REVIEW ABOUT CONTROL AND ESTIMATION STRATEGIES APPLIED TO BEARINGLESS MACHINES

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Abstract

Motors with magnetic bearings and bearingless machines have as a basic principle magnetic levitation to reduce wear on mechanical parts to increase their useful life and reduce the need for preventive and corrective maintenance, especially in equipment that operates in difficult-to-access environments. However, in order for them to achieve the desired performance, their respective control systems must operate efficiently and synchronously on: the radial rotor position, the torque, speed, and supply currents of these machines. In this context, the first systems developed used in a broad and unrestricted way the classic controllers PI (Proportional-Integrative), PD (Proportional-Derivative), and PID (Proportional-Integrative-Derivative), allied to state estimators based on inverse models of these machines to avoid the use of costly sensors. During the research, however, it was found that the non-linearities and parametric variations inherent to these special machines could affect the performance of the control and estimation systems developed. In order to compensate for these limitations, from the 2000s onwards, new researches were developed using the main modern control and state estimation techniques successfully applied to conventional electrical machines. In this context, the development of microelectronics and new microcontrollers such as, for example, the DSP (Digital Signal Processor) was fundamental to enable the implementation of these new systems. To recover the history of these works and contribute to the development of future systems, this article presents an overview of the main control and estimation techniques applied to different types of machines without bearings and levitation systems developed so far, highlighting, critically, the advantages and limitations of each of the techniques discussed.

Bearingless, Induction motor, DSP, Estimation techniques, control techniques.

1 Introduction

Electric machines that operate with the radial magnetic suspension of the rotor shaft provide a significant reduction in mechanical wear and, consequently, in the number of predictive and corrective maintenance of this equipment [1]. This advantage over conventional electric machines has resulted in the study and development of new models with the most varied topologies over the past decades. In this context, several types of machines that use the magnetic suspension protocol in their operation have been developed over the years. Among them, we can list: Active Bearing Machines (AMB), Bearingless Induction Machine (BIM) with double winding and split winding bearingless motors, permanent magnet and bearingless motors of variable reluctance. Each of these engines has characteristics that fit specific applications. The projects and the performance improvement obtained with these special machines were only possible due to the advances of microelectronics together with the control and estimation techniques developed for conventional electrical machines. However, these machines have nonlinearities, which significantly limits the application only of classic controllers based on plants with constant and known parameters. In order to get around the nonlinearities of bearingless machines, many control systems use the combination of two or more control and/or estimation techniques with the classic methods (based on machine parameters) for tuning the controllers optimally. In the next sections, the basic characteristics and applications of the main estimation and control techniques applied to the various types of bearingless induction machines or Active Bearing Motors are presented, highlighting their respective advantages and disadvantages. Finally, a general analysis of these techniques is presented to contribute to the development and/or optimization of other control systems applied to these special machines.

2 General Model of Control System applied to bearingless machines

To start the discussions on the control and estimation strategies applied to machines without bearings and magnetic levitation systems, Figure (1) presents the universal block diagram, in which the main stages are present in most of the systems already implemented. The difference between them is evident from the techniques used to control variables and state estimation of the controlled machines. Among the most studied variables are forces and radial positioning, rotational speed, electrical torque, flux position, and machine parameters.

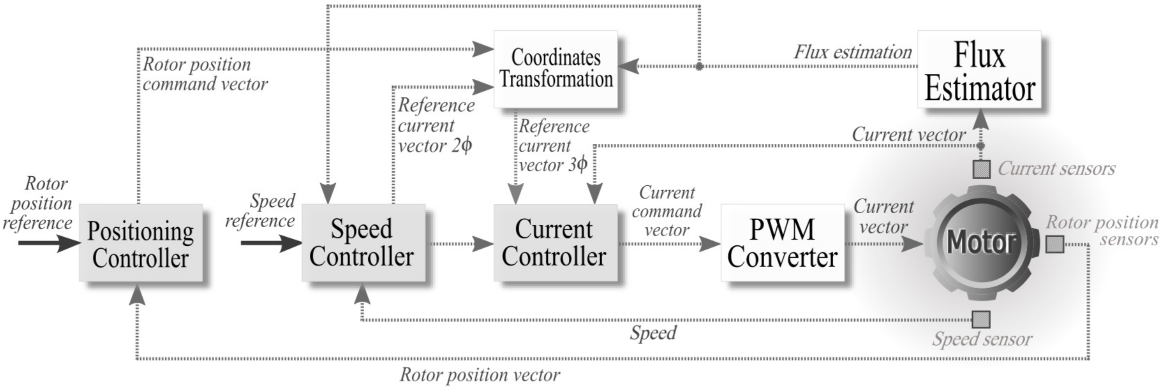


Figure 1: General diagram of a generic estimation and control system applied to bearingless machines and magnetic bearings.

This structure makes it possible to identify the following blocks: the radial positioning controller, the speed controller, the current controller, The PWM converter, the coordinate transformation block, and the flux estimator. The controllers most used in these stages are PI (Proportional-Integrative) or PD (Proportional-Derivative), or PID (Proportional-Integrative-Derivative). The estimator block is implemented by a flux-oriented vector model based on the inverse of the machine model. However, for plants with non-linear models with variable and unknown parameters, is necessary to replace or modify these control or estimation strategies with modern techniques based on artificial intelligence to improve the performance of these specialized machines. The PWM converter block is responsible for supplying the motor from the reference currents generated by the current controller; The coordinate transformation block converts two-phase control signals into three-phase reference signals, using the synchronous angle generated by the flux estimator. To this end, other strategies have been by using and implemented in recent years to assist the tuning of classic or modern controllers, making systems more robust to disturbances and parametric uncertainties. The estimation and control techniques covered in this article will be described in the following sections.

3 ESTIMATION TECHNIQUES APPLIED TO THE BEARINGLESS MACHINES

The states estimation and parameters of electrical machines aim to compensate for the difficulties of measuring these quantities in equipment with limited access or those which present significant variations under the influence of external phenomena, such as temperature and electrical and mechanical disturbances. The first estimation techniques developed were based on the internal model of the machine through which measurements of its inputs and outputs were made and, from the developed model, the values of the desired quantities were obtained. However, in most cases, the inverse models used for the estimation are linearized, operating at specific points. In addition, these models consider the machine parameters constant and immune to variations resulting from the influence of external agents. Several techniques have been studied and developed in the last decades to solve the limitations imposed by linearized models. One of those machines that have non-linearities is bearingless machines and machines with magnetic bearings. In order to understand the principle of operation and its respective applications, this article brought together the main estimation and control techniques applied to bearingless machines developed in the last decades. The description of the state of the art of these works as well as their applications will be presented in the following sections.

