Radial Position Control of a Bearingless Machine with Active Disturbance Rejection Control Fuzzy an Approach

Werbet Luiz Almeida Da Silva, Andrés Ortiz Salazar,
Paulo Victor Fernandes Vieira, Maxwell Cavalcante Jácome and
Elmer Rolando Llanos Villarreal

March 9, 2021

Radial Position Control of a Bearingless Machine with Active Disturbance Rejection Control Fuzzy an approach

Werbet L. A. Da Silva, *Member IEEE,* Andrés O. Salazar, *Member IEEE,* Paulo V. F. Vieira, Maxwell C. Jácome, and Elmer R. L. Villarreal, *Member IEEE*

***Abstract*—A new approach fuzzy active-disturbance rejection position controller of the bearingless induction machine (BIM) servo system is presented in this paper. This work investigates the application of the Active Disturbance Rejection Control (ADRC) Fuzzy technique on the stabilization and control of the rotor radial position of a bearingless induction machine with split winding. A control model for the radial position problem is proposed, and the ADRC-Fuzzy is used, aiming to improve the closed-loop system dynamic when a changing load occurs on the output. The simulations showed that the controller could stabilize the plant and reject disturbances. These results will guide a future experimental validation of the problem.**

Keywords: Control ADRC-Fuzzy, induction motor, magnetic levitation, robust controller.

I. INTRODUCTION

Bearingless electric machines based on induction motors appeared to meet industrial demand for less noisy motors, which could reach higher speeds and would not contaminate processes. With the development of this technology, a wide range of sectors could take benefit of it [1] [2] [3]. For example, the aerospace industry, which adopted bearingless machines because they can significantly reduce the number of maintenance events in systems operating in space. In the biomedical area, pumping systems that replace the human heart were able to extend its operational period to an interval of more than ten years thanks to the elimination of mechanical contacts [4].

The systems with magnetically suspended rotors, as the bearingless machine with split winding proposed by [5], work without mechanical bearings, which are usually the first component to fail in electrical machines [6]. Linear controllers may not achieve a stable and fast response for the proper suspension of the machine rotor. The emergence of microprocessors and power electronic devices provided conditions for applying advanced control theories, such as predictive controllers, by sliding modes, based on artificial neural networks, Fuzzy, and others [7].

With this technique, the effects of internal and external disturbances, parameter variations, and other uncertainties are estimated through a state observer and compensated in real-time by the control routine [8]. Its architecture makes the ADRC a control technique whose performance is independent of the mathematical model's knowledge of the process. In [9] a permanent magnet synchronous motor (PMSM) position, servo control system based on fuzzy active-disturbance rejection was proposed. Introducing fuzzy logic control into the design of ADRC controller, improving the self-tuning of the parameter of nonlinear states error nonlinear feedback controller which keeps the original features of the controller and reduces the adjustable parameter and enhances the performance of the control system. Combined with the speed loop and the position loop, a novel Fuzzy-ADRC position regulator is designed, which improves the robustness and keeps the dynamic characteristics of the system at the same time. In [10] was proposed, a control model for the radial position problem is proposed, and the ADRC is used to improve the closed-loop system dynamic when a changing load occurs on the output.

This paper studies the application of an ADRC controller in the position control of a bearingless machine with split winding. In addition to this introductory section, in the section (II), the modeling of the radial position system is performed. In section (III) explains the ADRC and shows its mathematical implementation. Section (IV) presents the Fuzzy Controller. section (V) presents the Fuzzy-ADRC Controller. In section (VI) presents the results of the simulated runs, followed by section (VII), in which the final considerations are made.

Werbet Luiz Almeida Da Silva and Andrés Ortiz Salazar are Department of Computer Engineering and Automation, Federal University of Rio Grande do Norte (DCA-UFRN), Natal, RN, 59072-970, Brazil.

