Simulation of a Neurofuzzy High Speed Estimation Applied to Magnetic Bearing Systems

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Abstract: The tendency to build light and high-speed rotors, to achieve a high performance of the machine, has as consequence a possible interaction between the rotor and its stator. During this interaction, the friction between the rotor and its stator, and the high energy of the former, can produce very complicated dynamical behavior. During contact the high energy of the rotor, which is dissipated by the frictional force, can severely damage both parts [1].
Estimating the rotor speed is an important task in conventional asynchronous motors. The elimination of the mechanical sensor as an encoder or a tachometer reduces the cost, improves the precision and the reliability of the whole system.
Magnetic bearings systems always use a velocity sensor. In the case of failure of this sensor, rotor speed estimation could be used, in order to bring the rotor to still stand in a safety away, avoiding the situation mentioned above, therefore, the contact between the rotor and its retainer bearings.
Several techniques are available in the literature for estimating the rotor speed of asynchronous motors. Recently, soft computing techniques are carried out to cover this proposal. The adaptive neuro-fuzzy inference system (ANFIS) technique has been successfully applied to estimating the speed of a conventional asynchronous motor.
This work presents a simulation of a neuro-fuzzy speed estimator for a high speed asynchronous motor within a magnetic bearing system. As mentioned, the reliability of the system can be increased.

Keywords: Neuro-Fuzzy, Speed Estimation, Magnetic Bearings, Safety

Introduction

For many years several research institutes and industries have been working in strategies of driving the induction motor (IM) in a high performance context. These researches have been focusing in new control strategies, modeling of the machine, estimation techniques as new materials and assembly methods as well.

When high performance is required vector control of the IM is required. Several control techniques have been proposed in the literature for years. The most stressed of them are the Field Oriented Control (FOC) and the Direct Torque Control (DTC). In FOC vector control [2], the torque of the machine is controlled in an indirect way. The main characteristic of this kind of control is the decoupling of the flux and torque components of the space phasor of stator currents.

When this kind of control is applied to a motor, which rotor is coupled in a shaft supported by magnetic bearing, safety aspects must be taking into account. To increase the safety of the whole system, an adaptive neuro-fuzzy inference system (ANFIS) based estimator was developed. In the case of velocity sensor failure, the estimated speed should be used for decision, shutting down the system, for example.

To verify different aspects of safety in a magnetic bearing system, an experimental apparatus was being built.

The next sessions are dived as follow: first, the dynamic aspects related to mechanical shaft are presented; after that, the indirect FOC (IFOC) asynchronous motor control is stressed; in the sequence, the ANFIS bases are pointed out; finally, the simulation results and conclusions are presented.

Design Criteria

The design of the test rig consists of a shaft suspended in contact free magnetic bearings. The test rig has been built supported by Muteki Automação Ltda, and by the Fapesp. All the magnetic bearings components and some technical support have been done by Mecos Traxler.

The test rig consists of a horizontal rigid rotor suspended in two radial magnetic bearings and one axial magnetic bearing. A small turbine is collocated at end of the rotor. The maximum speed of the rotor is set to be ω_{max} = 29300 rpm. This speed was chosen in order to exceed the nominally allowed maximum speed of some ball bearings, which will be tested.

High bending stiffness: The first eigenfrequency of the rotor should lie above its rotational frequency, i.e. above 500 Hz.

A finite element model was used to determine the eigenfrequencies of the system. For the Finite Element Analysis, we used the FE-program package Rotfe [3], which was developed specially for rotor dynamic problems. Apart from calculating the eigenfrequencies and vectors, the matrices can be used to adapt the control of the AMBs to the particular rotor.

Fig. 1 depicts the first elastic mode of the rotor. The rigid-body modes (rotation and translation) are calculated with high precision, whereas the elastic behavior is an approximation depending upon the quality of the modelling. For a more precise determination of the quantities, an experimental modal analysis has to be carried out.

Therefore, the calculated the first elastic eigenfrequency is ω=889 Hz.

If appears a failure in a horizontally assembled system, the rotor enters into a transient series of impacts, and can enter whirl motion or oscillate at the bottom of the bearing. A commonly obtained result was whirl motion [1].

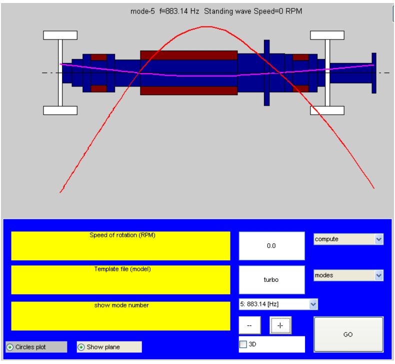

Figure 1: First elastic mode

Considering the stator to be a rigid body, a very important characterization of the interaction dynamics is the first elastic eigenfrequency of the rotor, rigidly supported on both sides, as shown in Fig. 2. Here we label this eigenfrequency as ω_{r1}, and it is essential to know or to estimate its value to calculate the worst case whirl in a retainer bearing. As show in Fig. 2 the ω_{r1} = 410 Hz for infinite stiffness.