3.1 Estimation techniques based on the machine model

Each type of electric machine has a specific mathematical model, which depends essentially on its topology and construction technology. Thus, some machines have relatively simple and approximately linear models, such as DC machines. AC machines have more complex models with non-linear characteristics, as the machines are based on the principle of magnetic levitation. The following subsections describe the characteristics and applications of the main estimation techniques based on the bearingless machines inverse model.

3.1.1 Vector Model

The vector control techniques with flux guidance for induction machines, unlike scalar control of the V/F (voltage/frequency) type, present high performance both in the permanent regime and during the transients of these machines. The decoupling between the torque and flux controllers is achieved by transforming the model of the induction machine into a model similar to DC machines, whose control is much simpler and effective for both high and low speeds. The main requirement of vector controllers is to know the exact value of the magnitude and the position of the rotating flux. This factor generates the need for the use of flux sensors placed inside the machine, which is often not feasible for certain systems, either due to the difficulty of access or even the high cost of these sensors. For this reason, is very common to use flux estimators instead of sensors. In the vector control technique, a flux reference is chosen to obtain the model. The usual flux references are the stator flux vector the air gap flux vector, and the rotor flux vector. Each of these references has advantages and disadvantages in relation to the number of state equations and implementation difficulties. Initially, vector control was developed for the three-phase induction machine. However, features such as simplicity of equation and ease of implementation allowed the expansion of its applications to other types of machines. In [14], the vector model of an induction bearingless machine with split winding was developed. In this work, it was possible to prove that the model developed is similar to the vector model of a conventional three-phase induction machine when the rotor is centralized by the action of the radial position controller.

3.1.2 LSE based on zero-sequence voltage equations

The zero-sequence voltage equations to represent the models of three-phase electric induction machines are based on the representation in symmetric components widely used in multi-phase power systems. To make this representation possible, this model considers that all parameters of the induction machine are constant. From this model, it is possible to use the least-squares (LS) strategy to estimate the parameters through a regression equation composed by a prediction vector that depends on a regression vector and the parameter vector. To illustrate an application of this type of estimator, the work described in [30] presents an independent radial force control system on a double coiled induction bearing machine operating at high speed. In this work, the limitations of the control guided by the air gap flux are identified in relation to the delays inherent to the digital processing of the algorithm in a DSP for machines operating at high speeds. To compensate for these limitations, the developed estimator uses the least-squares technique (LSE) on the model of zero sequence equations of the machine. The proposed algorithm performs the estimation of stator parameters such as the mutual inductances between the windings and the resistance from the reading. With these estimated parameters, it is possible to independently control the electromagnetic torque and radial forces without direct dependence on the stator flux.

3.2 Artificial Neural Network (ANN)

Among the techniques for estimating nonlinear plants in evidence, estimators based on Artificial Neural Networks (ANNs) stand out [16]. This highlight is due to its wide range of applications and the ability to adapt and learn neural estimators concerning the behavior of the states to be estimated. One of the most promising research areas for implementing the artificial neural networks is in the control area and estimation of parameters and states of electrical machines. Induction machines have non-linearities in their models and suffer variations in the values of their parameters due to internal factors such as the rotor magnetic saturation and the temperature variation. In order to circumvent these problems, neural estimators can be trained under different load conditions and at various points of operation to contemplate and compensate for variations in machine parameters and maintain the desired performance for system controllers, whether they are classic or modern. Among the possible applications of RNAs in electrical machines is the induction bearingless machine with split winding. This machine type presents complex modeling in the function of the variation of the values of its parameters in function of the radial position and the non-linearities present in its equations.

Flux-oriented vector control depends on the exact position of the chosen reference flux, be it the stator, the rotor, or the air gap. However, the flux estimation through the conventional model of the machines does not consider the parametric variations due to the action of external agents, such as temperature variations. In order to compensate and allow a self-adjustment of the estimator in relation to these variations, a radial position and speed control system for a bearingless motor with split winding was implemented in [15] using the ANNs to estimate the rotor flux through Backpropagation networks with offline training. The results obtained showed that the performance of the system operating under the guidance of estimated rotor flux through the neural estimator was superior to the conventional estimator based on the machine model in terms of stability of the control of the radial position and the speed of the response of the speed control. In [18], by using neural network configurations were tested for speed control of the same type of machine, and the simulations proved that other RNA topologies could be used for flux estimation.

3.3 Adaptive Neuro-Fuzzy Inference System (ANFIS)

Neuro-Fuzzy networks combine the characteristics of Fuzzy Inference (FIS) systems with the ability to learn artificial neural networks (ANNs), resulting in a system known as Adaptive Neuro-Fuzzy Inference System (ANFIS). With the combination of the characteristics of the Fuzzy controllers and the Neural Networks, it is possible to develop estimators that adapt to the parametric variations of the plant under control. An application of the ANFIS networks is presented in [17] to estimate the rotor flux necessary for the vector control of a three-phase induction machine with split winding. In this work, the control system's performance using a conventional rotor flux estimator is compared with an ANFIS estimator. In this comparison, it is possible to observe that the flux estimated by the ANFIS network accurately follows the flux estimated by the conventional estimator, and its responses of speed, torque, and machine currents offer better performance. Thus, ANFIS-type networks emerge as an important tool for treating non-linearities in bearingless machines split-coil or in other machines with similar characteristics.

Each of the estimation techniques described above has its advantages and limitations (see Table (2)). For this reason, choosing the ideal technique for each type of machine is an important step towards achieving the desired dynamic performance. This choice depends on the machine's constructive characteristics and the performance specifications foreseen for each application. However, the good dynamic performance of the machine is only possible if there is a perfect connection between the chosen estimation technique and the most suitable control strategy for each type of control variable of machines without bearings or levitation systems. In this context, several control techniques have been proposed to compensate for the limitations imposed by the classical controllers widely used in the first works, as discussed in the next section.

4 CONTROL STRATEGIES APPLIED TO THE BEARINGLESS MACHINES AND LEVITATION SYSTEMS

As shown in Figure (1), it is common for control systems to have state estimators operating together with the controllers so that the machine without bearings or levitation system achieves the desired performance within the conditions defined in the project. For this, several types of controllers have been developed, tested, and compared to each other to overcome the limitations imposed by the controlled machine to guarantee operating stability, rejection to external disturbances, and robustness to parametric variations. The following sections present and discuss the basic design and operation principles of the main control techniques applied to bearingless machines and magnetic levitation systems.

