Vectorial Speed Control using a Flux Estimator for Bearingless Machines with Divided Windings

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Abstract – **This work describes the Vectorial Speed Control System of a triphasic bearingless induction machine with divided windings of 1.1 kW. The control strategy used in this system is the quadrature vectorial control. To implement the control algorithm, was chosen the rotor flux referential, which is being estimated through the stator winding currents and the rotor speed. The vectorial speed controller operates in synchronism with the radial positioning controller, but these controllers should work with low mutual influence. The control system is being implemented in a 16 bits DSP (Digital Signal Processor), which operates at 40 MHz. The algorithm was developed in the ANSI C language.**

Index Terms – **Vectorial, Control, Bearingless, Machine, DSP.**

I. INTRODUCTION

The induction machines are robustness and presents low costs of operation. But, they ones still need several periodic maintenances for replacement, mainly the machine bearings.

With the purpose of minimizing the mechanical waste of the induction machines, have been proposed some special machines that use the rotor magnetic levitation as basic principle to substitute the mechanical bearings. The radial positioning is done by the stator field control to maintain the rotor axis centralized.

Together with the radial position control, it is necessary to make the torque control by the stator currents.

To accomplish these tasks, some induction machines models are proposed. One of models is the machine with independent windings, where there is one two pole winding for the radial positioning control and other four poles winding for the rotational torque control[1]. In this case, these machines need a special stator to allocate the two windings sets.

Another constructive model is the bearingless induction machine with divided windings [2][3], which uses the same four poles windings to implement the radial positioning control and the speed control. This machine model allows the use of the conventional induction machines stators. This proposed model minimizes the project and the manufacture costs.

This paper describes the vectorial speed control stage for a triphase bearingless induction machine with divided windings of 1.1 kW.

In this work is being used the quadrature vectorial control technique. This strategy facilitates the implementation of motors drive control in DSPs (Digital Signal Processor).

To implement the speed control is necessary to do the rotor flux position and magnitude estimation due to this variable presents a difficult measurement, mainly in this machines type.

All control system is being implemented in a 16 bits DSP which operates at 40MHz, and the programming is made in ANSI C language with fixed point.

This work also analyzes the influence of radial positioning control on the vectorial speed controller.

II. DESCRIPTION OF THE BEARINGLESS INDUCTION MACHINE

The used bearingless induction machine has the stator structure similar to the conventional induction machines. This characteristic facilitates the manufacture process of this constructive model and, consequently, its costs will be reduced.

The main purpose is to use a single winding set to apply the vectorial speed control synchronized to the radial positioning control.

The bearingless machine constructive model presents two independents stators and two rotors. The rotors are coupled by a longitudinal axis[4].

The machine's structure is shown in the Fig. 1.

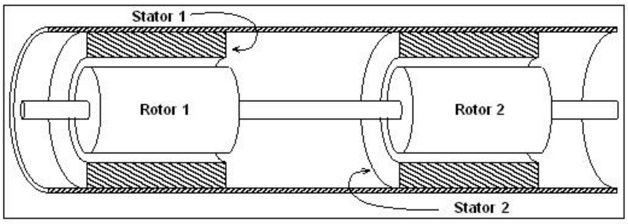

Fig. 1 Structure of the bearingless induction machine with divided widings.

This structure allows the rotor radial positioning control in six possible directions and it is equivalent to two conventional induction machines coupled by the axis[5][6].

The radial controllers in the several directions operate independently to maintain the rotor always centralized. This task is accomplished by individual current controllers in each winding set. The resulting currents produce internal fluxes which generate forces able to compensate the possible rotor displacements.

Each phase of the machine has two winding sets. The windings structure is showed in the Fig. 2. This model results in a four poles machine.

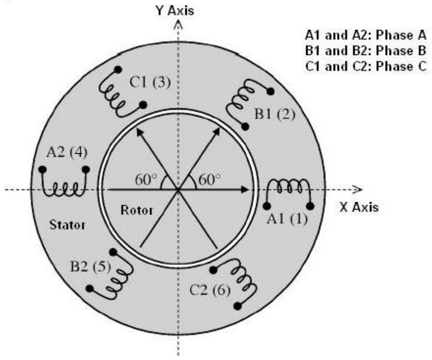

Fig. 2 Stator winding sets structure.

Each winding set in this structure is drived by six independent currents controllers, which are implemented digitally.

The used rotor in this machine is based on the special model proposed in [7].

