A Bearingless Machine - An Alternative Approach

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Abstract: This work presents the analysis, synthesis and implementation of an alternative kind of bearingless machine that find application in industrial processes where vertical motor disposition and low torque requirement are needed. This proposal uses the own conventional electromagnetic machine structure to obtain simultaneously forces for rotation and radial positioning through the superposition of currents imposed by power electronic inverters to the stator windings. Analog and digital controllers were used to test a prototype. This solution has the same advantages of commercially available magnetic bearings and additionally calls for less space. Experimental results show the validity of the methodology and control method used.

1 Introduction

The bearingless machine, due to its characteristics of no mechanical contact, absence of lubrication system and ability to operate at high velocities, has application in many industrial areas: turbomachinery, pumps, flywheels, machine tools, aerospace and physics [1].
A conventional magnetic system has the basic structure shown in Fig. 1. It is constituted by four blocks: the conventional machine, two radial active bearings and a longitudinal thrust bearing. In this work, two smaller conventional machines and a thrust bearing, as shown in Fig. 2, are proposed as an alternative system. Each machine does simultaneously two functions: torque generation and active bearing, but unlike other methods [2,3,4] that use separate windings for position and rotational control, in this proposal, the own stator windings are employed. In [5,6,7] an analog control based on this approach was previously published and here, results of an advantageous digital version are presented.

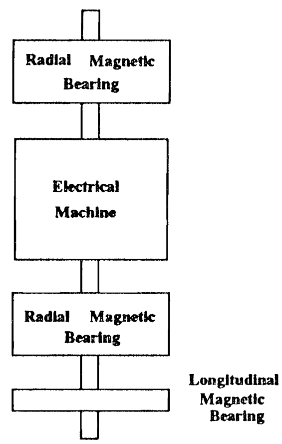

Fig.1 Conventional system with magnetic bearings.

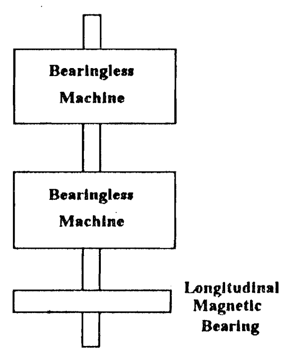

Fig.2 System with two bearingless machines.

2 Machine Structure

In order to probe this approach, a vertical 4-pole, 2-phase squirrel cage induction machine, as shown in Fig. 3, was used as one of the bearingless machines. At the bottom side, a mechanical bearing simulates the bottom unit and the longitudinal thrust bearing of Fig. 2. An auxiliary mechanical bearing in the top of the shaft is present for an eventual mechanical, power or control system failure. The stator A phase is split in four windings as it is depicted in Fig. 4, each one supplied with a MOSFET current-regulated voltage source inverter. In fig 5, the actual field distribution of the centered machine is shown. The B phase is also split in four windings but connected in series and supplied with a fifth inverter.

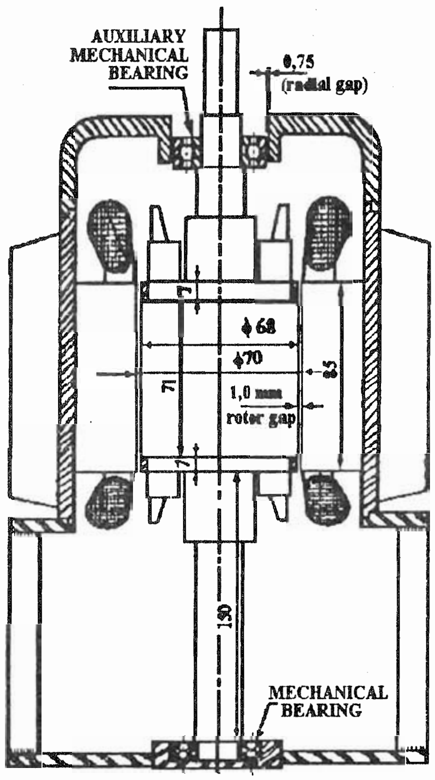

Fig.3 Mechanical structure of the machine.