4.1 Classic Controllers (PI, PD e PID)

Conventional PI, PD, and PID controllers were the first to be used in the control loops of systems applied to bearingless machines or even in magnetic levitation systems [1], [11] [13]. Because they are easy to implement and have consolidated theory, they are still widely used in the control systems of electrical machines that operate under constant torque and speed conditions. They are controllers with designs based on linear models with fixed parameters. However, due to non-linearities and parametric uncertainties, the tuning of these controllers becomes ineffective for some types of applications. In these cases, it is common to use a hybrid system composed of meshes implemented with PI, PD, and PID controllers, but with the aid of some modern estimation and control techniques for the online adjustment of its parameters [15], [26], [29], [30]. Thus, even with the emergence of modern control techniques, classical controllers should not be disregarded at first [5], [10], [12], [20], [21], [25], [27]. Initially, it is important to test them to identify possible limitations and define which estimation and/or control techniques should be added to compensate for them.

4.2 Convergent Control Algorithm

The convergent control algorithm (CC) is a control technique that operates in the frequency domain in which the Fourier coefficients of the controller input signal operating at excitation frequency are obtained by an adaptive control law [2]. If the excitation is composed of several frequencies, the convergent control algorithm must be applied to each excitation frequency separately through adaptive loops until the performance conditions are reached. Some works implement convergent control in machines without bearings to compensate for possible mechanical vibrations of the rotor at certain frequencies. The work presented in [3]. implements an active control of flexural vibration of the rotor using an adaptive harmonic controller LQR to attenuate the components of low-frequency vibrations, together with a convergent controller for radial positioning. The results obtained in the simulation show that the union of the techniques embedded in the system presents itself as a viable strategy for the control of vibrations at low frequencies in flexible rotors in an induction machine without cage bearings. In [2], the rotor's flexural vibrations with a two-pole cage rotor are studied. For this, the machine is equipped with a radial forces actuator and a supplementary winding located inside the stator slots. The model obtained from the machine uses the movement of the rotor coupled to the voltage and flux equations. The actuator built into the machine is a controller based on the Convergent Control Algorithm (CC) to attenuate periodic vibrations. The results showed that the controller used was able to attenuate the flexural vibrations of the rotor by up to 85%. In addition, the control technique implemented can also be used in the monitoring and diagnostics of machine failures.

4.3 Linear Quadratic Regulator (LQR)

The Optimal Control theory of a system considers that a good performance system depends on operating dynamics with minimal cost. Considering that a set of linear differential equations can represent the dynamics of the system and that the cost function is defined from a linear quadratic equation, the Quadratic Linear Regulator (LQR) is a control technique based on state feedback, stable and robust, whose main objective is to minimize the cost function. For this, the LQR control algorithm performs the adjustment of its coefficients through an iterative process. Some studies using LQR controllers have shown good results in the application of this control technique. In [28], the authors propose a decentralized LQR controller (LQRd) to control the radial position of a bearingless machine with double winding. In it, a direct comparison of the performance of the LQRd controller is made in relation to a conventional PD controller for radial positioning. The results obtained showed that the LQRd controller has a superior behavior to the PD controller and that the LQRd controller can be considered a PD controller with optimized parameters. Another work presented in [9] proposes an LQR controller combined with the theory of the Linear Inequality Matrix (LMI) for the optimization of the parameters of the Multiple Resonant controllers (MRC) to compensate the periodic oscillations generated by the disturbances on a multisector machine permanent magnet (MSPM). The results demonstrated that the control system combining the mentioned techniques presented a robust and efficient behavior in relation to oscillations in the radial position. Another application of the LQR controller is presented in [22]. In this work, a pole positioning controller is combined with the LQR controller to act in the radial position control of a permanent magnet dual machine with 4 degrees of freedom, double wound, and 10 kW. The article presents tests and simulations to check the stability of the radial position control at low speeds. When comparing the adopted controllers in relation to the PID controllers, it is shown that the LQR controller surpasses the performance in the radial positioning of the rotor. In addition, designing an LQR controller is simpler by using intuitive adjustments.

4.4 Decoupled torque and force control technique (FTD) and FTD with Harmonic Compensation (HFTD)

The articles that involve this technique use a machine structure without bearings with a permanent magnet rotor in which a single set of stator coils is responsible for generating the radial positioning forces and electromagnetic torque. In this machine model, the stator is divided into sectors, and a three-phase inverter controls each sector. The objective is to obtain an independent control of the x and y axes of radial position from the interaction of the magnetic fields resulting from each sector.

The FTD technique expresses the radial force F as a vector that can be decomposed into vectors on the x and y axes. These vectors, in turn, can be decomposed into three other axes (each axis corresponds to a spatial sector of the stator). The FTD technique uses the flux-oriented field control theory and shows that is possible to control radial and rotational forces in an uncoupled manner. In this technique, the "d" axis is responsible for controlling the radial positioning forces, and the "q" axis is responsible for the control of the electromagnetic torque. From this, as the intensity of the force F is controlled by the intensity of the component "d" of current of each sector, it has that the force F is maximum in the direction "d" of a determining sector when the resulting vector F is aligned with that "d" direction. The FTD technique controls the angle of force alignment F in relation to each sector's "d" components to carry out the radial position control. The control using the FTD technique does not include any compensation for synchronous disturbances. Therefore, the response of the position control system is highly interfered with by the action of an magnectic force F_m, resulting from the action of the centrifugal force caused by the unbalance of the rotor mass. To compensate for these synchronous disturbances, a modification in the FTD technique was proposed, resulting in the HFTD (Harmonic Force Torque Decoupled) technique. The HFTD technique alters the control law by including some parameters related to the synchronous frequency, which must be calculated using finite elements. Therefore, the HFTD control technique offers a harmonic compensation in a table form that must be updated according to the rotor position and the load torque to ensure the machine's stable operation. The work presented in [7] performs a direct comparison between the FTD, HFTD, and Pseudo Inverse Matrix (PIM) techniques, described in the following section. In this work, it was possible to prove that the FTD technique offers a good magnitude of radial forces and simplicity of computational implementation. However, the quality of these forces and the losses due to the Joule effect were significantly impaired by synchronous oscillations during the operation of the machine. When comparing the mentioned techniques, the HFTD technique provided an effective compensation for synchronous oscillations. However, its computational implementation is more complex than that required by the Pseudo Inverse Matrix technique (PIM).

