BEARINGLESS MACHINE MODELLING

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***Abstract* – This paper presents a proposal of a bearingless machine that is obtained from a conventional induction machine approaching modifications in system model and in inductance attainment. The utilization of a beringless machine can bring benefits and can be necessary when the bearing is under serious consumption and/or the system is inaccessible.**

***Keywords* - Machine modeling, magnetic bearings, magnetic levitation, winding function.**

I. INTRODUCTION

The bearingless induction machine presents some advantages under conventional machines such as low power losses and absence of vibration. Moreover, it is silent, free of contamination and it has low costs of maintenance.

This paper presents the transformation of a conventional induction machine, with mechanical bearings, into a machine where its rotor radial position can be controlled magnetically.

‘To reach this goal it is necessary to use the machine windings in the radial position control, or either, the magnetic field generated to control the radial position is obtained as a combination from the drive magnetic field without modification in torque.

II. THE MACHINE

The machine tested is a three-phase four-pole induction machine with 1.5kW of power. This machine presents a mechanical bearing only for protection, to avoid the stator being touched by the rotor in starting or in case of control failing.

The studied machine had an alteration in winding to make it possible to implement the radial position control. Both stator and rotor were modified, despite these modifications the induction machine characteristics were not deprived.

The stator machine is divided in two parts, then each phase has two windings what makes possible the radial poisoning control. The winding currents are controlled independently where each is feed by an exclusive inverter. This topology allows the radial positioning control, without the addition of another winding as it is made by [1]. Therefore, the same winding is responsible by driving machine and radial positioning control too, just controlling magnetic fields of divided winding [2].

The four-pole bearingless induction machine flux shows the same characteristics of the conventional machine when the rotor is centered. However, when the rotor is not centered there is a bigger flux line concentration in region that demands a bigger force to reposition the rotor.

There is a weighed division in the winding currents from the same phase and, therefore, when the system is controlling the rotor position, the winding currents from the same phase is unequal, the current is increased in one winding and decreased in the other one, both in the same phase. Then the control increases the force in the biggest air gap direction and weakens the force in opposite direction, but the addition of the currents in the same phase is always the same value, to guarantee the rotating field is not modified.

The Figure 1 shows the stator winding distribution, where **T1** to **T12** are the machine accessible terminal. The blue, green and red windings represent the phase **a**, **b** and **c** respectively.

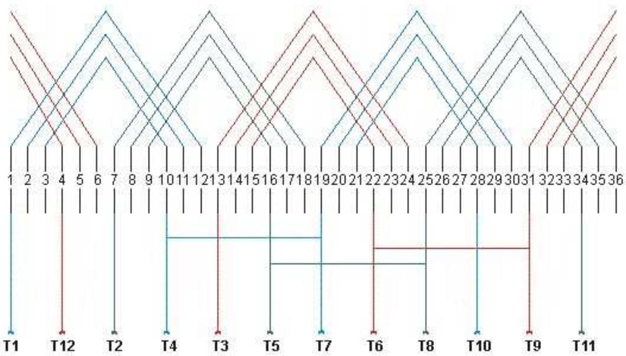

Fig. 1. Stator winding.

A cage rotor is like a “mirror”, if the stator generates two poles of current then in rotor also flows two poles of current. This rotor characteristics is undesired for bearingless machines because there are not only driving currents in the stator, but also the positioning control currents are present. If cage rotor is used in bearingless machine, the positioning control currents that are flowing in rotor induces a decreasing in machine force levels. However, the used rotor [3] also is a “mirror” but only for desired currents in torque generation.

This rotor is short-circuited and it is obtained easily, it is just necessary to wind it adequately.

III. WINDING FUNCTION THEORY

The inductance array of induction machines is known largely, but it is not integrally applicable for bearingless machine. Some features are considered for conventional machines, as all windings have the same characteristics once they are made from the same material and have the same number of turns, the winding spatial distribuition is uniform, the air gap is constant in all radial directions and the generated magnetic field is symmetrical throughout the machine circumference. However, some of these features cannot be applied to bearingless machines. As the rotor is free to move radialy, the air gap is modified according to X and Y rotor displacement (in a perpendicular plan). The flux lines have different densities and paths because the non-uniform air gap in result of the non-constant inductances, which vary according the air gap value.

The bearingless machine model depends strongly of inductances variation that folows radial rotor position. The inductance array calculus is based on winding function theory, which is supported by windings spatial distribution.