This rotor model minimizes the induced currents influence over the radial positioning during the torque control application and it provides a better internal flux distribution inside of the machine. This rotor model is used to get a decoupling among the speed vectorial controller and radial positioning controller.

The representation of the one circuit is shown in the Fig. 3.

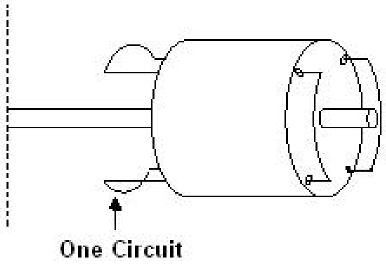

Fig. 3 Representation of the one rotor circuit.

The bearigless induction machine designed in this work uses two identical rotors composed by 12 closed electric circuits disposed in 48 slots forming four poles. The rotor winding distribution is shown in the Fig. 4.

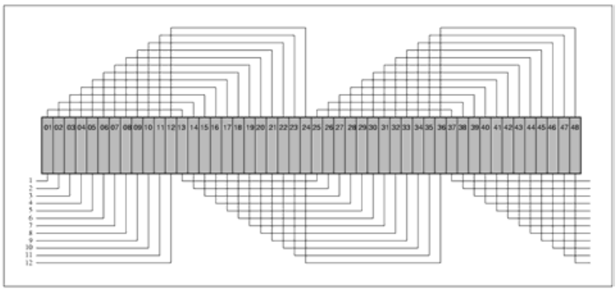

Fig 4 Rotor winding model proposed with 12 isolated circuits.

III. VECTORIAL MODELING

All the vectorial control techniques need the exact rotating field positions and magnitudes to execute the control with minimum slip and high torque. However, the flux sensors are expensive and sometimes, the machine's structure don't allow the installation of them. In this way, it´s necessary to accomplish the flux estimation through the electric induction machine model in a specific referential.

In this work, was chosen the rotor flux reference to run the vectorial speed control. This referential minimizes the computational effort requested to execute the estimation algorithm by DSP device, due to this model needs only the values of the instantaneous stator currents and the rotor speed value.

For the rotor flux estimation, is being used the vectorial model of conventional induction machine which is described for the following equations[8]:

$$\frac{di_{mR}(t)}{dt} = \frac{i_{sd}(t)}{T_R} - \frac{i_{mR}(t)}{T_R} \tag{1}$$

$$i_{mR}(t+h) = i_{mR}(t) + h.\frac{di_{mR}(t)}{dt} \tag{2}$$

$$\frac{d\rho(t)}{dt} = \omega_{mec}(t) + \frac{i_{sq}(t)}{T_R i_{mR}(t)} \tag{3}$$

$$\rho(t+h) = \rho(t) + h.\frac{d\rho(t)}{dt} \tag{4}$$

$$m_M(t) = k.i_{mR}(t) i_{sq}(t) \tag{5}$$

$$k = \frac{2}{3}(1-\sigma)L_S \tag{6}$$

where h is the integrative step, $i_{mR}(t)$ is the magnetizing current, $i_{Sd}(t)$ e $i_{Sq}(t)$ are the Park currents, $\rho(t)$ is the rotor flux position, $mM(t)$ is the electric torque, $\omega_{mec}(t)$ is the rotor mechanical speed, T_R is the rotor time constant, L_s is the stator inductance and σ is the leakage factor.

IV. SYSTEM DESCRIPTION

The vectorial speed control stage is being developed together with the radial positioning controller and the current controllers, both already implemented in DSP[9].

The Figure 5 shows a block diagram of the proposed system[10].