4.5 Pseudo Inverse Matrix

The control technique through the Inverse Pseudo Matrix [7], [8], [10] was developed from the inverse model of a multi-sector permanent magnet bearingless motor (MSPM) with 18 slots and 6 poles with reconfigured winding. The mathematical modeling of the machine in question was based on the conventional permanent magnet machine in which the magnetic decoupling between sectors is considered, maintaining the geometric and symmetry characteristics. A matrix of K_E coefficients is found from the model obtained that characterizes the electro-magneto-mechanical outputs obtained by reading the currents responsible for the radial forces and torque. With these coefficients in place, the control action of the currents mentioned above is defined by obtaining the inverse K_E matrix. However, the matrix generates only three equations that differ from the number of state variables that depend on the number of sectors. In this way, the system of equations obtained presents infinite possibilities for solutions. Therefore, it is necessary to define a single solution that meets the minimum performance requirements. In order to minimize losses due to the joule effect, a solution using the Moore-Penrose pseudo matrix is proposed as a generalization of the inverse K_E matrix. In [7], the control technique is compared with the Decoupled Force and Torque (FTD) and Decoupled Force and Torque control techniques with Harmonic compensation (HFTD). The results obtained demonstrate that parameters such as: Magnitude and quality of radial forces minimize losses by Joule effect are equivalent between the HFTD and PIM techniques and better than FTD. However, the control technique based on the Pseudo Inverse Matrix (PIM) offers a simpler computational implementation than the HFTD technique. The only difficulty with the proposed technique is obtaining the Inverse Matrix K_E. For this, the computational technique SVD (Single Value Decomposition) is used with offline processing to minimize the computational effort during the Control System operation.

4.6 Support Vector Machine (SVM)

A support vector machine (SVM) is a concept in computer science for a set of supervised learning methods that analyze data and recognize patterns used for classification and regression analysis. The standard SVM takes a set of data as input and predicts each given input, which of two possible classes the input is part of, which makes SVM a non-probabilistic binary linear classifier. Given a set of training examples, each marked as belonging to one of two categories. An SVM training algorithm builds a model that assigns new examples to one category or another. An SVM model represents examples as points in space, mapped so that the examples in each category are divided into a clear space that is as wide as possible. The new examples are then mapped into the same space and predicted to belong to a category based on which side of the space they are placed on. The

SVM technique has been applied in some control systems of bearingless machines. In some cases, SVM is used in conjunction with other techniques. In [21], a decoupled control system based on the Least Squares Inverse Support Vector machine (LSSVMI) is proposed, applied on an induction machine of 5 degrees of freedom. This work presents the structure of the motor and its inverse mathematical model, which is obtained using the regression capacity of the nonlinear theory of the least squares support vector machine. In addition, the work proposes an optimization algorithm for the parameters, which improves the accuracy of the model's adjustment and prediction. The initial simulation results demonstrate the efficiency of the control strategy.

4.7 Active Disturbance Rejection Control (ADRC)

Active Disturbance Rejection Control (ADRC) is a robust controller based on non-linear functions that estimate and compensates for various disturbances and variations in plant parameters. For this, the equations of the ADRC controller consider the total disturbance (composed of unmodulated dynamics, nonlinearities, uncertainties, and load variations) as a new state of the system to be estimated in real-time through an extended state observer. These characteristics make the controller's performance independent to the plant model, which is ideal for controlling electrical machines. As a disadvantage for applying this technique, we can mention a large number of the controller parameters and the lack of a systematic method of tuning. As an application example of the ADRC controller, the work presented in [4] proposes an ADRC controller based on the inverse model of the rotor flux for the radial positioning and speed controls of a double winding induction machine, replacing the conventional PID controllers. The implemented ADRC controller considers the cross-couplings of torque and radial position, parametric variations, and loads as disturbances within the control law. An extended state observer (ESO) estimates the total disturbance and compensated by a non-linear state error controller. The simulation results showed that the proposed control system has the robustness and better performance in the responses of rotation speed and radial positioning in relation to the system implemented with conventional PI controllers. Another application of the ADRC controller is found in [19]. In this work, the performance of the proposed ADRC controller is compared to the performance of the PID controller. Among the control variables compared are: the response to the positioning step in the x and y directions, the radial displacement of the rotor, the speed response during the start and with the application of load variations. All the results obtained showed that the ADRC controller had a superior performance because they reduced the speed overshoot, quickness in the transient responses, and robustness to the parametric variations.

4.8 Sliding Mode Control (SMC)

Sliding mode control is a strategy with several applications in recent decades. It is indicated for plant control systems with strong nonlinear characteristics with great sensitivity to disturbances and parametric variations. The technique consists of direct control in two modes directing the system to a hyperplane, representing the plant's desired dynamic behavior. The trajectory of the outputs within this surface is known as operation in sliding modes. The technique has the advantages of quick response, negligible effects of unmodulated dynamics, and does not depend on plant parameters and external disturbances. The main problem with the SMC is that the control signal is applied at a high frequency to keep the output on a hyperplane to result in an unwanted phenomenon known as "Chattering". To decrease the Chattering effect, it is necessary to apply corrections to the control signal, replacing the discontinuous signal by a function with the saturation or the sigmoid function and limiting the signal level. Consequently, it is common for a finite error to appear permanently due to this correction of the control signal. In [23], a system for controlling the suspension of the rotor by sliding modes for an engine without variable reluctance bearings (BLSRM) is proposed. The results obtained in simulations with the proposed radial position control system demonstrated that the rotor remained stable both during acceleration and during the steady-state, with low vibrations. The rotor suspension and stabilization times were satisfactory.

4.9 Multi-Ressonant Controller (MRC)

Like the HFTD controllers applied to motors with magnetic bearings and machines without bearings, the Multiple Resonant Controllers (MRC) are used to mitigate the effects of periodic disturbances in the control of the radial position of the rotor. These disturbances arise mainly due to the misalignment of the geometric axis in relation to the center of mass of the rotor and the position sensing surface's constructive and magnetic imperfections. It is common to have cyclical disturbances of different frequencies in the same system, so the controller must be able to attenuate each one of them. In position control systems with MRC, there is usually a controller responsible for stabilizing the radial position operating in conjunction with the MRC controller dedicated to promoting the rejection of cyclic disturbances. This controller produces an infinite gain whenever the error has a frequency ωr. The reference tracking problem can be addressed by using n resonant controllers that lead to multiple resonances or multiple resonant controllers. The main idea is to generate an oscillating dynamic (sinusoidal mode) corresponding to the fundamental frequency of the signal of interest and its respective most significant harmonics. To exemplify an application of this type of controller, the system described in [9] implements an LQR type controller for a machine without a permanent magnet multi-sector bearing (MSPM) in which a mathematical model was developed to generate optimally current references. To minimize losses by Joule effect. In it, an MRC controller is incorporated into the system to compensate for periodic disturbances. The experimental results demonstrated the effective rejection of oscillations on the radial position, which significantly improved the performance of the magnetic levitation system.

