Review of Control Strategies and Model Estimation Techniques applied to Bearingless Induction Machine with Divided Winding

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Abstract

The bearingless induction machines exhibit significant nonlinearities, creating the need for implementation of control systems that combine the classic control techniques with modern model observers. Aiming to contribute to the development of new systems, this paper presents an overview of the main control and estimation strategies implemented in laboratory using the induction bearingless machines with divided winding, highlighting the advances and difficulties arising from these type of systems.

1 Introduction

The bearingless machines operates as an induction motor and as a magnetic bearing too, acting on the rotor levitation. This feature reduces the mechanical losses by friction and minimizes the number of machine maintenance. In recent decades, several machine models have been proposed. Among them, is possible to highlight the stator models with double winding and divided winding (Salazar, Chiba, & Fukao, 2000) (Suzuki, Salazar, & Chiba, 2000). Coupled with the development of these machines were implemented control system and estimation strategies acting on the radial positioning, torque and current control (Kauss, Gomes, Stephan, & David, 2008) (Paiva, Salazar, & Maitelli, 2010) (Rodriguez & Santisteban, 2011).

In order to discuss and collaborate with the development of the others levitation systems with induction machines, this paper presents a review of implemented works on the bearingless induction machine with divided winding using different estimation and control techniques.

2 Windings Configuration Types

The bearingless machine operation can be explained by Figures 1 (a) and 1 (b). In these figures, is represented a double winding machine model, being a two-pole windings N_{2a} and N_{2b} to the radial position control in the X and Y directions, respectively, and a four-pole N4 winding to the torque and speed control.

Initially, with no-load conditions, if there is a rotor axis displacement in the negative X-direction, must feed the coil N_{2a} and N_4 according to the direction shown in figure 1 (a) adding the fluxes ψ_{2a} and ψ_4 on the right side and decrease the flux density on the left side, generating a force $\vec{F}$ in the positive direction. Similarly, for a rotor axis displacement in the positive X-direction, the current in the coils N_{2a} must be reversed as shown in Figure 1 (b) to add the fluxes ψ_{2a} and ψ_4 on the left side and a decrease in the flux density on the right side, generating a force $\vec{F}$ in the negative direction of the X direction to centralize the machine axis. The radial positioning control in the Y direction is done in an analogous manner by the current control on the coil N_{2b}.

The principle of operation presented for the double winding model can be extended to all models of bearingless machine. For this, it is necessary to control the distribution of internal fluxes according to the winding configurations of the proposed machine model.

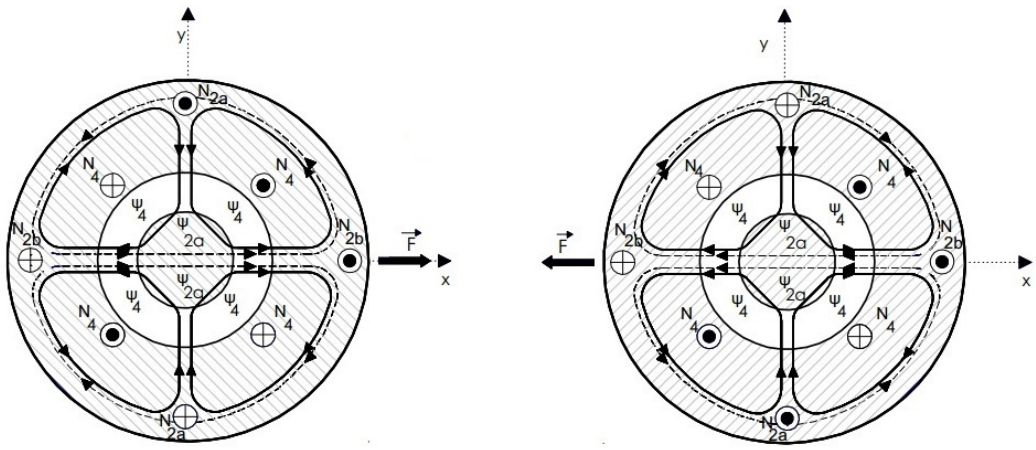

Figure 1 – Principle of radial force generation to bearingless induction machines.

