac{\mu_0 n^2 A_a I_{C0}}{h^2}. \quad (10)$$

Similarly, along the direction "*y*", the force f_{Cy} will be:

$$f_{Cy} \cong k_{Cp}y + k_{Ci}I_{Cy}. \quad (11)$$

From (10) and (11) f_{Cx} depends only on x and I_{Cx} while f_{Cy} on y and I_{Cy}. This characterize de-coupled forces.

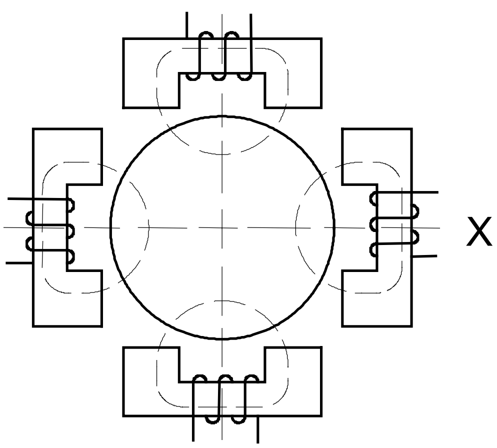

Fig. 4 - Magnetic flux distribution in conventional radial magnetic bearing.

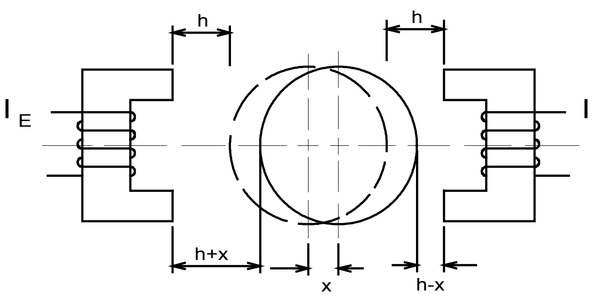

Fig. 5 – Electromagnets operating in a differential way.

III. THE INDUCTION BEARINGLESS MOTOR

The possibility to generate simultaneously torque and radial positioning forces has been reported in several works with different approaches [7],[8],[9],[10]. In Brazil, a particular approach has been developed since a little more than a decade. In this proposal the own windings of a commercial induction motor are used [11], [12], [13], [14], [15].

Among countless configurations of induction motors, the 4 poles two-phase type is of specific interest because its poles are mutually perpendicular (it could also be three-phase type). The simplified outline of its windings is shown in Fig. 6. It has two groups of 4 poles, geometrically separated by 45^o. The actual distribution is shown in Fig. 7. These groups (linked to the phases A and B) are supplied by alternate electric currents of same amplitude; same frequency ω but electrically 90^o out of phase. In this condition, a revolving magnetic field and torque, due to the induced currents in the rotor, are established [16], [17].

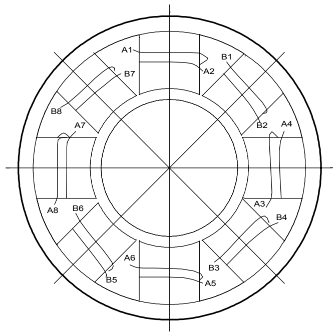

Fig. 6 - Simplified representation of two-phase motor with 4 poles.

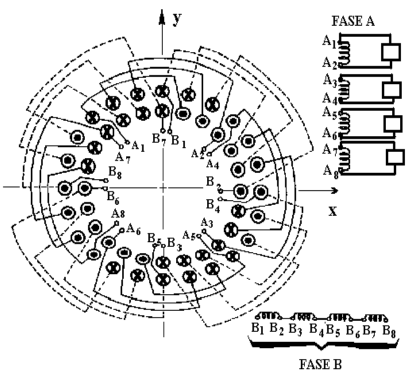

Fig. 7 Windings of two-phase motor with 4 poles.

The magnetic flux linkages just associated to one of the phases of the electric motor and without considering the induced currents of the rotor are shown in Fig. 8. Comparing them with those shown in Fig. 4, it is verified that, in spite of the largest complexity, there exists a similarity among the two configurations, given that in both of them there are four poles aligned with perpendicular directions around the rotor axis. The complexity is due to the fact that each of the four magnetic fluxes in each pole is linked by the windings of the other poles, while in the conventional magnetic bearing, each flux is associated with only one electromagnet (Fig. 5). In this way, the de-coupling discussed previously is loosed.