4.10 Fuzzy Controller

The Fuzzy controller seeks to embody the human way of thinking in a control system. It emerged as an alternative to the classic control method as it does not require the knowledge of its mathematical modelling, thus facilitating control in non-linear systems that are difficult to modelling. The controller design is based on deductive reasoning, on the experience of the system operators, or on a desired behavior for the system. Fuzzy controllers are an important application of the fuzzy set theory (Fuzzy sets) and can be used in conjunction with other types of controllers such as PID and Neuro-Controllers. A recent proposal for applying Fuzzy controllers for a three-phase induction machine without bearings with split winding is presented in [5]. This article presents a Fuzzy controller with PD controller characteristics for radial positioning. The design of the controller took into account the knowledge of the desired performance of the system when using a PD controller to keep the rotor axis centralized. From this condition, the input and output pertinence functions were defined together with the rules of the Fuzzy controller. The work results showed that the Fuzzy controller with PD characteristics applied to the x and y axes offers good performance and robustness in the control of the radial position, as long as the operating frequency of the motor is close to the nominal frequency of the machine. However, for operation at frequencies below 60 Hz, the Fuzzy control performance was impaired, indicating the need for modifications in the adjustment of the controller parameters. Even with significant oscillations, the rotor has not exceeded the stability limits, which demonstrates the viability of the technique for some simpler applications.

4.11 H_∞ Controller

The H_∞ controller is a feedback controller of the same order as the plant. The H_∞ controller synthesis must be understood as a system optimization technique in the frequency domain. Its main objective is to minimize the norm of the system's frequency response when it is desired to guarantee its stability and good performance. The norm of a system is related to the maximum gain existing between the inputs and outputs in the entire spectrum of possible operating frequencies. A thesis paper was presented in [6]. In it, an H_∞ controller is proposed for the radial positioning of a bearingless motor in order to maintain stability and robustness even with parametric variations. The thesis provides a detailed description of the concepts necessary to understand the H_∞ control. Soon after, the work describes the theory, the design, and the synthesis of the controller H_∞ , performs several simulations to verify stability in radial positioning and its behavior under the action of harmonic disturbances, and presents the implementation and operation of the prototype. After analyzing the results of the tests, it was found that the H_∞ control system meets the specified performance requirements. Thus, the work concludes that the H_∞ controller is a very promising technique for application in bearingless motors because it is a complex and non-linear modeling plant.

4.12 μ-Synthesis

The μ-Synthesis control technique is an extension of the H_∞ method and presents itself as a robust controller for plants with a high degree of uncertainty, whether parametric or dynamic. However, for the application of this method, it is necessary to know the uncertainties of the plant in detail and in a structured way. In addition, the μ-Synthesis method generates a higher-order controller, which requires a recursive process of interactions to obtain the optimal solution, which must meet the performance conditions required for the plant. The robust control technique μ-Synthesis has some recent applications in levitation systems as described in [24]. In this work, the μ-Synthesis control technique acts in the recovery of levitation of an active magnetic bearing (AMB). The proposed strategy uses the model in the theory-Synthesis controller theory to find the controller parameters to provide the necessary forces that prevent the saturation of the control signals that occur during large deflections due to levitation problems. After the design and synthesis of the controller, experimental tests were carried out in which the levitation system was brought to instability simulating failures during operation. The work proposes that the μ-Synthesis controller is automatically activated in case of loss of support of the rotor. The results obtained demonstrated that the control system responded quickly to the recovery of levitation. However, the system was studied in a simplified model, which does not generate the need to expand research on machines with more complex models.

4.13 PWM modulation control techniques for inverters

To control the static switches of the inverters responsible for driving the electrical machines, is traditionally used the pulse width modulation (PWM) technique. Unfortunately, this high-frequency switching causes harmonic distortions that affect the quality of voltages and currents applied to electrical machines. In order to minimize these distortions and approximate these signals to perfect sine waves, several techniques were developed and implemented, significantly improving machine performance and control systems performance. The following subsections provide a brief description of these switching techniques.

4.13.1 Space Vector Modulation (SVM)

The technique known as Space Vector Modulation (SVM) is a strategy applied to the PWM (Pulse Width Modulation) signals that control the PWM inverters of an AC converter. Its operation can be defined by a specific sequence in the activation of the inverter switches so that the converter's output approaches the maximum of a sinusoidal signal. The main objective of this technique is to minimize the effect of harmonic components present in switched signals. Several works use the SVM technique combined with conventional control techniques to optimize the reference voltages and currents applied to the machines. An example of this combination of the SVM control technique applied to the PWM signals of the inverters is presented in [19]. Although this work is dedicated to the implementation of ADRC controllers for radial positioning, speed, and electromagnetic torque, the power stage uses SVM modulation in conjunction with a DTC (Direct Torque Controller) controller, resulting in a controller (SVM-DTC) for the supply of optimized voltage reference signals for the individual converters, for the supply of the two-pole windings (responsible for the radial positioning control) and four-pole windings (for the torque control) in order to guarantee the decoupling between the controllers and the reduction of high frequency harmonic components.

4.13.2 Direct Levitated Force Control

For the radial positioning control of bearingless machines, it is common to use flux-oriented vector control techniques synchronized with the torque and speed control. However, this type of control is strongly influenced by the machine parameters causing its radial levitation forces to be controlled indirectly. As a consequence of the indirect radial suspension force control, it is common the occurrence of lags on the flux angle that guides the radial positioning, resulting in the appearance of oscillations and sensitivity to disturbances. In order to ensure operating stability, minimize oscillations and make the positioning control more robust, the work presented in [12] proposes a new strategy for the direct control of levitation forces for an induction bearingless machine double-winding. This strategy executes an algorithm with predictive characteristics that calculates the future value of the angular position of the radial positioning flux from the difference between the current values of this angle and the angular position of the air gap flux, responsible for the torque and velocity control. For this, is necessary that in addition to the magnitude and phase values of the radial positioning flux predicted in the previous step, the magnitude and phase of the air gap flux are available, either through a sensor or calculated using a vector estimator flux. In this sense, to avoid using sensor flux, the cited work introduces an optimized model for the flux estimator responsible for the torque. For the optimized control of the inverter switching, the proposed system uses the SVPWM (Space Vectorial Pulse Width Modulation) technique.