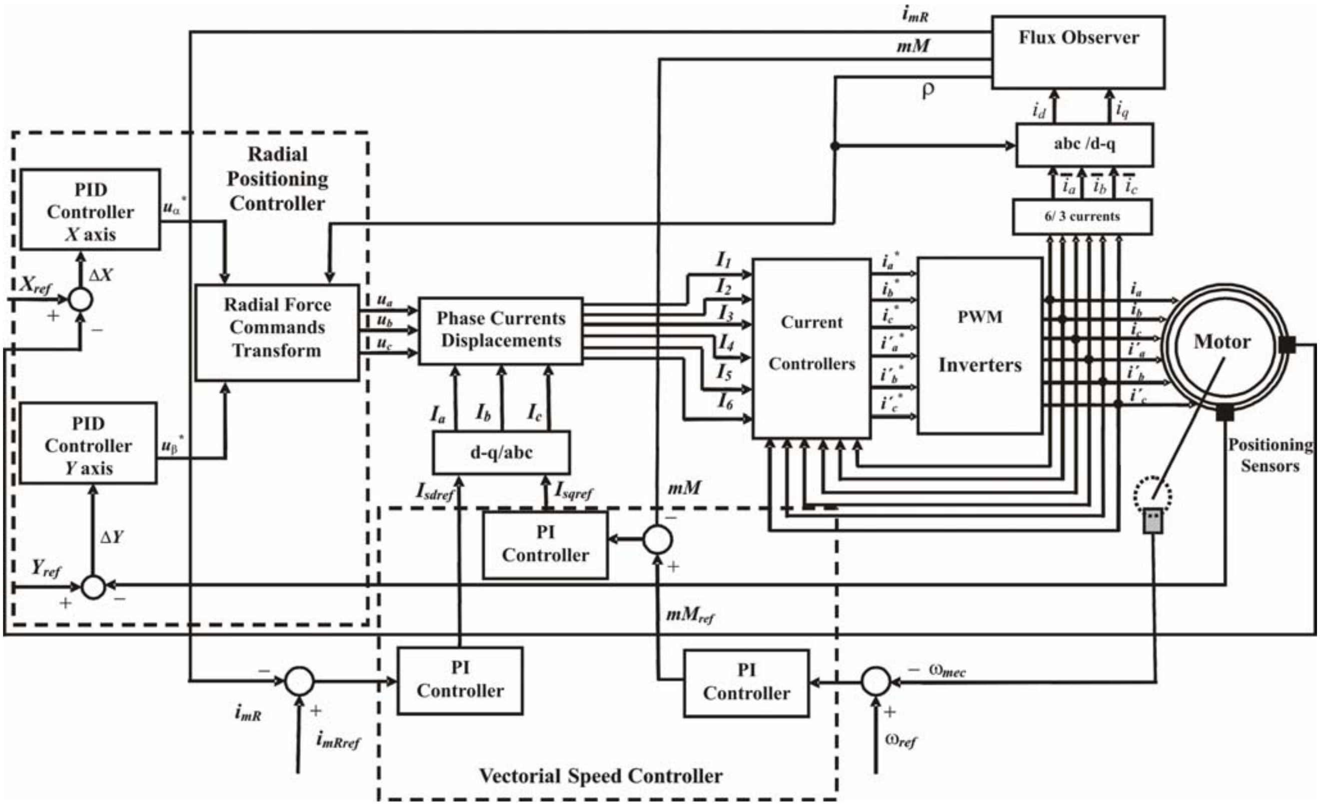

Fig. 5 Control system Diagram.

The speed controller is composed by tree PI (Proportional-Integrative) type controllers, which apply the flux control and the rotational torque control. These two controllers must to operate decoupled.

The radial positioning controller is composed by two PD(Proportional-Derivative) type controllers.

The command signals u_x and u_y from positioning controllers are transformed in rotational commands u_α and u_β, as is described in (7). This transformation is modulated by the rotor flux angle ρ.

$$\begin{bmatrix} u_\alpha^* \\ u_\beta^* \end{bmatrix} = \begin{bmatrix} sin(\rho) & -cos(\rho) \\ -cos(\rho) & -sin(\rho) \end{bmatrix} . \begin{bmatrix} u_x \\ u_y \end{bmatrix} \qquad (7)$$

Another transformation is necessary to change the commands signals u_α and u_β to the *abc* coordinates. This transformation is showed in (8).

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} u_\alpha^* \\ u_\beta^* \end{bmatrix} \qquad (8)$$

These transformations are represented by the block named “Radial Force Commands Transform”, into the control System diagram.

The command signals u_a, u_b and u_c are added in one direction and subtracted another from the reference currents I_a, I_b and I_c, respectively. These operations are presented in (9).

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} = \begin{bmatrix} I_a + u_a \\ I_b + u_b \\ I_c + u_c \\ I_a - u_a \\ I_b - u_b \\ I_c - u_c \end{bmatrix} \qquad (9)$$

These unbalanced currents try to compensate the position displacements.

To complete the system, were implemented six independent PI (Proportional-Integrative) type current controllers which are applied in the bearingless machine windings.

The controller’s settings were made independently, but the global system behavior was adjusted in real time mode.

The driver stage in the proposed system is composite by the six independent PWM inverters operating at 10kHz. This switching frequency generates interrupts of 100μs and this timer is used to run the control algorithm.