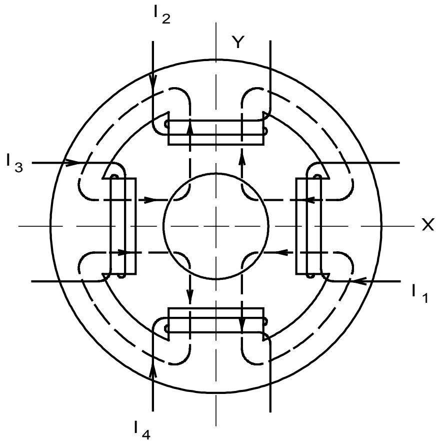

Fig. 8 – Flux linkages associated to the phase A of 4 poles two-phase motor.

Unlike the conventional magnetic bearing, that usually operates with continuous currents, the induction bearingless motor must operate with alternate currents in order to generate torque. Similar to the conventional magnetic bearing, rotor displacements are corrected through modifications of the stator electric currents. The operation strategy consists of maintaining the phase B windings operating in their original way, and to split the phase A in four electric circuits, as indicated in the Fig. 7, what allows the appropriate modification of the amplitude of the pole winding currents. Like the conventional magnetic bearing, the pole windings of the induction bearingless motor are supplied with a differential current strategy as explained before.

So, all phase A windings are supplied considering a base current:

$$i_{0A}(t) = I_{0A}\ \mathrm{sen}\ \omega t\,. \tag{12}$$

And, to the windings 1 and 3, aligned with the direction X, a current $i_x(t)$ is added in the differential way, resulting:

$$i_1(t) = i_{0A}(t) + i_x(t) = I_{0A}\ \mathrm{sen}\,\omega t + I_x\ \mathrm{sen}\,\omega t\,, \tag{13}$$

$$i_3(t) = i_{0A}(t) - i_x(t) = I_{0A}\ \mathrm{sen}\,\omega t - I_x\ \mathrm{sen}\,\omega t\,. \tag{14}$$

In the case of the poles 2 and 4, aligned with the direction Y, a similar procedure is applied.

On the other hand, to the phase B windings, a base current is applied:

$$i_{0B}(t) = I_{0B}\ \mathrm{sen}(\omega t + \pi/2)\,, \tag{15}$$

In balanced operation I_{0A} and I_{0B} amplitudes will usually be the same, however they could also be different, given that an average torque also could be generated in that condition.

As in conventional radial magnetic bearings, forces depend on unbalanced magnetic airgap fluxes, what can be obtained supplying stator currents like that shown in (13) and (14), however, it should be remembered that, with rotor currents, their amplitude will decrease [12], [15]. This fact can be understood looking at the per-phase equivalent circuit of an induction motor (Fig. 9). Imposing a fixed amplitude stator current, the airgap flux will decrease as the rotor current increases. An additional detail is the non-phase characteristic between stator current and airgap current. To put in evidence these facts a factor "r" and an angle "α" will be included in the equations shown below [13].

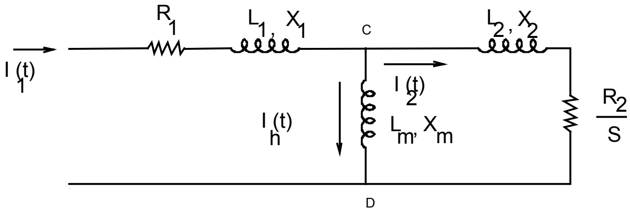

Fig. 9 - Per-phase equivalent circuit of an induction motor

One method to deduce analytically the radial forces is to start from the total magnetic energy stored in the airgap and to derivate it with respect to the displacements "x" and "y", but another alternative is to start directly from equation (1). This was just proved through symbolic simulation [18], [19]. Taking the last method, each pole airgap flux is deduced considering all the instantaneous reluctances in the magnetic structure. Fig. 10 suggests this approach for pole 1.

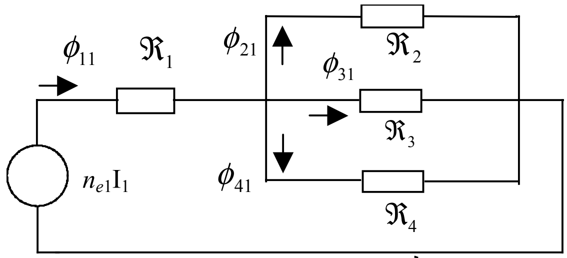

Fig. 10 – Per-pole equivalent magnetic circuit.