The results obtained in the simulations and experimentally demonstrated that the technique of direct control of the levitation forces proposed improved the stability of the control of the radial position of the rotor, reduced the oscillations in the rotor levitation, and increased the disturbances rejection.

4.13.3 Direct Torque Control(DTC) and Direct Suspension Force Control (DSFC)

The Direct Torque Control (DTC) technique is a technique that allows direct control of stator flux and torque through optimal drive state selection using designer-defined switching tables. Due to the simplicity of its structure, it is common for the appearance of high levels of ripple in the torque signals, which significantly affects the performance of the DTC controller. Therefore, works such as the one presented in [19] propose adding other switching techniques added to the DTC controller. In this work, the SVM-DTC technique was proposed to smooth the torque ripple effect, resulting in a significant improvement in the performance of the torque and flux control system. In addition to torque and flux controls, control systems for bearingless machines must ensure efficient control of the radial positioning of the rotor. In general, radial positioning control uses the torque vector controller itself to generate the command of lifting forces necessary for radial positioning. However, most of the time, this over-radial positioning action only occurs after modulation of the torque controller, which results in indirect control. This characteristic makes it considerably difficult to calculate the exact suspension forces required for radial positioning, impairing the overall behavior of the control system. To solve this limitation, the work presented in [19] proposes a direct control algorithm based on the strategy presented in [12], called Direct Levitation Force Control, resulting in the control technique DSFC (Direct Suspension Force Control). With these techniques, suspension forces are calculated using the flux link read and updated in real-time. In this way, the algorithm uses the difference between the suspension forces to calculate the ideal flux for the machine windings responsible for radial positioning. Also, in [19], ADRC controllers are implemented to modulate the signals from SVM-DTC controllers for torque and flux and DSFC for radial positioning to replace PID controllers. The results obtained in the simulation confirm the efficiency of the proposed system.

5 General analysis of the techniques presented

By analyzing the various works listed in this article, essential aspects of implementation could be extracted as a way to collaborate in the development of future systems. Are they:

- Originally, most estimation systems were based on the inverse models of the machines under study. However, uncertainties related to parametric variations and nonlinearities led to the search for more robust estimation techniques to these limitations.

- Since the first works, the classic PI, PD, and PID controllers have been used due to their ease of implementation and many industrial applications in electrical machines. Therefore, even in advanced control systems, it is common to use them together with the proposed controllers.

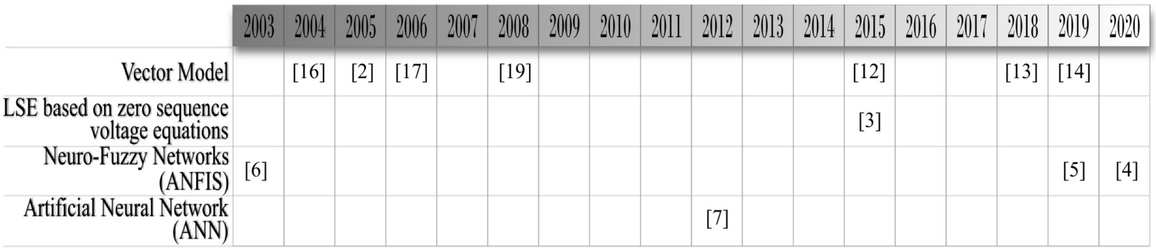
- For the implementation of each estimation or control technique, it is essential to know the system's behavior operating with estimators based on the inverse model and the classic controllers mentioned above. This knowledge makes it possible to identify the limitations of classical strategies and the correct choice of the advanced estimation and/or control technique to be used, according to the individual characteristics of each type of bearingless machine or levitation system. of the estimation and/or control strategies demand a significant computational processing capacity. For this reason, before implementing systems on an industrial scale, it is necessary to analyze the resources and specifications of the hardware devices available at the time of the control system's development to make it possible to choose the most suitable model for each application.

- Some estimation techniques are dedicated to parameter estimation, others to state estimation. Therefore, knowledge and identification of the difficulties and limitations of each machine or system are one of the first steps in choosing the appropriate technique for that problem (see table 3).

- In general, advanced control techniques seek to compensate for some limitations of classic controllers (PI, PD, and PID) related to aspects such as: speed of response, stabilization time, robustness to parametric uncertainties and disturbances. For this reason, carrying out intensive tests of the machine under study, under the command of these controllers under the most diverse operating conditions, is essential for choosing the most appropriate control and/or estimation technique(s). (see table 4).

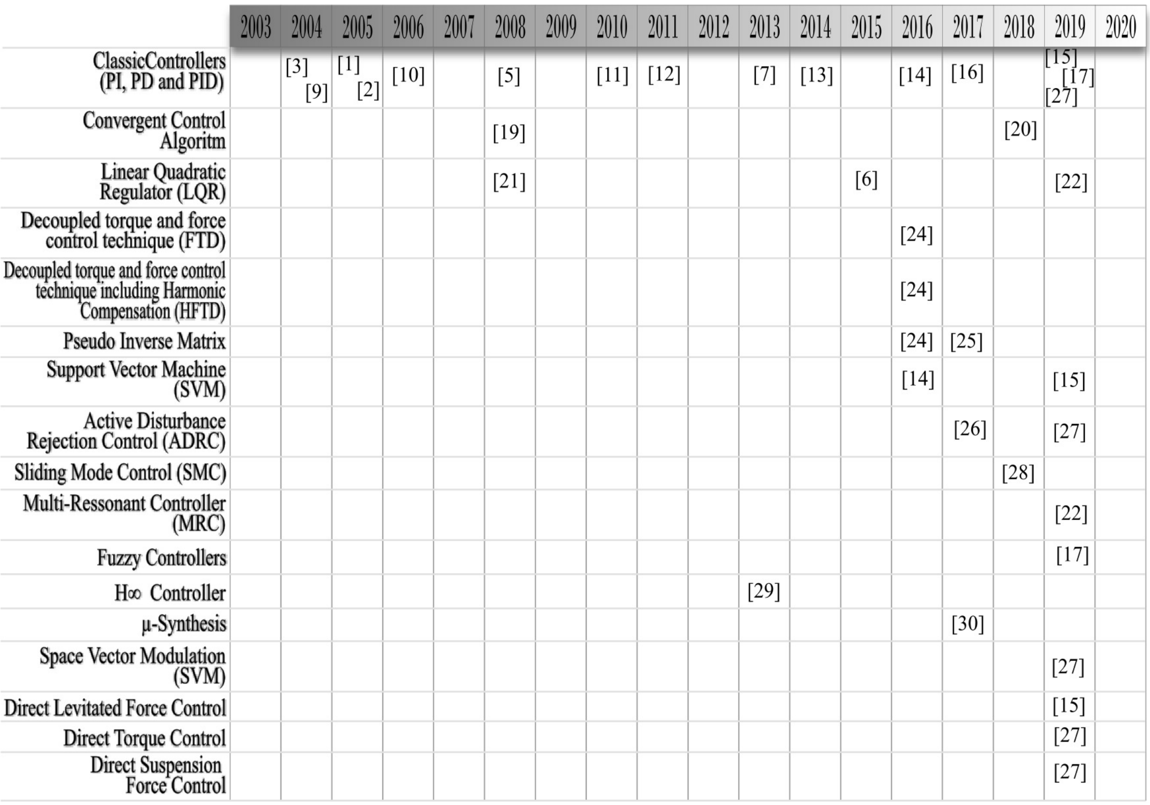
It is important to emphasize that this article does not intend to exhaust and address all the contents related to the estimation and control techniques developed so far and applied to machines without bearings and magnetic levitation systems. However, by relating the strategies presented in this work, it was possible to verify the importance and influence of advanced and technical techniques for other types of electrical machines in order to expand the possibilities of new tools in the coming years in view that, until the moment, there is no single type of controller or estimator, operating individually or together, that definitively compensates the performance limitations of all types of bearingless machines in their various applications.