The winding function theory is an approach that makes the determination of many parameters, which are involved in electrical machine study easier, such as magnetic field, inductances and torque.

The Theory considers the turn function, which represents the number of windings, those that are carrying positive current between a referential point and an arbitray position point [4]. The turn function is a winding feature and can be obtainde by analysis of conductor's disposal in machine slots.

The winding function is reached from turn function and is defined as shown in (1) for an arbitrary winding Z.

$$N_Z(\theta) = n_Z(\theta) - avg(n_\theta) \qquad (1)$$

Where:

$n_Z(\theta)$ - turn function
avg - average value
θ - arbitrary position in stator.

As for a single case as showed in Figure 2, the stator winding is distributed in four conductors that are spaced equaly on rotor surface what characterizes a four-pole distribution.

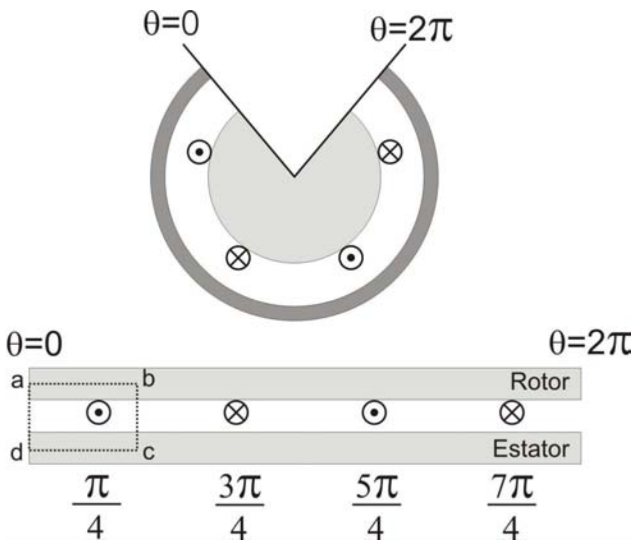

Fig. 2. Exemple of winding distribution.

The current enlaced by closed path **abcd** varies following the angle θ increasing. When the angle θ is smaller than $\frac{\pi}{4}$ (for instance) no current is enlaced by the closed path **abcd**, however when angle θ has a value between $\frac{\pi}{4}$ and $\frac{3\pi}{4}$ the closed path **abcd** involves a total current that is not zero. This is used to determine the turn function.

It is important to observe the turn function mean is not the same for the non-uniform air gap [5].

IV. INDUCTANCES

The winding function present in (1) is valid when the rotor is centered. For application in bearingless machine the equation for winding function is

$$N_Z(\theta) = n_Z(\theta) - \frac{\int_0^{2\pi} n_Z(\theta)P(\theta)d\theta}{\int_0^{2\pi} P(\theta)d\theta} \qquad (2)$$

Where (1) is a particular case of (2). The function $P(\theta)$ is air gap inverse function and is defined as

$$P(\theta) = \frac{1}{g_0}\left(\frac{1}{\sqrt{1-\delta^2}} + \frac{2}{\sqrt{1-\delta^2}}\left(\frac{1-\sqrt{1-\delta^2}}{\delta}\right)\cos(\alpha-\gamma) + \frac{2}{\sqrt{1-\delta^2}}\left(\frac{1-\sqrt{1-\delta^2}}{\delta}\right)^2 \cos(2\alpha-2\gamma) \right) \qquad (3)$$

Where

α - reference angle from stator
g_0 - air gap when rotor is centered

$$\delta = \frac{\sqrt{x^2+y^2}}{g_0}$$

$$\gamma = \begin{cases} \operatorname{arctg}\left(\frac{y}{x}\right) & \text{for } x \le 0 \\ \operatorname{arctg}\left(\frac{y}{x}\right) + \pi & \text{for } x < 0 \end{cases}$$

The Figures 3, 4 and 5 show the winding function when the rotor is centered, when the rotor is displaced +40% in axis Y and when the rotor is displced -60% in axis X, respectively.

The indexes a1, a2, b1, b2, c1 e c2 refer to windings 1 and 2 from phases a,b e c.