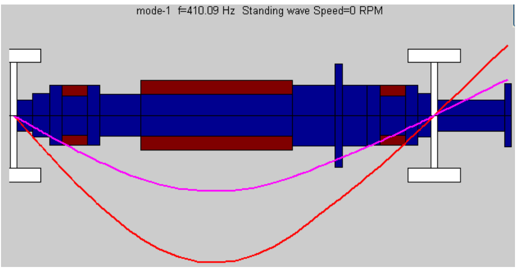

Figure 2: First rigid-rigid elastic mode

After permanent contact, the whirl velocity accelerates quickly up to a coupled frequency. This frequency is a first coupled eigenfrequency and can be explained by the elastic coupling between the rotor eigenfrequency and the eigenfrequency of the stator. This physical behavior of a rotor touching an elastically supported stator was predicted by [4], and observed by [5], and [1].

The first elastic rigid-rigid eigenfrequency of the rotor ω_{r1} = 410 Hz was estimated. In this case the support is rigid and the eigenfrequency ω_{r1} can be seen as the maximal value for the first "coupled" eigenfrequency that the rotor can achieve.

If a rotor entered a state of whirl motion, as in our case, it was always a cylindrical whirl motion. Consequently, the maximum cylindrical force can be estimated based on that kind of motion. In the cylindrical case, we obtain the well known equation for the normal force on each bearing: $F_{\mathbf{cyl}}=m\,\omega_{r1}^{2}\,\rho/2$.

Considering in our experiment the mass of the rotor m= 5,52 Kg, the air gap (ρ) between the rotor and the retainer bearing is 0.3 mm, the normal cylindrical force can reaches a value of $F_{\mathbf{cyl}}$ = 4.7 kN.

In our experimental apparatus, we have chose a particular ball bearing (SKF 6005), which supported this maximal cylindrical force.

An asynchronous motor-generator provides the drive power to the rotor. The motor has nominal power of 9 kW, the frequency range is up to 500 Hz, outer diameter is 49 mm and air gap is 0.50 mm.

All parts such as the rotor, bearings, motor and retainer bearings are integrated into an aluminum housing. The air gap between the rotor and the radial bearing is 0.5 mm and between the rotor and motor it is 0.4 mm. The air gap between the rotor and the contact ring is 0.3 mm. Fig. 3 presents an overview of the system.

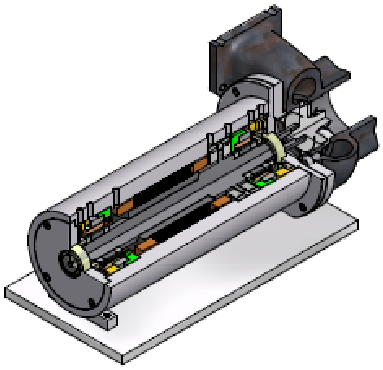

Figure 3: Whole system overview

Indirect Field Oriented Control

Magnetizing Flux Oriented Control. To control the induction motor a magnetizing flux oriented control with impressed stator currents [6] is proposed in this work. Fig. 4 presents the IM simplified model and Fig. 5 presents the magnetizing reference frame for stator space phasor voltage.

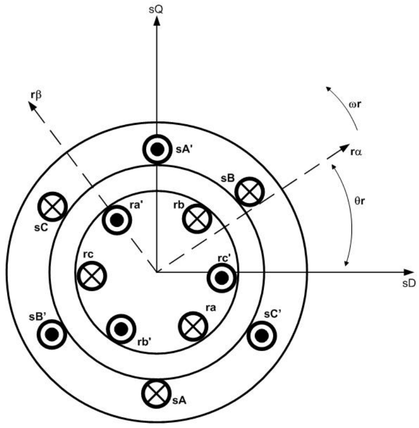

Fig. 4: Simplified asynchronous motor

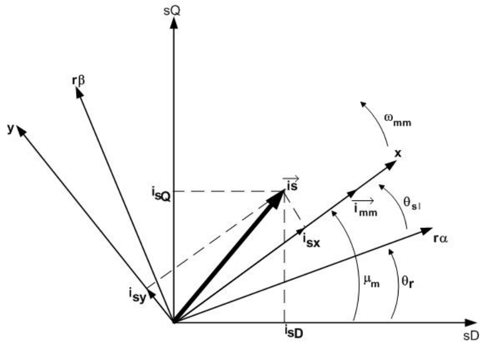

Fig. 5: Magnetizing reference frame

Impressed Stator Currents Drive. To drive the induction motor, simulations were carried out using the magnetizing-flux-oriented control scheme with impressed stator currents [6].

The following Eqs. 1 and 2 are necessary to implement the magnetizing FOC with impressed stator currents. In these equations i_{sx}, i_{sy}, T_r, i_{mm}, T_{r1}, ω_{sl} and p, are the direct and quadrature components of stator current, the rotor time constant, the magnetizing current, the linkage rotor time constant, the slip frequency and the derivative operator, respectively.

$$i_{sx} = \frac{(1+T_r p) i_{mm} + i_{sy} T_{r1} \omega_{sl}}{1+T_{r1} p} \qquad (1)$$

$$\omega_{sl} = \frac{(1+T_{r1} p) i_{sy}}{T_r i_{mm} - T_{r1} p i_{sx}} \qquad (2)$$

ANFIS: Adaptive Neuro-Fuzzy Inference System

It is presented now the ANFIS concepts as proposed in [7]. The ANFIS gather the characteristics of artificial neural networks and the fuzzy systems. The number and shape of each membership function related to the input variables can be obtained in an optimized way from data sets of inputs and output associated with a training algorithm. The ANFIS can approximate all non linear systems with reduced data set, fast response and accuracy [8].