The main implemented systems and application using the Induction Bearingless Machines basically use two different models. Among the researches currently developed, we highlight the model of two set winding and the model with divided winding, as described in the following subsections.

2.1 Two set winding model

The two set model of bearingless induction machine allows the speed and radial positioning controls separately. For this, the stator has a set of two poles to control the radial positioning and other set of four poles windings to speed control (Salazar, Chiba, & Fukao, 2000) (Suzuki, Salazar, & Chiba, 2000). The structure of such a wound is shown in the Figures 2(a) and 2(b).

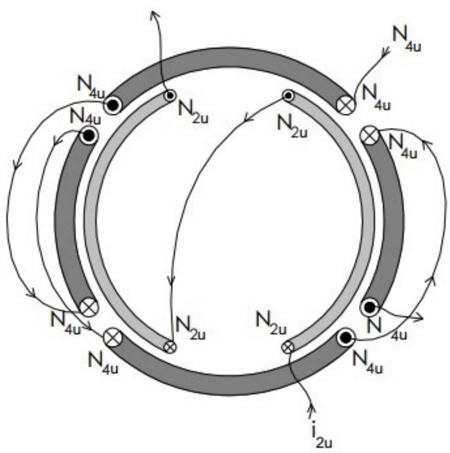

Figura 2. The two winding set model

Spite of facilitate the rotation and radial positioning control operating in uncoupled mode, this configuration requires the construction of special stators with to allocate the individual sets of windings. This characteristic increases the cost for large scale production of these machines.

2.2 Characteristics of Bearingless Machine with Divided Winding

Searching for minimizing manufacturing costs, The bearingless induction machine whit divided winding uses a conventional stator to generate radial forces associated with the torque and speed control. (Salazar, Chiba, & Fukao, 2000) (Ferreira & Salazar, 2007). The circuit diagram of this winding type is shown in Figure 3.

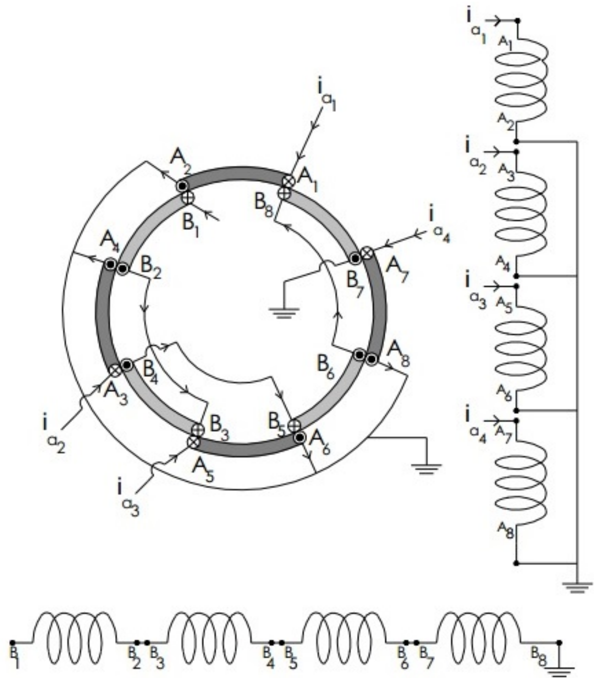

Figura 3. The divided winding set model.

The operation of this machine model is based on the unbalanced phase currents to compensate the rotor shaft displacements. This operation can be represented by the following equations:

$$I_{A1}=i_A + \Delta i_A \quad (1)$$

$$i_{A2}=i_A - \Delta i_A \quad (2)$$

$$i_{B1}=i_B + \Delta i_B \quad (3)$$

$$i_{B2}=i_B - \Delta i_B \quad (4)$$

$$i_{C1}=i_C + \Delta i_C \quad (5)$$

$$i_{C2}=i_C - \Delta i_C \quad (6)$$

This machine is a four-pole model which operates inducing currents in the same number of rotor poles. With unbalance the stator currents, conventional rotors such as the squirrel cage rotors have the speed control hindered due to the unbalanced components for controlling the radial position.