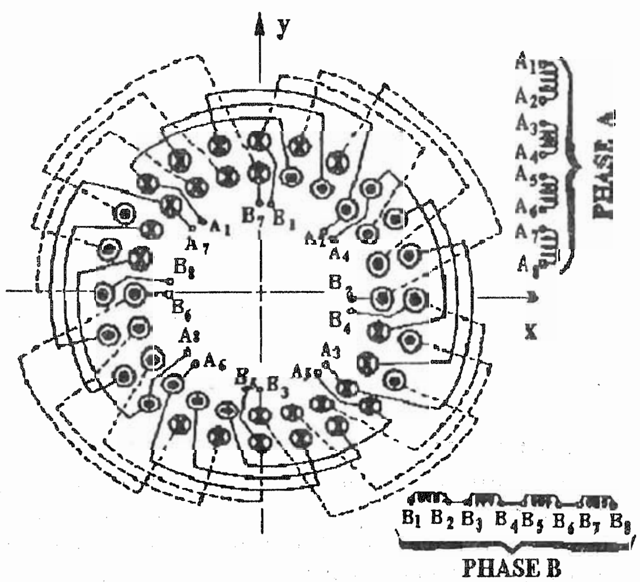

Fig. 4 Stator windings of the induction machine.

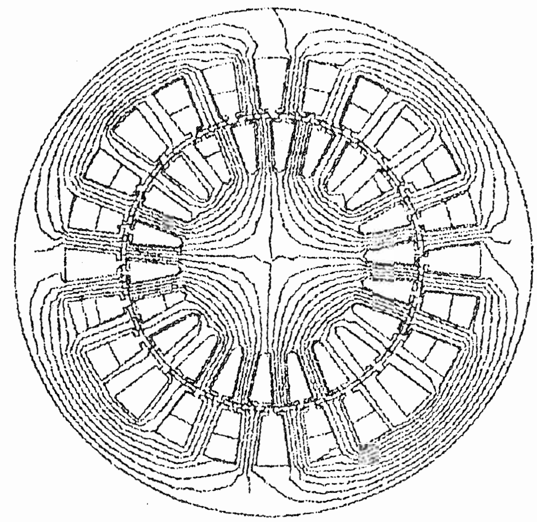

Fig. 5 Field distribution.

3 Operation Principle

With low load, slightly radial deviations of the rotor and saturation, it can be shown [5,6,7] that the radial positioning forces on the rotor depend only on the four windings of phase A. Thus, for each winding on orthogonal directions *x-y*, forces F_x, F_y can be approximated as:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} \partial W_m / \partial x \\ \partial W_m / \partial y \end{bmatrix} = \begin{bmatrix} \frac{1}{2} i_x^2 \, \partial L_x / \partial x \\ \frac{1}{2} i_y^2 \, \partial L_y / \partial y \end{bmatrix}, \tag{1}$$

where W_m stands for magnetic energy, L_x, L_y inductances and i_x, i_y the winding currents.
In this equation L_x and L_y depend on the type of machine and so F_x and F_y.
Thus, for an induction motor, with L_o and L_1 constants and g as the main air gap length, inductances can be approximated as:

$$L_x = L_o + L_1 / (g+x) \tag{2}$$

$$L_y = L_o + L_1 / (g+y) \; . \tag{3}$$

Next, imposing sinusoidal currents $i(t)=I_{max}\cos(\omega t)$, radial forces take the form of eq. (4) below:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} \frac{1}{4} I_{max}(1-2\cos 2\theta)[L_1/(g-x)^2] \\ \frac{1}{4} I_{max}(1-2\cos 2\theta)[L_1/(g-y)^2] \end{bmatrix}. \tag{4}$$

The second harmonics in (4) do not produce average radial forces and are absorbed by the rotor mass. Then the amplitude of I_{max} can control the position of the shaft.

With opposite windings with current amplitudes given by:

$$I_{x1} = I_{max} + \Delta I_x \quad (5)$$

$$I_{x2} = I_{max} - \Delta I_x, \quad (6)$$

the linearized transfer function between displacement and current variation will be:

$$G(s) = \frac{\Delta x(s)}{\Delta I_x(s)} = \frac{K_i/m}{(s^2 - K_x/m)}, \quad (6)$$

where K_i and K_x are constants that depend on the system operating point. As it is known, a PD controller can stabilize this system.

4. System implementation.

In Fig. 6 the block diagram of the experimental system is shown. Current references are obtained with help of two 90 degrees shifted sinusoidal signals whose default amplitude, I^*_{maxo}, set the system stiffness. Phase A amplitude is further modulated through the closed loop position control. In the analog version, discrete circuits were used to implement the two Proportional Derivative controllers for the orthogonal radial displacements. Meanwhile, in the digital version, a PC\AT 486 with two acquisition boards was used. An external board that performs analog addition, multiplication and generation of the fundamental frequency of the winding currents was implemented . With this configuration one saves one D/A converter and gives more free time to the microcomputer.