With that approach and after linearization, the net force on "x" owing to phase "A" is:

$$\begin{aligned} f_{Ax}(x, I_x) &= k_{Ap}[1 - \cos 2(\omega t + \alpha)]x + \\ &+ k_i[1 - \cos 2(\omega t + \alpha)]I_x \end{aligned}, \tag{16}$$

where:

$$k_{Ap} = \frac{\mu_0 A n_e^2 I_{0A}^2}{h^3} \bullet r^2\,, \tag{17}$$

$$k_i = \frac{\mu_0 A n_e^2 I_{0A}}{h^2} \bullet r^2\,, \tag{18}$$

n_e is the equivalent number of coils which take into account the constructive details of the stator motor, "r" is the correction factor lower than unity that, together with the α angle takes into account the rotor currents and the parameters of the per-phase equivalent circuit of the motor [13], [15].

In this point is important to highlight that the phase B will have an additional contribution [13] in the net force along axes "x' " and "y' " (45^o axis) only owed to displacements (Fig. 11). When this contribution is projected in axes "x" and "y", the final expression of the net force along the axis "x" can be written as:

$$f_x(x, I_x) = [k_{Ap}\{1 - \cos(2\omega t + 2\alpha)\} + \\ + k_{Bp}\{1 - \cos(2\omega t + 2\alpha + \pi)\}]x + \\ + k_i[1 - \cos 2(\omega t + \alpha)]I_x, \quad (19)$$

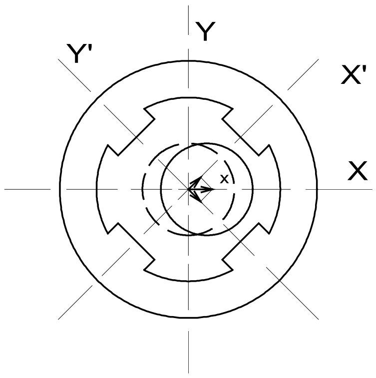

Fig. 11 - Phase B net force due to displacement "x".

where:

$$k_{Bp} = \frac{\mu_0 A n_e^2 I_{0B}^2}{h^3} \bullet r^2. \quad (20)$$

For the particular case: $I_{0A} = I_{0B} = I_0$, (19) changes to:

$$f_x(x, I_x) = k_p x + [1 - \cos 2(\omega t + \alpha)]k_i I_x, \quad (21)$$

where:

$$k_p = k_{Ap} + k_{Bp} = \frac{2\mu_0 A n_e^2 I_0^2}{h^3} \quad (22)$$

Analogously, net force along the axis "y" can be written as:

$$f_y(y, I_y) = k_p y + [1 - \cos 2(\omega t + \alpha)]k_i I_y. \quad (23)$$

Comparing equations (8) and (11) with (21) and (23), we can see that they are similar except by the harmonic components.

Although the complexity, this approach has been experimentally tested using two bearingless induction motor and an axial superconductor bearing as reported in [13], [20] and [21].

IV. CONCLUSIONS

In spite of the largest complexity of the induction bearingless motor, which is shown by analytical equations involving forces, displacements and electric currents, with some restrictions, the perpendicular axes de-coupling is possible, so a simple control system for dynamic stabilization of a levitating rotor can be designed.

While conventional magnetic bearings in steady state refer to continuous current components I_{C0}, I_{Cx} and I_{Cy}, induction bearingless motor refer to I_0, I_x and I_y, which are the amplitudes of sinusoidal alternated currents.

The equations that describe the radial force of an induction bearingless motor are the same except by the harmonic term with twice the feeding frequency ω. Depending on the mechanical structure, such term tends to have its influence decreased as the frequency increases.

The additional factor k_{Bp} tends to decrease the capacity of stabilization of the induction bearingless motor. This has already been experimentally tested [15], what forced to adopt the strategy of use phase B only during the starting.

Even with conventional magnetic bearings, the de-alignment of the rotor of the induction motor is cause of disturbance with continuous and harmonic components as shown in equation (19).