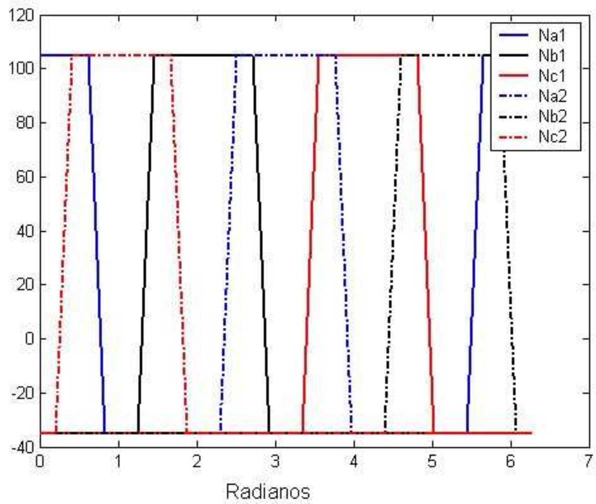

Fig. 3. Stator winding function for centered rotor.

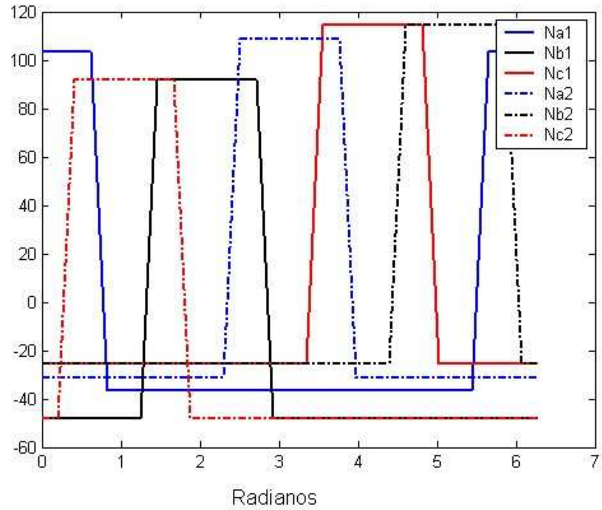

Fig. 4. Stator winding function for rotor displaced +40% in axis Y.

Considering the winding function theory, the magnetic field can be expressed as

$$H_Z(\theta)=i_z N_Z(\theta)P(\theta) \tag{4}$$

and the linkage flux is

$$\lambda_Z(\theta)=rl\int_0^{2\pi} n_Z(\theta)B_Z(\theta)d\theta \tag{5}$$

Where:

$B_Z(\theta) = \mu_0 H_Z(\theta)$
r - Rotor radius
l - Rotor package length

Then

$$\lambda_Z(\theta)=rl\mu_0 i_Z\int_0^{2\pi} n_Z(\theta)N_Z(\theta)P(\theta)d\theta \tag{6}$$

Therefore self-inductance is defined as

$$L_{ZZ}(\theta)=\frac{\lambda_{ZZ}}{i_Z}=rl\mu_0\int_0^{2\pi} n_Z(\theta)N_Z(\theta)P(\theta)d\theta \tag{7}$$

and the mutual inductance is defined as

$$L_{ZW}(\theta)=\frac{\lambda_{ZW}}{i_W}=rl\mu_0\int_0^{2\pi} n_Z(\theta)N_W(\theta)P(\theta)d\theta \tag{8}$$

The Figures 6 and 7 show how the self-inductances vary according to rotor displacement in X and Y axis respectively. The Figures 8 and 9 show the mutual inductances related to centered rotor and rotor displacement of +40% in axis Y respectively.

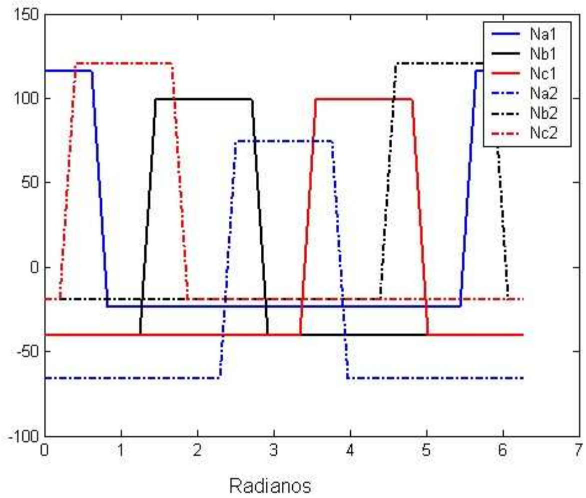

Fig. 5. Stator winding function for rotor displaced -60% in axis X.