Fig. 6a [7] presents the Sugeno fuzzy system with two rules. Fig. 6b [7] presents the equivalent ANFIS system. In this figure nodes of the same layer have similar functions.

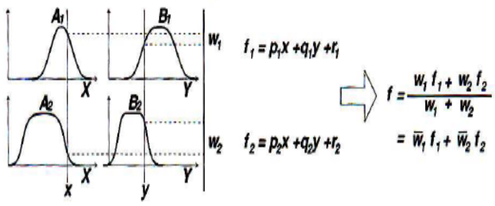

Fig. 6a: Sugeno fuzzy system with two rules

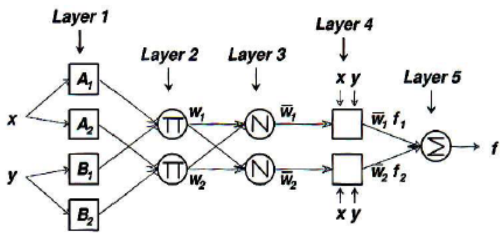

Fig. 6b: Equivalent ANFIS architecture

To generate the membership functions in layer one, subtractive clustering was considered [9]. The final adjustments were carried out using the hybrid learning algorithm [7].

Simulation Results

The ANFIS package of Matlab/Simulink software was used to training and validation of the neuro-fuzzy estimator. For the IFOC drive a recurrent ANFIS system presented the best results when the inputs were chosen as $i_{sy}(K)$, $i_{sy}(K-1)$, $i_{sy}(K-2)$, $\omega(K-1)$ and $\omega(K-2)$.

Table 1 presents the motor parameters used in simulations. To train the ANFIS speed estimator three different speeds were considered: 1pu, 0.5pu and 0.05pu. Figures 7, 8 and 9 present the estimated responses for those three speeds, respectively.

Table 1: Motor parameters

Parameter	Value
R_1 (stator resistance)	0,229 [Ω]
R_2 (rotor resistance)	0,186 [Ω]
X_{L1} (stator reactance)	1,09 [Ω]
X_{L2} (rotor reactance)	1,29 [Ω]
X_{Lm} (magnetizing reactance)	39,6 [Ω]
J	0,0017 [Kgm^2]
P (pole pairs)	1
Power	9 [KW]
Rated Voltage	220 [V]
Rated frequency	500 [Hz]

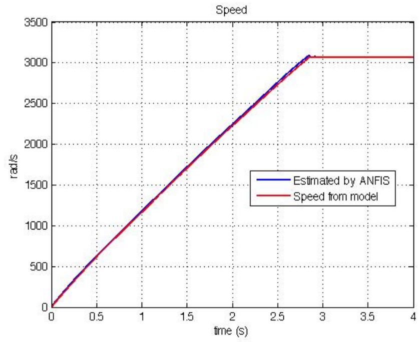

Figure 7: Speed responses for 1pu command

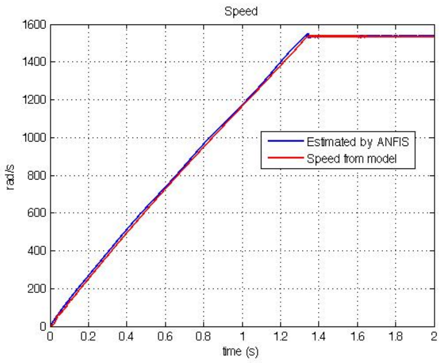

Figure 8: Speed responses for 0.5pu command

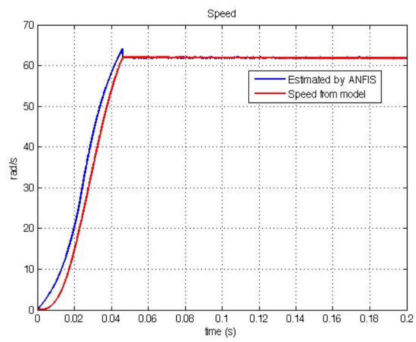

Figure 9: Speed responses for 0.05pu c

Conclusions

This paper presented an efficient ANFIS estimator for rotor angular speed of induction motors. It was observed a fast training and low error associated. A magnetizing flux oriented control with impressed stator currents was simulated and a ANFIS system was trained using a recurrent scheme. The proposed ANFIS estimator differs from the others estimation methods in simplicity and robustness as presented.

In the case of velocity sensor failure, the estimated speed should be used for decision, shutting down the system safety. To verify different aspects of safety in a magnetic bearing system, an experimental apparatus was being built. For the future development retainer bearings will be also of interest.

Acknowledgments

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