4.1 Displacement sensors

In order to sense the displacement of the rotor shaft, an array of hall-effect devices was used in the analog version while optical devices were used in the digital version. In both cases, linear behavior near the operation point guaranteed a good performance of the system. In Fig. 7 and Fig. 8 details of the array of infrared optical sensors are depicted. It can be shown that for little variations around the desired position, a differential mode arrangement of these non-linear devices gives an acceptable linear behavior [9].

4.2 Controllers

Theoretical analysis around the desired operation point, gives a linear model that shows that a PD regulator is quite sufficient to get a stable system, however, this approach doesn't consider some facts such as the rotational or unbalance effects as is reported in practical implementations [10]. This fact calls to modify the regulator parameters while the system is running, that is, adaptation of the control parameters. With the digital approach this possibility can be attended.

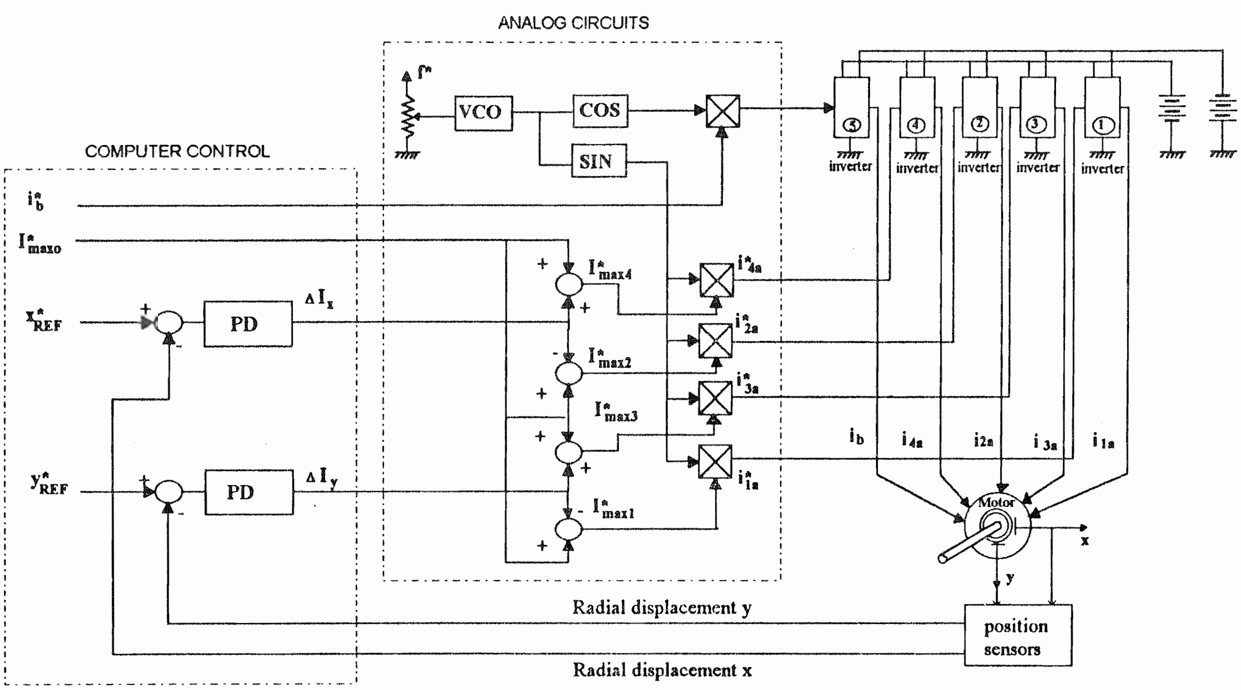

Fig. 6 Block diagram of the bearingless machine system

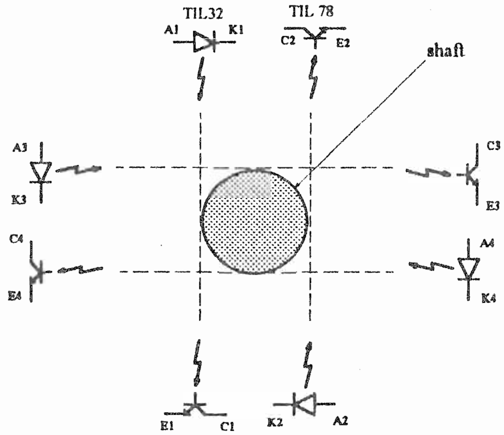

Fig. 7.- Spatial distribution of the infra red position sensors.