Paulo Victor Fernandes Vieira is graduation Interdisciplinary in Science and Technology, Federal Rural University of Semi-arid (BC&T-UFERSA), Mossoró, RN, 59625-900, Brazil.

Maxwell Cavalcante Jácome is Program Postgraduate in Engineering Mechanical Federal University of Rio Grande do Norte (PPGEM/CT-UFRN), Natal, RN, 59072-970, Brazil.

Elmer Rolando Llanos Villarreal is Department of Natural Sciences, Mathematics, and Statistics, Federal Rural University of Semi-arid (DCME-UFERSA), Mossoró, RN, 59625-900, Brazil. (Correspondence: elmerllanos@ufersa.edu.br).

e-mail:(werbethluizz@hotmail.com ; andres@dca.ufrn.br; fernandes_victor2001@hotmail.com ; maxwellc.jacome@hotmail.com; elmerllanos@ufersa.edu.br .)

https://orcid.org/0000-0001-7197-6957; https://orcid.org/0000-0001-5650-3668; https://orcid.org/0000-0003-2668-5362; https://orcid.org/0000-0001-6635-3632; https://orcid.org/0000-0002-3059-3340.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and in part by the process 23091-014712/2019-87-UFERSA.

Manuscript accepted February , 2021; IEEE ICA/ACCA2021: 2021 IEEE International Conference on Automation /XXIV Congress of the Chilean Association of Automatic Control (ICA-ACCA), Santiago, Chile, March 22-26, 2021.

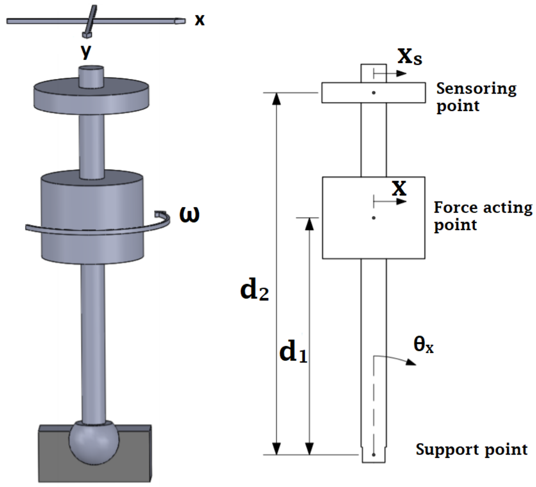

Fig. 1. Rotor free body diagram.

II. System modeling

Currently, several topologies of bearingless machines are available in the literature. The topology used in this work was studied by [11], which developed the dynamic model of the rotor radial position from the characteristics of a real experimental prototype. This prototype works vertically and is supported on the lower end of the shaft by a pivoted bearing that prevents radial and axial movements but allows angular movements. This type of system has two degrees of freedom for position control [12], and the rotor displacement occurs in the directions of x and y axes.

Starting from the application of the second motion law to Figure 1, [11] developed a $G(s)$ function that relates the control signal $U(s)$ to the output position $Y(s)$ of the rotor. The dynamics of the x-axis is equal to the y-axis, and both are described by:

$$G(s) = \frac{3.68 \times 10^6}{(s + 91.51)(s - 91.51)} \tag{1}$$

Equation (1) show that the radial position model has a unstable pole, thus a controller is fundamental to the system operation.

III. ADRC controller

The first version of the ADRC controller was presented in Chinese by its creator, Jingqing Han, in a work entitled "Auto disturbances rejection controller and its applications" in 1998 [13]. In order to promote advances in the theory and practice of control engineering, Jingqing Han researched the characteristics of nonlinear into closed-loop control problems and proved the efficiency of the controllers designed from them. According to [14], when compared to linear functions, nonlinear ones are potentially more effective in tolerating uncertainties and disturbances; and in improving systems dynamics.