Aiming to minimize the influence of the induced currents by the higher order torque frequency components in the radial forces, a rotor with optimized windings, whose bars were independent circuits (Paiva, Salazar, & Maitelli, 2010), as shown in Figure 4.

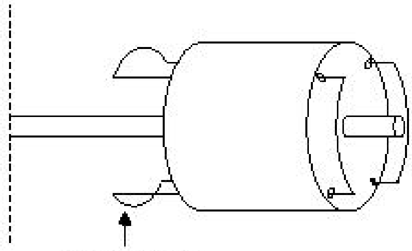

Figura 4 – Special rotor with optimized winding model.

The two winding set and the divided winding set models have in common the need to use a control strategy that includes the nonlinearities of these machines and also reach the desired performance, either during transients and in steady state. Furthermore, is desired that speed and radial positioning control operating in uncoupled mode to wide ranges even with the application or load variation on the machine´s shaft.

Presently, research developed with the conventional induction machines using high performance techniques for controlling the torque and speed of these machines. This goal has been achieved by using the vector model of induction machines that approximates the model of these machines to the DC motor (Leonhard, 1988).

Considering the constructive similarities between the conventional induction machines with the bearingless induction, some control systems based on vector modeling presented as a viable option because of its advantages over scalar control methods.

Over the last decade, several studies using vector control were implemented with significant results (Paiva, Salazar, & Maitelli, 2010) (Rodriguez & Santisteban, 2011). Nevertheless, one of the requirements of vector control is the precise angular flux position, because all model variables depend on this information. This requirement leads to the need to use sensors or flux estimator.

Due to the difficulty of allocation of these sensors and their high cost, a viable alternative is the use of vector estimators based on the machine inverse model or even in non-linear models based on modern techniques such as Artificial Neural Networks among others.

The following sections present and discuss the various aspects of control and estimation systems already implemented using bearingless machines with divided winding to contribute to the development and optimization of new control systems of control that, in general, can be extended to other machines types.

3 Estimation and Control Techniques applied to the Bearingless Induction Machine

The bearingless machines present significant nonlinearities. For this reasons, several systems have been implemented and are still under development using advanced techniques of estimation and control.

The firsts implemented systems to radial and speed control associated to flux estimation based on the machine's parameters had been used classic control strategies as, for example, the PI (Proportional Integrative), the PD (Proportional Derivative) and the PID (Proportional Integrative Derivative) controllers to the currents, radial positioning and torque loops control (Paiva, Salazar, & Maitelli, 2010) (Rodriguez & Santisteban, 2011).

In general, the most common elements used in the control systems of the bearingless machines are shown in the block diagram of Figure 5. The difference between the various systems already implemented is the choice of control strategies and estimation techniques to be applied. This choice takes into consideration factors such as: the type of application for which the machine will be used, the performance limitations found in other similar systems, the processing capacity control devices used and the machine model to be adopted (two set winding model or divided winding model).

In these schemes, elements as speed sensors, position and radial currents send information to their respective control loops that must act to maintain the radial positioning synchronized with the speed and torque control loops.

The use of vector modeling generate the use of modeling vector generates the need to obtain the exact position of the rotating field, which can be obtained by estimators. These estimators can be based on inverse machine model or any strategy based on artificial intelligence such as Artificial Neural Networks (ANNs) among others. These strategies, generally, allow the joint operation with the classic controllers like P, PI and PID type or still using some modern control strategies as the robustness controllers. The versatility from this model system is only possible due to its implementation in programmable devices such as DSPs (Digital Signal Processors) which, allow easy comparison and performance optimization between various types of controllers and also between different estimation techniques. However, it is essential that the digital device resources are compatible with the system controllers and estimators to be implemented. Thus, while the device choosing it is necessary to observe some characteristics as processing capacity, arithmetic data (fixed or floating point) type, memory capacity, number of Analog/Digital channels, number of PWM outputs, number digital capture channels and serial ports among others. This choice influences significantly the system performance, especially when the type of estimators or controllers to be implemented requires high processing capacity.