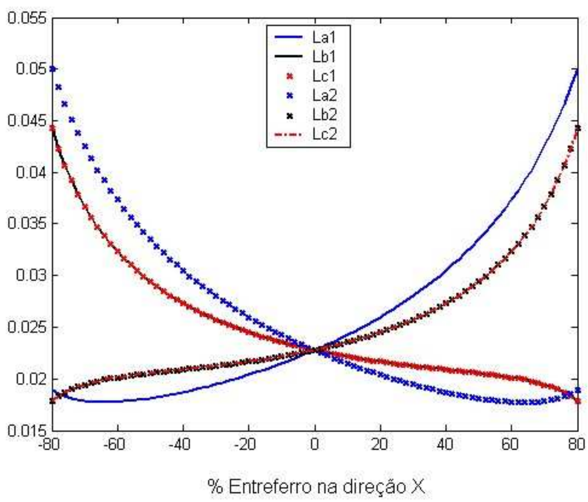

Fig. 6. Stator self inductance related to rotor displacement in axis X.

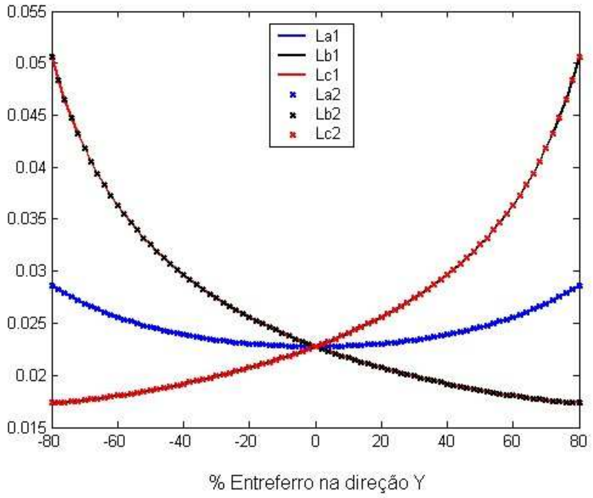

Fig. 7. Stator self inductance related to rotor displacement in axis Y.

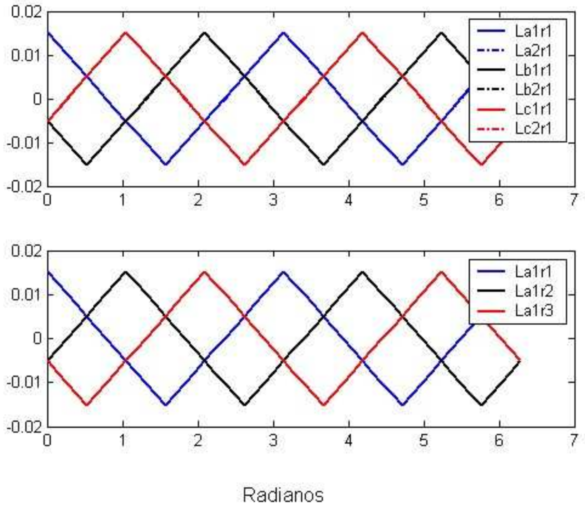

Fig. 8. Mutual inductances between stator and rotor related to centered rotor.

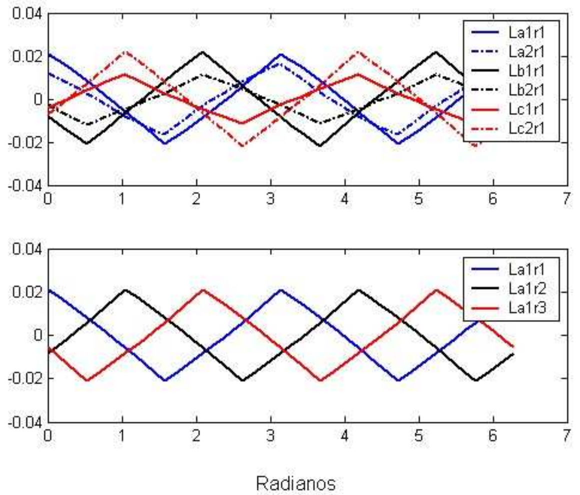

Fig. 9. Mutual inductances between stator and rotor related to rotor displaced +40% in axis Y.

V. RESULTS

The results obtained from the bearingless machine have shown that a machine model based on inductances calculated using winding function theory are in accordance to physical machine features.