Tables (1) and (2) with representation (Fig. (2) and Fig. (3)) show the chronological sequences of the works analyzed and their respective control and estimation techniques implemented. Next tables (3) and (4) with representation (Fig. (4) and Fig.(5)) present a general summary of the advantages and limitations of the control and estimation techniques analyzed in this article.



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Vector Model		[16]	[2]	[17]		[19]							[12]			[13]	[14]	
LSE based on zero sequence voltage equations													[3]					
Neuro-Fuzzy Networks (ANFIS)	[6]																[5]	[4]
Artificial Neural Network (ANN)										[7]								

Figure 2: Timeline: Main estimation techniques applied to machines bearingless.

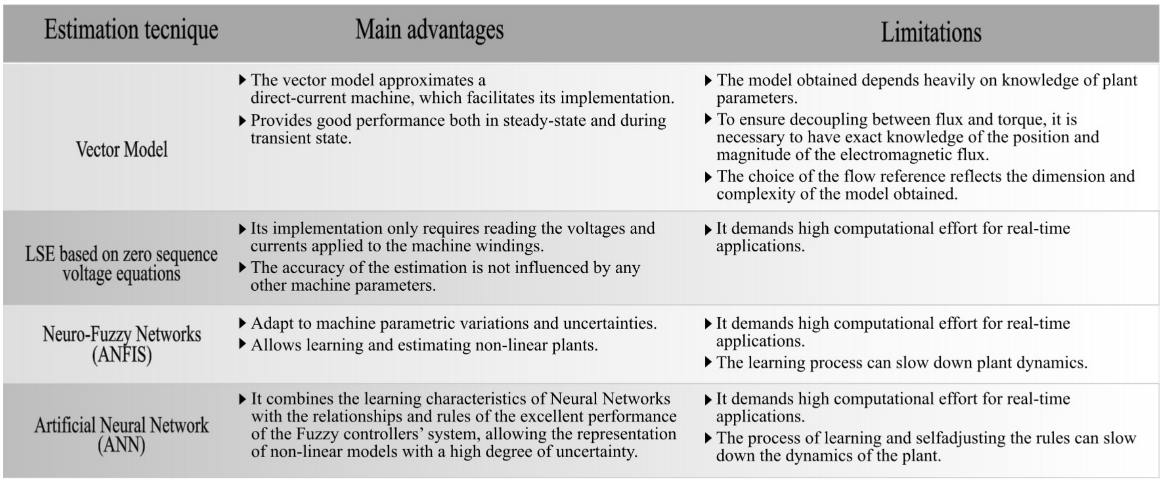


	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
ClassicControllers (PI, PD and PID)		[3] [9]	[1] [2]	[10]		[5]		[11]	[12]		[7]	[13]		[14]	[16]		[15] [17] [27]	
Convergent Control Algoritm						[19]										[20]		
Linear Quadratic Regulator (LQR)						[21]							[6]				[22]	
Decoupled torque and force control technique (FTD)														[24]				
Decoupled torque and force control technique including Harmonic Compensation (HFTD)														[24]				
Pseudo Inverse Matrix														[24]	[25]			
Support Vector Machine (SVM)														[14]			[15]	
Active Disturbance Rejection Control (ADRC)															[26]		[27]	
Sliding Mode Control (SMC)																[28]		
Multi-Ressonant Controller (MRC)																	[22]	
Fuzzy Controllers																	[17]	
H∞ Controller											[29]							
μ-Synthesis															[30]			
Space Vector Modulation (SVM)																	[27]	
Direct Levitated Force Control																	[15]	
Direct Torque Control																	[27]	
Direct Suspension Force Control																	[27]	

Figure 3: Timeline : Main control techniques applied to the bearingless machines.

6 Conclusions

This article presented a general analysis of the main estimation and control techniques applied to machines that use the principle of magnetic levitation in their operation. Throughout the research, it was observed that most of the systems proposed in the analyzed works are based on control systems already developed and consolidated for conventional electrical machines. However, these special types of electrical machines have characteristics such has non-linearities and parametric uncertainties that



Estimation tecnique	Main advantages	Limitations
Vector Model	▸ The vector model approximates a direct-current machine, which facilitates its implementation. ▸ Provides good performance both in steady-state and during transient state.	▸ The model obtained depends heavily on knowledge of plant parameters. ▸ To ensure decoupling between flux and torque, it is necessary to have exact knowledge of the position and magnitude of the electromagnetic flux. ▸ The choice of the flow reference reflects the dimension and complexity of the model obtained.
LSE based on zero sequence voltage equations	▸ Its implementation only requires reading the voltages and currents applied to the machine windings. ▸ The accuracy of the estimation is not influenced by any other machine parameters.	▸ It demands high computational effort for real-time applications.
Neuro-Fuzzy Networks (ANFIS)	▸ Adapt to machine parametric variations and uncertainties. ▸ Allows learning and estimating non-linear plants.	▸ It demands high computational effort for real-time applications. ▸ The learning process can slow down plant dynamics.
Artificial Neural Network (ANN)	▸ It combines the learning characteristics of Neural Networks with the relationships and rules of the excellent performance of the Fuzzy controllers' system, allowing the representation of non-linear models with a high degree of uncertainty.	▸ It demands high computational effort for real-time applications. ▸ The process of learning and selfadjusting the rules can slow down the dynamics of the plant.