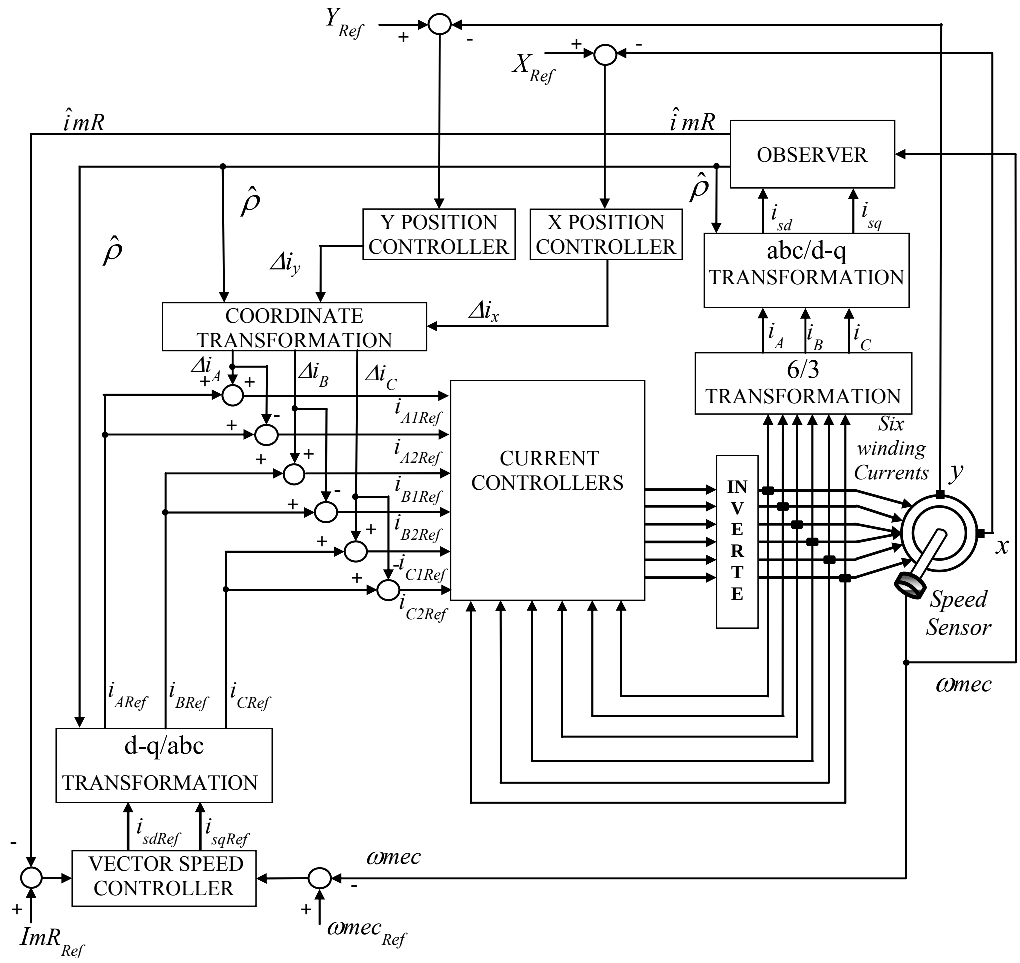

Figure 5 – General Scheme of control system to the bearingless machine using a flux estimator.

In recent decades, important control systems applied to the induction bearingless machines were implemented aimed at improving the speed and radial positioning performances. In Wang and Liu (2010) proposes a system-oriented vector control for rotor flux seeking compensation for delays and errors generated by the rotor currents in the radial position. The simulation results show the reduction of coupling of suspension forces F_X and F_Y.

Rodrigues and Santisteban (2011) propose a new system guided by air-gap flux which takes account the changes of magnetic energy. In this work, we propose also an automatic correction of the angular flux orientation. The presented results show the effectiveness of these techniques for a wide operation range.

Other systems implemented in the laboratory provide important strategies to radial positioning control in order to optimize the performance of systems implemented in DSP.