In a more recent publication, Han described the ADRC as a digital closed-loop system control technique, developed from a digital platform rooted in computer simulations, which inherits from the proportional-integral-derivative (PID) controller it is characteristic of greatest success: a control law mainly based on error, and not just on the plant model; in addition, it uses state observers, a technique from the theory of modern controllers; and also makes use of nonlinear control tools for the realization of its structure [15].

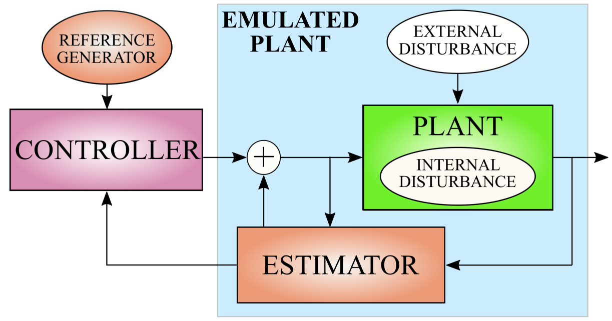

Fig. 2. ADRC - General idea.

The ADRC controller uses a state observer to estimate any unknown information (dynamics, disturbances, nonlinearities, parameter variations, time-delays, etc.) about the real system to be controlled. Then, the algorithm subtracts the estimated information from the system dynamics in order to emulate a model with simpler general behavior. On the ADRC structure, there is the observer, a reference generator, and a controller block (Figure 2). To achieve its goal, the ADRC groups all the uncertainties involved in the process into a single parameter named "generalized disturbance." This parameter is then defined as a state variable of the system to be estimated through the observer. Once estimated, this parameter is subtracted from the system's control loop, which the controller sees as a simpler system, formed only by cascaded integrators (Han's canonical form), whose control has already been extensively studied in the literature. Therefore, Han's canonical form is taken into account for the control block design, and the knowledge about the real system parameters is not important.

A. ADRC mathematical description

The ADRC structure is based mainly on nonlinear functions and its original complete version is composed by three blocks: an extended state observer (ESO), a tracking differentiator (TD), and a nonlinear control law (Figure 3).

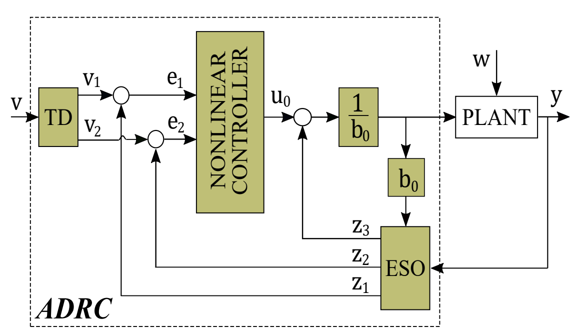

Fig. 3. ADRC - Control structure.

1) tracking differentiator: The TD operates on the reference signal in order to filter it and smooth its transition. For a second-order system given by:

$$\begin{cases} \dot{v}_1 = v_2 \\ \dot{v}_2 = u \end{cases} \tag{2}$$

the optimal solution for this system is given by:

$$u = -rsign(v_1 - v + \frac{v_2|v_2|}{2r}) \tag{3}$$

Therefore, the system can be rewritten as:

$$\begin{cases} \dot{v}_1 = v_2 \\ \dot{v}_2 = -rsign(v_1 - v(t) + \frac{v_2|v_2|}{2r}) \end{cases} \tag{4}$$

thus, $v_1(t)$ follows the input signal $v(t)$ with a speed adjusted by r. The variable $v_2 = \dot{v}_1$ is an approximation of the derivative of $v(t)$.