Figure 4: Main estimation techniques applied to machines bearingless.

make it difficult to implement estimators based on their models based on constant parameters and classical controllers (PI, PD, and PID). From this study, it was possible to gather and systematize the advantages and limitations of the strategies presented to collaborate with the development of new works.

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Control tecnique	Main advantages	Limitations
ClassicControllers (PI, PD and PID)	▸ Consolidated theory in academia and industry. ▸ Large number of applications in electrical machines. ▸ It is easy to implement.	▸ Difficulty of tuning in non-linear plants. ▸ It has high sensitivity to parametric variations and disturbances.
Convergent Control Algoritm	▸ Allows attenuation of vibrations generated by periodic power signals.	▸ Needs accurate identification of frequencies responsible for vibrations.
Linear Quadratic Regulator (LQR)	▸ High performance and simple implementation.	▸ It is Sensitive to disturbances and parametric variations.
Decoupled torque and force control technique (FTD)	▸ Provides decoupling of radial force and torque controllers ▸ It is easy to implement computationally. ▸ Provides high magnitude of radial forces.	▸ Has low quality of radial force signals. ▸ Generate high losses due to the joule effect. ▸ It does not show good performance in the attenuation of total harmonic distortions (THD). ▸ Generates considerable errors in the directions of radial forces compared to other techniques such as HFTD and PIM.
Decoupled torque and force control technique including Harmonic Compensation (HFTD)	▸ Provides decoupling of radial force and torque controllers. ▸ Provides high magnitude of radial forces. ▸ Presents good quality of radial force signals. ▸ Provides efficient attenuation of total harmonic distortions (THD). ▸ Considerably reduces errors in radial force directions compared to FTD technique.	▸ Needs accurate identification of frequencies responsible for vibrations. ▸ The computational implementation is more complex.
Pseudo Inverse Matrix	▸ Provides a reduction in computational effort for online operation compared to other techniques such as HFTD. ▸ It is able to compensate for imbalances in radial forces. ▸ Provides stable generation of radial forces without the need for additional control stages. ▸ Allows the generalization of the technique to other plants of a higher order. ▸ Allows the generation of optimized reference currents resulting in a reduction in copper joule losses.	▸ Provides intermediate performance in reducing total harmonic distortion compared to other techniques such as HFTD. ▸ It presents high computational effort for the online processing of the matrix.
Support VectorMachine (SVM)	▸ It allows the supervised learning used to estimate a function that classifies the input data of the plants for the recognition of patterns with performance superior to the ANNs. ▸ They are robust for large data sets.	▸ It is sensitivity to the choice of parameter values and the difficulty of interpreting the model.
Active Disturbance Rejection Control (ADRC)	▸ It does not require the exact model of the machine. ▸ Estimates and cancels the disturbance effects. ▸ High degree of adaptability and resistance to disturbance.	▸ There is no a systematic tuning method. ▸ The number of parameters makes difficult the controller tuning.
Sliding Mode Control (SMC)	▸ Fast dynamic responses. ▸ Disregards the effects of the plant nonmodeled dynamics. ▸ Regardless of the parameters of the plant and the disturbances on it	▸ It presents unwanted oscillations caused by the high-frequency switching (Chattering) of the inverters.
Multi-Ressonant Controller (MRC)	▸ Provides the suppression of oscillations in the radial position caused by disturbances of a periodic nature.	▸ Needs accurate identification of frequencies responsible for vibrations. ▸ System dimension becomes large for a large amount of disturbance frequencies.
Fuzzy Controllers	▸ It allows the representation of models with a high degree of uncertainty through rules of inputs and outputs.	▸ They depend on the operator's knowledge for tuning the controllers.
H∞ Controller	▸ It provides good dynamic response and robustness to parametric variations and rejection of disturbances.	▸ Controller design is complex for multiple input and multiple output systems. ▸ Tuning parameters (weights) and choosing controller functions tend to be difficult, especially in a high-order system. ▸ The high computational effort for highorder controllers.
µ-Synthesis	▸ Provides a reduced settling time. ▸ It is suitable for plants with a high degree of uncertainty. ▸ Allows the processing of multiple parametric uncertainties and their interactions. ▸ It is robust to parametric variations and disturbances.	▸ The large number of method iterations can result in long calculation times, which can degrade the overall performance of the system.
Space Vector Modulation (SVM)	▸ Optimizes control of inverter switch states to make the output nearly sinusoidal. ▸ Reduces harmonic distortions caused by switching. ▸ Reduces heat losses and torque ripple. ▸ Allows digital implementation of switch control, including for multilevel inverters.	▸ Its implementation requires a little more processing than conventional PWM modulation. However, it can become easier when used in multilevel inverters.
Direct Levitated Force Control	▸ It is a controller based on a predictive model that provides direct control of radial forces. ▸ Minimizes the controller's dependence on machine parameters present in the traditional vector model.	▸ There is still a strong dependence on the accuracy of flow observers (torque and levitation) used. ▸ The computational effort for real-time operation of observers together with controllers tends to be high.
Direct Torque Control	▸ The structure of the control algorithm is simple. ▸ Allows direct control of stator torque and flux. ▸ Allows the generation of approximately sinusoidal stator fluxes and currents. ▸ Provides high dynamic performance. ▸ No need for coordinate transformations. ▸ No need for modulation blocks or the addition of other controllers for flux and torque. ▸ Provides fast torque responses.	▸ They can generate instability during machine startups. ▸ They need flux and torque estimators, which creates the need for exact knowledge of the parameters. ▸ Its torque and flux signals are ripple.
Direct Suspension Force Control	▸ It is a controller based on a predictive model that provides direct control of radial forces. ▸ It minimizes the controller's dependence on the machine parameters present in the vector model.	▸ There is still a strong dependence on the accuracy of flow observers (torque and levitation) used. ▸ The computational effort for real-time operation of observers together with controllers tends to be high.

Figure 5: Main control techniques applied to the bearingless machines.