In Kauss (2008) are presented aspects of modeling and implementation of a digital controller Decentralized Linear Quadratic (LQRd) which is an adaptation from the LQR strategy. The results presented show that the performance of the controller LQRd performance is superior to traditional PD controller. Thus, the proposed controller can be viewed as a PD controller optimized. Thus, the proposed controller can be seen as a PD controller with optimum parameters choice.

The following section presents an example of comparative performance of the system implemented in Paiva, Maitelli and Salazar (2010).

4 Results and Analysis Examples

The first results of the several implemented systems showed good behaviors in limited operating points. This fact generated the need for uses of some advanced estimation techniques as the Artificial Neural Networks (ANNs) combined with the cited classics controllers among others (Paiva, Salazar, & Maitelli, 2010).

As an example of implemented system, the results shown below compare the performance of bearingless Induction machine with divided winding using estimator based on ANNs versus the same system using conventional observers. The Figure 6 shows the behavior of the mechanical speed and position signals also in the X and Y directions subjected to an acceleration ramp. The motor parameters measured in the laboratory are: nominal power 1,1, kW, nominal speed w_{nom} = 1800 rpm, nominal voltage V_{nom}=220V, nominal current I_{nom}=1A, stator resistance R_S=4.5853W, rotor resistance R_R=32.0894W, stator and rotor inductance L_S=L_R=459.6mH, magnetization inductance L_M=278.6mH, pole par number p=2, inertia moment J=6.06.10-3 kg.m^2 and dispersion fator σ=0.1.

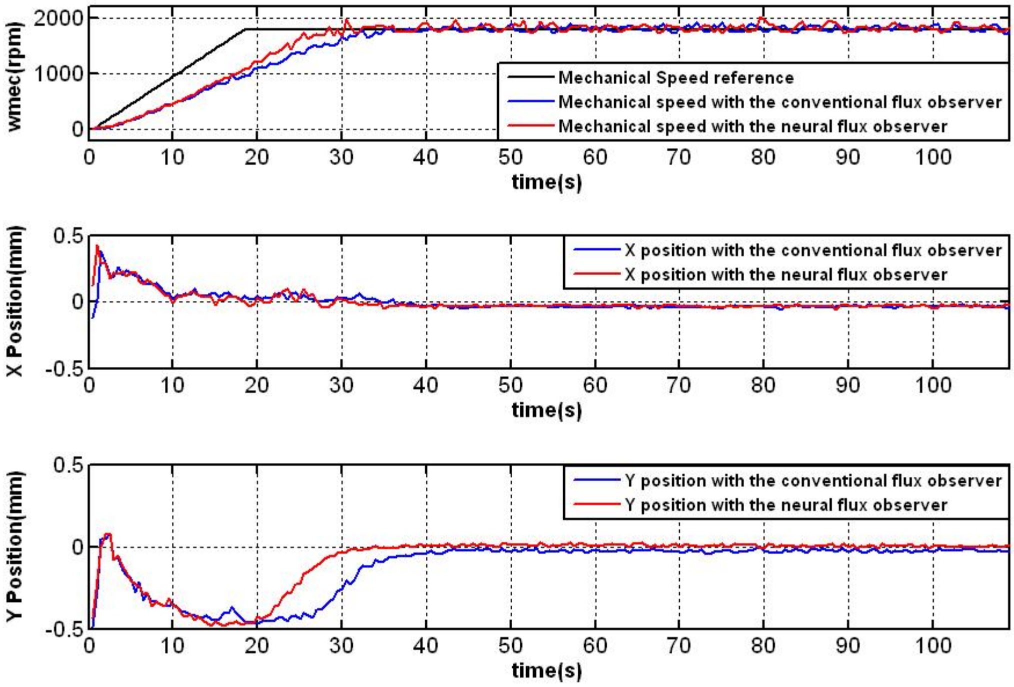

Figure 6 – Comparative analysis of speed and radial positioning responses with the system guided by conventional and neural estimators.

In the Figure 6, a performance comparison is made with the system implemented using conventional estimator based on the vector model and the same system using a neural estimator. It is observed that the system behaves much smoother when using Neural estimator. This is due to the feature adaptation of neural networks to nonlinearities of induction machines without bearings.