The Figures 10 and 11 show a comparison between calculated (based on model) and measured parameters. The torque is presented in figure 10, where the acquired value has a dynamics close to the calculated from the model. The same occurs in Figure 11 with the mechanical speed. Both figures were obtained under positioning control working.

The Figure 12 present a comparison between calculated an measurd torque, in the moment of rotor displacement, the torque only varies when the rotor is displaced and comes back to normality when control is on operation, at least the rotor weight in axis Y needs to be compensated. This shows the torque does not change because current variation, it only is disturbed when air gap is modified.

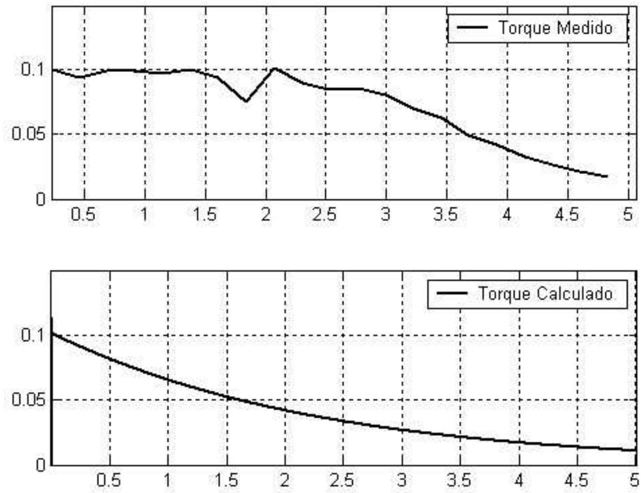

Fig. 10. Comparison between measured and calulated torque (Nm x seconds).

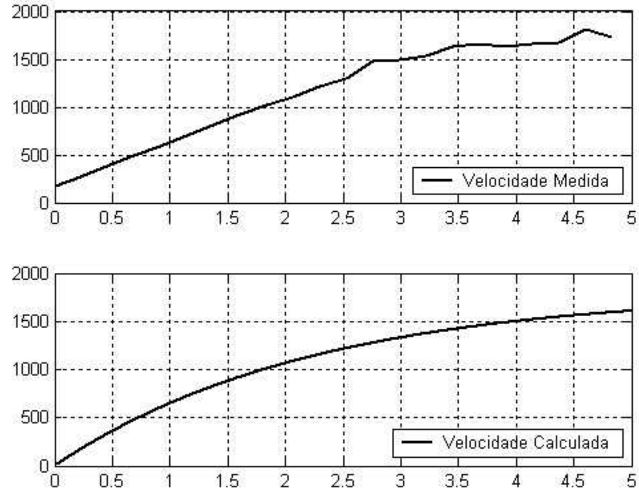

Fig. 11. Comparison between measured and calulated machanical speed (RPMx seconds).

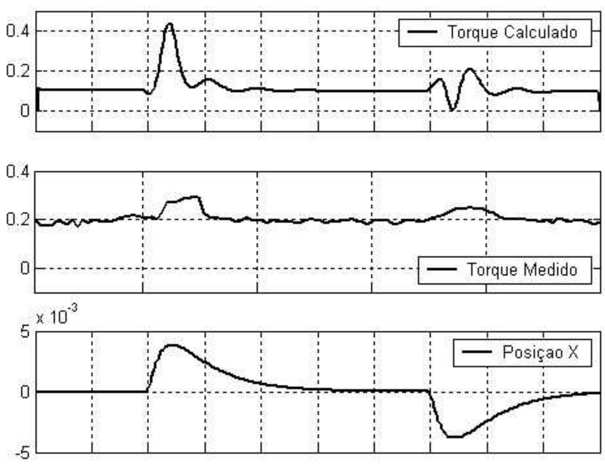

Fig. 12. Comparison between measured and calulated torque related to rotor displacement in axis X (Nm x seconds).

VI. CONCLUSION

The bearingless machine is an efficient alternative when there is accessibility problem for the maintenancy. However, its application sholud be anylised carefully because it implies increased costs for machine control.

The obtained model shows the bearinless machine has the same behavior of the conventional machine when the rotor is centered and it is in accordance with references and experimental results when the rotor is displaced.

Positioning control works modifying the current value and this does not affect the torque. It is just modified when the rotor is displaced, therefore, when the positioning control does not work.

This paper has shown a way to obtain a bearingless machine from a conventional induction one. The main modifications in the machine model also was discussed and experimental results were in agreement with anylised theory.

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