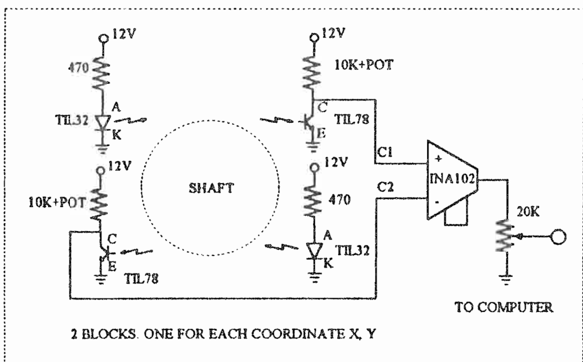

Fig. 8.- Position detector circuit.

5 Experimental Results

The start up is realized supplying initially phase A at 60 Hz, a pulsing field is established and the positioning requirements attended. After that, phase B is made active with low current, enough to initiate the rotation. At steady-state speed, either biphase or monophase operation is possible. Further speed increment is obtained through frequency variation using the VCO in Fig. 6.

In the following figures some experimental dynamic responses of the system are shown. Fig. 8 shows the step responses for each axis from -0.3mm to 0.3mm, with the motor running at 1500 RPM. Fig. 9 corresponds to the case when the motor is running at 2100 RPM and Fig. 9 when the motor is running at 2700 RPM. In all cases, time test was 2 seconds and speed is near supply frequency because there was only the inertial load in the shaft. In all these tests, the parameters of the regulators were appropriately adjusted while speed motor was continuously increasing.

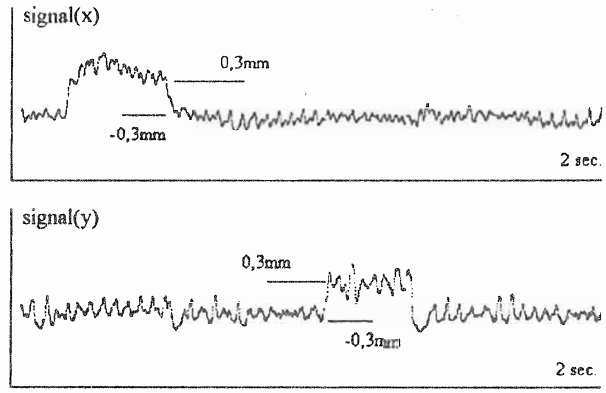

Fig. 9.- Step responses while motor is running at 1500 RPM. Supply frequency is 50 Hz.

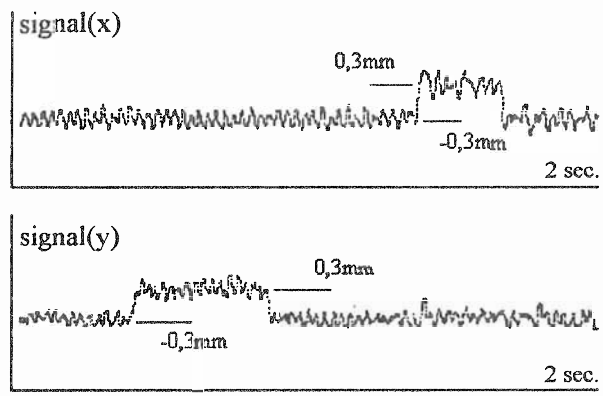

Fig. 10.- Step responses while motor is running at 2100 RPM. Supply frequency is 70 Hz.

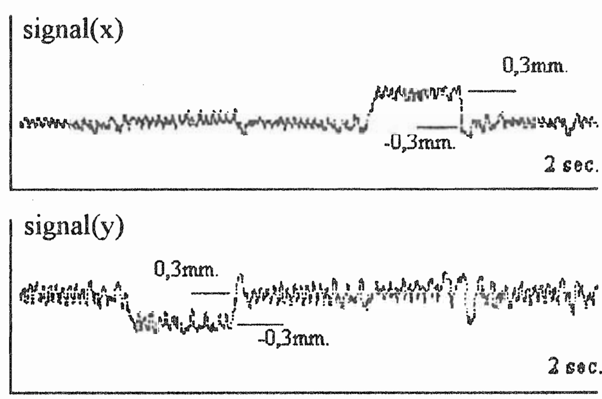

Fig. 11.- Step responses while motor is running at 2700 RPM. Supply frequency is 90 Hz.

6 Conclusions

An alternative approach of a bearingless machine was presented. The advantages of the digital version respect to the analog one were emphasized. An experimental array of optical sensors showed their good feasibility. Dynamic results showed the validity of the use of the own stator windings to get positioning and rotation forces. The laboratory prototype used for the experimental results was a 2-phase machine but the operation principle can be applied to 3-phase machines as well.

Acknowledgments

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