As result of the soft radial positioning, the Figure 7 shows the behavior of the radial position machine under the ramp presented in Figure 6.

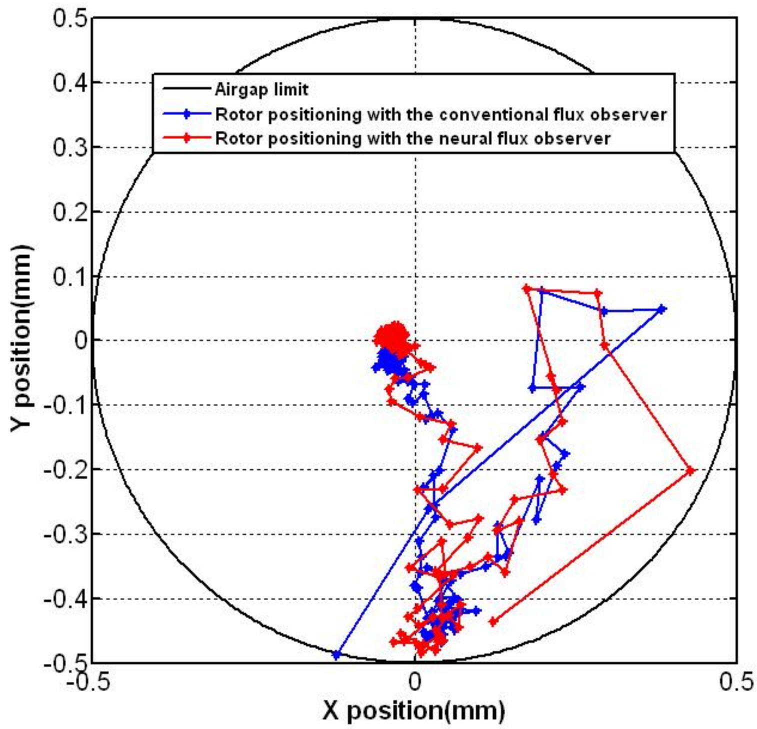

Figura 7 – Response to mechanical speed ramp and to position X and Y.

In Figure 7, is observed that the radial positioning error is significantly smaller during the system operation oriented by the neural flux estimator.

An important characteristic of this system type is the possibility of joint operation of classic controllers like P, PI and PID guided by estimators based on Artificial Intelligence.

Following this trend, other systems are being proposed using techniques based on artificial intelligence. Among the new options are estimation systems with ANFIS architecture, which aims to combine the advantages of artificial neural networks to fuzzy inference systems.

The constructive imperfections presented by the prototype used in the example difficult significantly the system performance. To resolve this limitation of constructive order, Victor (2012) propose the adaptation of a conventional induction motor of four-pole and twelve terminals to be used as bearingless machine with divided winding. Laboratory tests proved the possibility of using this type of machine.

Therefore, it is necessary to reconfigure the connection of the stator windings replace the conventional mechanical bearings by other smaller bearings allowing the rotor magnetic levitation and changing the connections of the rotor circuits according to the model shown in Figure 3.

This modified machine model perfectly serves the objective of reducing the manufacturing costs of bearingless induction machine with split winding and increases the range of application possibilities due to its availability in the market.

Spite of all the progress made with this type of model, its operation is still limited because of some problems such as the electromagnetic torque losses due to the unbalance of the phase and its small load capacity among others.

5 Conclusion and Perspectives

The first applications with the bearingless induction machine with divided winding using advanced estimation and control strategies proved the high feasibility and potential of these techniques for this type of machine (Paiva, Salazar, & Maitelli, 2010). Currently, several systems are being developed using techniques as robust control combined with the RNA and the Fuzzy logic systems.

However, this type of machine also has serious physical limitations such as low electromechanical torque generated due to the imbalance of currents, unsatisfactory performance at low speeds and low bearing capacity to ensure the desired radial positioning.

Finally, all these features create the need for research expansion in the area to facilitate the use of these machines on a large scale. For this it is essential that other control and estimation strategies other techniques are proposed and tested for the resolution or minimization of these limitations imposed by these type of machines.

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