2) ESO: It consists of an estimator with nonlinear gains that detects information about the states of the plant in real-time from the observation of the inputs and the output. It is the most important block of the controller, as it is responsible for detecting disturbances involved in the process. The observer design, for this work, is given from the second-order system by:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1(t), x_2(t), w(t), t) + bu \\ y = x_1 \end{cases} \tag{5}$$

where y is the measured output that must be controlled;; $f(x_1(t), x_2(t), w(t), t) = F(t)$ is a multivariate function of states $(x_1(t), x_2(t))$, external disturbances $(w(t))$, and time (t); i.e., the total disturbance. Assuming that $F(t)$ is a system state variable, $F(t) = x_3$ and $\dot{F}(t) = G(t)$ is its derivative. Therefore, the extended representation of the system given by (5) is:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ \dot{x}_3 = G(t) \\ y = x_1 \end{cases} \tag{6}$$

From this representation, the observer's structure is proposed [16]:

$$\begin{cases} \dot{z}_1 = z_2 - \beta_{01} fal(e, \alpha_1, d_1), \\ \dot{z}_2 = z_3 - \beta_{02} fal(e, \alpha_2, d_2) + b_0 u \\ \dot{z}_3 = -\beta_{03} fal(e, \alpha_3, d_3), \end{cases} \tag{7}$$

the fal function is defined by:

$$fal(e) = \begin{cases} |e|^{\alpha} sign(e), & |e| > d \\ \frac{e}{d^{1-\alpha}}, & |e| \le d \end{cases} \tag{8}$$

The variables α_1, α_2, α_3, d_1, d_2 e d_3 are the parameters of the nonlinear functions. The observer output give the values of the states z_1, z_2 e z_3, i.e., it estimates the numerical values of the states z_1, z_2 and of the function $F(t)$. From this, the effect of $F(t)$ is removed from the system dynamic through the operation:

$$u = \frac{u_0 - F(t)}{b_0} \tag{9}$$

So, the emulated dynamics of the system becomes:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u_0 \\ y = x_1 \end{cases} \tag{10}$$

which corresponds to a simple double integrator system, whose control is widely known in the literature.

3) Control law: The work [15] indicates the following nonlinear strategy:

$$u_0 = \beta_1 fal(v_1 - z_1, \alpha_1, \delta) + \beta_2 fal(v_2 - z_2, \alpha_2, \delta) \tag{11}$$

However, it emphasizes that different strategies can be used in the the control law block.

IV. Fuzzy Controller

The basic structure of a rules-based fuzzy controller consists of three stages: fuzzification, inference, and defuzzification [17]. In the fuzzification, input data are converted into fuzzy values, i.e., qualitative values comprehensible by the inference mechanism.

A. Rules Basis

Defining the rule sets is directly related to the aim of the control. Since the bearingless motor aims to keep the rotor centralized, the main task is to minimize the position tracking error. The higher the error, the higher the control input. However, a change in error also affects the value of the control input. Consequently, the error and change in error are used in the control rules as the linguistic variables. The variables $e[k]$ is the actual error and $e[k-1]$ the error calculated in the previous sample of k. These are defined as:

$$e_1 = \ error_1 = v_1 - z_1 \tag{12}$$

$$e_2 = \ error_2 = v_2 - z_2 \tag{13}$$

$$\begin{aligned} \Delta e_1 &= \ change\ in\ error_1 = e_x[k] - e_x[k-1] \\ \Delta e_2 &= \ change\ in\ error_2 = e_y[k] - e_y[k-1] \end{aligned} \tag{14}$$

wherein e is the error signal. The a, b, c and d mean Δ_{ex} , e_x , Δ_{ey} and e_y, respectively.

The rules of fuzzy controller are of the form:

$$If\ error_1 \ = \ A\ and\ change\ in\ error_1 = B \quad Then\ u = C \tag{15}$$

$$If\ error_2 \ = \ C\ and\ change\ in\ error_2 = D \quad Then\ u = G \tag{16}$$

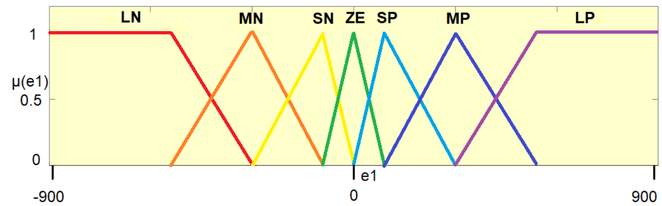

Fig. 4. Membership functions of input variables.