The rotor speed is read by the optical sensor. Its digital signal is sent to DSP, where the number of pulses is transformed in a RPM speed value to be used in the control algorithm.

V. THE CONTROL ALGORITHM

The control algorithm is showed in the Fig. 6.

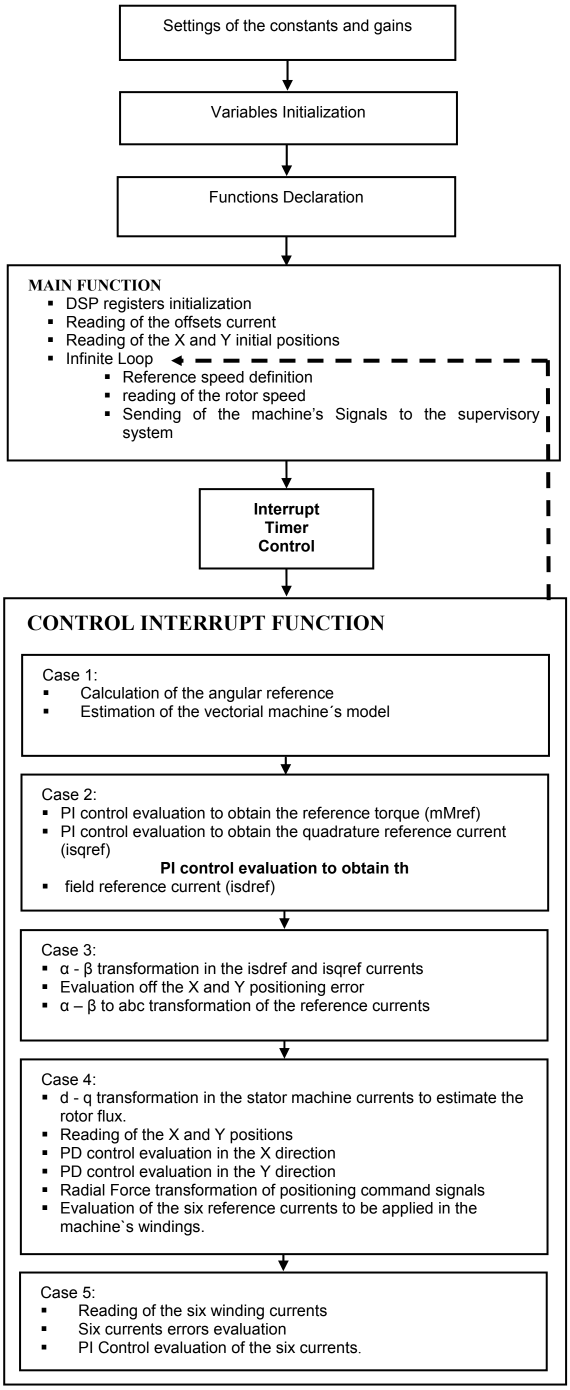

Fig. 6 Diagram of the control algoritm.

This algorithm is divideded in six parts. The first part of this algorithm executes the main function in ANSI C language. The main function is responsible to execute the following tasks: the registers configuration, the initial signals reading, the speed reference definition, the continuous rotor speed reading and the internal signals sending to the supervisory system.

The five remaining parts are distributed inside of the interruption function. This function is responsible several actions as the estimation of the rotor flux speed, the reading of the X and Y signals positions, the reading of the stator winding currents, the rotational transformations in the currents, the rotational transformations in the position displacements, and still executes the vectorial speed control, the radial positioning control and the current control.

Each part of the interrupt function is executed during the interval between two interruption signals, resulting in a total sapling and control cycle of 500 μs.

The presented control algorithm was developed with the purpose of maintaining a low coupling among the radial positioning control and the vectorial speed control. Like this, each controller can be adjusted individually.

VI. EXPERIMENTAL RESULTS

After the practical implementation of the proposed system, were obtained some important experimental results. These results show the behavior of the vectorial speed control operating together with the radial positioning control.

The following results demonstrate that the system is viable under certain conditions and they still allow a more specific analysis of the speed control influence over the radial positioning control.

VI.1. RADIAL POSITIONING

The first results of the radial positioning were obtained through the positioning sensors signals in the X and Y directions. The rotor behavior is shown in the Fig.7.

This figure presents: the orbit limits of the rotor axis which is represented by the circle, a central orbit area represented by the gray trace and the instantaneous position of the rotor axis, represented by the black trace.