V. ACKNOWLEDGMENT

The authors would like to thank to CNPq and FAPERJ by their support.

VII. REFERENCES

[1] Schweitzer, G., Bleuler, H.,Traxler, A., *Active Magnetic Bearings*, 1 ed. , vdf Hochschulverlag an der ETH Zürich, 1994.

[2] Actidyne®, "Hydroturbines in Japan", The International Magazine of Actidyne® Magnetic Bearings, N^o 5, Maio 1995.

[3] Moon, F. C., *Superconducting Levitation-Applications to Bearings and Magnetic Transportion*, John Wiley & Sons, 1994.

[4] Sheahen, T.P., *Introduction to High-Temperature Superconductivity*, New York and London, Plenum Press, 1994.

[5] Sinha P. K., *Electromagnetic Suspension*, Peter Peregrinus Ltd., London, UK, 1987.

[6] Société de Mécanique Magnétique - S2M, homepage da empresa francesa fabricante de mancais magnéticos, url: http://www.s2m.fr

[7] Chiba, A., Ciba, K., Fukao, T., "Principles and characteristics of a reluctance motor with winding of magnetic bearing", in International Power Electronics Conference, Tokyo, Japan, v.2, 1990, pp. 919-26.

[8] Chiba, A., Power, D.T., Rahman, M.A.,"Characteristics of a bearingless induction motor", IEEE Trans. Magn., v.27, pp 5199-5201, 1991.

[9] Bichsel J., "The Bearingless Electrical Machine", in NASA Conference Publication 3152, part2, 1991, pp. 561-573.

[10] Schob, R., Bichsel, J., "Vector control of the bearingless motor", in *ISMB*, Zürich, 1994, pp. 61-68.

[11] Salazar, A.O, "Uma proposta de motor elétrico sem mancal mecânico", Tese de doutorado, COPPE/UFRJ, Rio de Janeiro, Brasil, Março 1994.

[12] Santisteban, J. A., "Estudo da influência de uma carga torsional sobre o posicionamento radial de um motor-mancal", Tese de doutorado, COPPE/UFRJ, Rio de Janeiro, Brasil, Março 1999.

[13] David, D. F. B., "Levitação de Rotor por Mancais-Motores Radiais e Mancal Axial Supercondutor Auto-Estável",Tese de doutorado, COPPE/UFRJ, Rio de Janeiro, Brasil, Dezembro 2000.

[14] Salazar, A.O., Stephan, R.M., "A bearingless method for induction machines", IEEE Trans. on Magnetics, v.29, no.6, pp 2965-2967, 1993.

[15] Santisteban J. A., Stephan, R. M., Ortiz, A., "Modelling and Analysis of a Loaded Bearingless Machine",. European Power Electronics Journal. England: , v.10, n.1, p.32 - 39, 2000.

[16] Chapman, S.J., *Eletric Machinary Fundamentals*, 3rd Edition, New York, McGraw-Hill, 1991.

[17] Krause P.C. et al, "Analysis of Electric Machinery", IEEE Press, 1995.

[18] Chan B. W. et al., "MAPLE V Language Reference Manual", Springer - Verlag, 1991.

[19] Matlab®, Matlab 5.3.0.10183, 1999.

[20] Nicolsky, R., Gorelov, Y., Pereira, A.S., David, D.F.B., Santisteban, J.A., Stephan R.M., Ripper, A, De Andrade Jr., R., Gawalek,W., Habisreuther,T., Strasser, T., 1999, "Superconducting axial bearing for induction machines with active radial magnetic bearings", *IEEE Transactions on Applied Superconductivity*, v. 9, pp. 964-967, 1999.

[21] Nicolsky, De Andrade Jr, R., Ripper, A, David, D.F.B., Santisteban, J.A., Stephan, R.M., Gawalek,W., Habisreuther,T., Strasser, T, 2000, "Superconducting-electromagnetic hybrid bearing using YBCO bulk blocks for passive axial levitation", *Superconductor, Science and Technology*, v. 13, pp. 870-874, 2000.

[22] Hayt, W.J., "Eletromagnetismo", LTC S.A., 1983.

[23] Salazar, A., O., Chiba A., Fukao T., "A Review of Developments in Bearingless Motors", in *Seventh International Symp. On Magnetic Bearings*, Zürich, August, 2000, pp. 335.