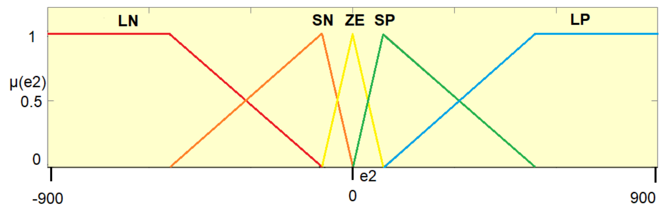

Fig. 5. Membership functions of input variables.

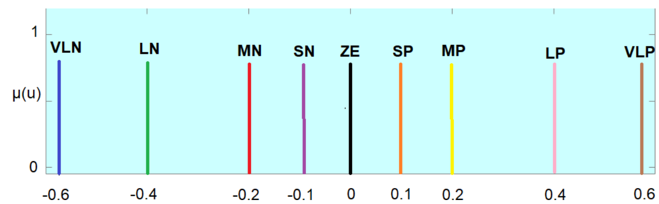

Fig. 6. Membership functions of input variables.

V. FUZZY ADRC CONTROLLER

In the synchronous rotating coordinate system, using vector control strategies, using the equation (5) we can obtain position loop two order dynamic equation of BIM:

$$\ddot{\theta} = -\frac{B\omega}{J} - \frac{T_L}{J} + \frac{1.5p\psi_f}{J}u(t) \quad (17)$$

$f(x_1(t), x_2(t), w(t)) = -\frac{B\omega}{J} - \frac{T_L}{J}$, $b = \frac{1.5p\psi_f}{J}$.

$u(t) = i_q$, where $f(x_1(t), x_2(t), w(t))$ is the known friction disturbance of system,$w(t)$ is the unknown load disturbances of system, through these two parts can estimate the total disturbance of system and compensate for it, making the system has great robustness to the load and friction disturbance. Under the condition of position sensor, ω is the known quantity, its the differential is also a known quantity and the state equation of position loop is available:

$$\begin{aligned} \dot{x}_1 &= x_2 = \frac{d\theta}{dt} \\ \dot{x}_2 &= \frac{d^2\theta}{dt^2} = f(x_1(t), x_2(t), w(t)) + bu(t) \quad (18) \\ y &= x_1 = \theta \end{aligned}$$

According to rotational transformation is obtaining parameters $\beta_0, \beta_1, \beta_2$. Finally, with the principles of Fuzzy ADRC parameters tuning, we can obtain Fuzzy-ADRC. Its structure is shown in Figure (7) and Its structure with rotational transformation is shown in Figure (8).

It can be seen, every part of the position Fuzzy-ADRC controller can be designed, Its whole control structure is shown in Figure (8). In it, θ^* is the given rotor position, i_q^* is the

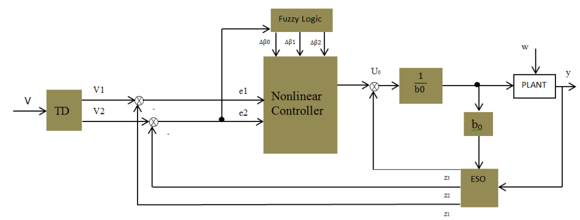

Fig. 7. Fuzzy-Self-adapted ADRC structure.