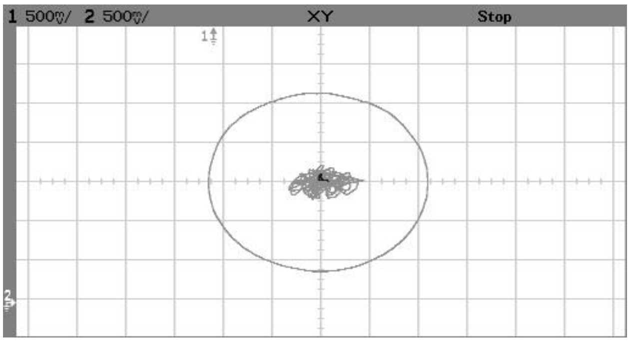

Fig. 7 Rotor axis behavior when the radial positioning control is applied during the motor acceleration (0.25mm/Div).

This rotor behaviour was captured during the ramp aceleration in steps of 50 RPM. The applied reference speed range was of 100 RPM up to 1800 RPM.

This result demonstrates that the rotor stay inside of the central area when submitted to the radial positioning control, even under variation of speed.

With this result, it is proven that the system can operate efficiently with the controllers operating in a synchronized way.

VI.2 VECTORIAL SPEED CONTROL

The results of the vectorial speed control are shown in the Figs. 8 and 9, respectively.

The Fig. 8 presents the reference speeds behavior ω_{ref} in a ramp of 100 RPM up to 1800 RPM and the respective rotor mechanical speed ω_{mec} during the acceleration.

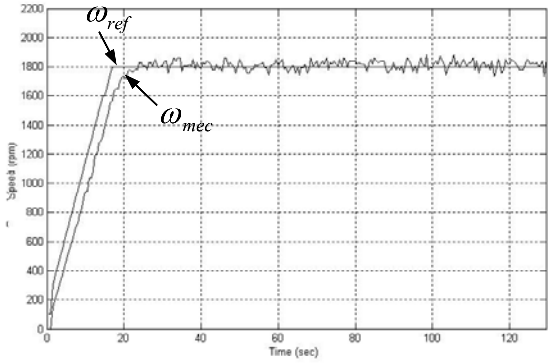

Fig. 8 Speed behaviour of the vectorial controller.

In spite of the noises generated by the speed sensor, this result shows a good response of the vectorial speed control during the acceleration and during the steady state too.

The result presented in the Fig. 9 shows an initial reference speed variation in a ramp form of 100 RPM up to 1800 RPM and later, is applied alternative ramps among 1800 RPM down to 1200 RPM in intervals of 25 seg.

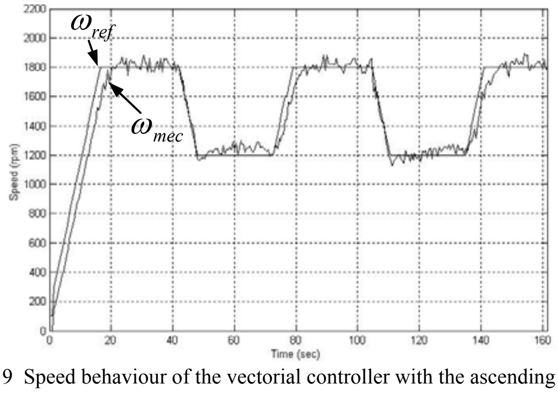

Fig. 9 Speed behaviour of the vectorial controller with the ascending and descending ramps.

This result also demonstrates that the rotor mechanical speed ω_{mec} follows the reference speed efficiently.

All the presented results were monitored by the supervisory system, which was developed in a PC computer and operates in real time mode.

VII. CONCLUSIONS

After the first experimental results obtained, were observed some aspects that will be used in the control system improvement.

The main aspect to be considered in the system improvement is the influence of the vectorial speed controller over the radial positioning control. This influence is significative during the abrupt reference changes. This fact forced to establish maximum and minimum limits values to the reference currents. Like this, it is only possible to consider the positioning system stability inside of the small accelerations ranges.

During the general system development was also observed a significant dependence of the global system behaviour in relationship to used DSP. The used DSP is relatively slow, and the control program is large. These system characteristics generate the necessity of the future DSP substitution.

The noisy signal from the optical speed sensor generates measurement mistakes. These mistakes influence the system performance. In this way, a stable sensor is required for this application.

In spite of the practical limitations imposed by the system components, it can be proven the viability of the vectorial speed controller operating together with the radial positioning controller.

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