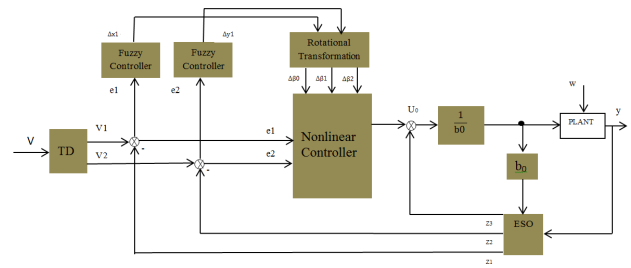

Fig. 8. Fuzzy-Self-adapted ADRC structure with rotational transformation.

given $q-$axis current, θ is the rotor position feedback signal, v_1 is the tracking signal of θ^* , v_2 is the differential signal of θ^* , z_1 is the tracking signal of θ , z_2 is differential signal for z_1, z_3 is system observation of the uncertain part of the disturbance that is $w(t)$ as the observation for the certain part, where the differential is different from the differential signal in a controller, its effect is not amplified, but disincentive to the noise signal.

A. Fuzzy controller model

Based in [18], this article introduces the fuzzy logic controller, according to the input of , e_1, Δe_1, e_2, Δe_2 and using fuzzy control rules to change the ADRC parameters $\{\Delta i_x, \Delta i_y\}$, with rotacional transformation is obtaneid approaching the optimal parameters $\{\beta_0, \beta_1, \beta_2\}$. To meet the requirements of the $\{e_1$, Δe_1, e_2, $\Delta e_2\}$ parameters of the Fuzzy ADRC, in the controller, the fuzzy variables are e_1, e_2, $\{\Delta i_x, \Delta i_y$, , in your domain, five language sets defined such as {Large Negative (NB), Small Negative (NS), Zero (ZO), Small positive (PS), Large positive (PB) }. Select the input variables e_1, e_2 for the Gaussian association function, output variables $\{\Delta i_x, \Delta i_y\}$ for triangular membership function. In this article, the basics e_1, domains are $[-900, +900]$, a range variation of $[10, +10]$ and e_2 domains are $[-900, +900]$ for a range variation of $[10, +10]$. Thus the variables $\{\Delta i_x, \Delta i_y\}$, with rotational transformation is obtaneid $\Delta\beta_0\}$ $\Delta\beta_1\}$,$\Delta\beta_2\}$ domains are $[-6, +6]$, $[-6, +6]$, $[-0.6, +0.6]$. Fuzzy reasoning using the Mamdani type and defuzification is the weight average method. According rules of the human mind, diffuse control rules are devised by

summarizing the technical knowledge of the engineering team and practical experience.

An initial rule base was developed using prior knowledge of the system. Then adjustments were made based on the behavior of the system during the experiments. The rules were changed until they could no longer improve the response, so

TABLE I
LINGUISTIC LABELS ADOPTED TO DESCRIBE FUZZY SETS.

Label	Signification
VLN	Very Large Negative
LN	Large Negative
MN	Medium Negative
SN	Small Negative
ZE	Zero
SP	Small Positive
MP	Medium Positive
LP	Large Positive
VLP	Very Large Positive

the membership functions were adjusted. The adjustments of the rules are intercalated with the adjustments of the membership functions, never both at the same time. The adjustments originated the error and change in error membership functions illustrated in Fig. 4, 5 and the output membership functions depicted in Fig. 6 and the rules summarized in Table (II).

For $\{\Delta i_x, \Delta i_y\}$ parameter configuration, fuzzy control table are established, as shown in Tables (II) and (III) .

TABLE II
RULES FOR X-AXIS FUZZY CONTROLLER.

a \ b	LN	MN	SN	ZE	SP	MP	LP
LP	VLN	VLN	VLN	VLN	LN	SN	MN
SP	VLN	MN	MN	SN	SP	LP	LP
ZE	LN	SN	ZE	ZE	ML	LP	VLP
SN	VLN	MN	SN	ZE	SP	LP	LP
LN	MP	MP	LP	LP	SP	VLP	VLP

TABLE III
RULES FOR Y-AXIS FUZZY CONTROLLER.

c \ d	LN	MN	LN	ZE	SP	MP	LP
LP	VLN	VLN	VLN	LN	MN	MN	LN
MP	VLN	MN	MN	MN	ZE	SP	MP
ZE	LN	MN	ZE	ZE	SP	MP	MP
SN	SN	ZE	SP	SP	MP	LP	VLP
LN	LP	MP	LP	LP	SP	VLP	VLP

According to the table of allocation of members of fuzzy set Tables (II) and (III) . and the fuzzy control model of parameters, and with diffuse synthetic reasoning to project diffuse matrix, then defuzzification and correction parameters found $\{\Delta i_x, \Delta i_y\}$, with rotational transformation is obtaneid $\{\Delta\beta_0, \Delta\beta_1, \Delta\beta_2\}$ and replaced it in the equation:

$$\beta_0 = \beta_0' + \Delta\beta_0 \tag{19}$$
$$\beta_1 = \beta_1' + \Delta\beta_1 \tag{20}$$
$$\beta_2 = \beta_2' + \Delta\beta_2 \tag{21}$$

Where $\beta_0, \beta_1, \beta_2$ is the nonlinear controller initial value.

VI. RESULTS

For the results described in this section, the following considerations must be made:

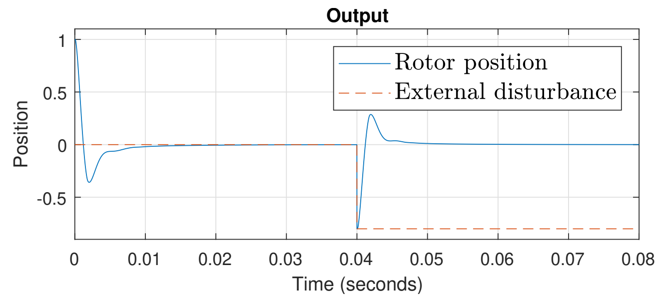

Fig. 9. System output.

- Given that the dynamic response is the same for x and y axes, the results for only one axis is showed.
- The control goal is to maintein the radial position of the machine's rotor in $(x = 0, y = 0)$ position, so the reference signal v is kept in 0 and the TD block of the Figure 3 is not necessary
- ESO was implemented according to (7) and the control law is given by (9).
- The controller tuning was carried out by trial and error.
- The system was simulated with initial conditions: $x_1(0) = 1$ and $x_2(0) = 0$. This situation indicates that the machine rotor was stopped in an unwanted position before the controller start acting.
- A step-shaped disturbance was added at the output of the system at the instant $t = 0.04$ seconds. In a practical situation, disturbances of this type are caused by loads added to the axis of the machine in operation.

The Figure 9 shows the output of the plant controlled with ADRC. The controller corrected the plant output to the desired reference value and was able to recover this condition even under a load change condition.

The efficiency of the ADRC in controlling the output of the system depends directly on the ability of ESO to estimate the states of the plant, that is: $x_1 \to z_1$, $x_2 \to z_2$ e $F(t) \to z_3$. Figure 10 compares the dynamic response of the real states with their respective values estimated by the observer. From the Figure 10, it is clear the ability of the ESO in provide proper estimates of the plant states. The efficiency of the Fuzzy ADRC Controller in controlling the output of the system depends directly on the ability of ESO to estimate the states of the plant.

The simulations results are part of a project that aim to carry on experiments with ADRC controller and a bearingless machine prototype. A experimental setup (Figure 11) at Federal University of Rio Grande do Norte will be used in future experiments.

VII. CONCLUSIONS

According to practical requirements, this paper applies, Fuzzy -ADRC theory to high-performance AC permanent magnet servo system, and designs two-order Fuzzy-ADRC position regulator to enhance the anti-interference ability of the the system, and using ESO to estimate the disturbance, which achieving high precision control of servo motor with position sensor. Simulation and experiment results show that

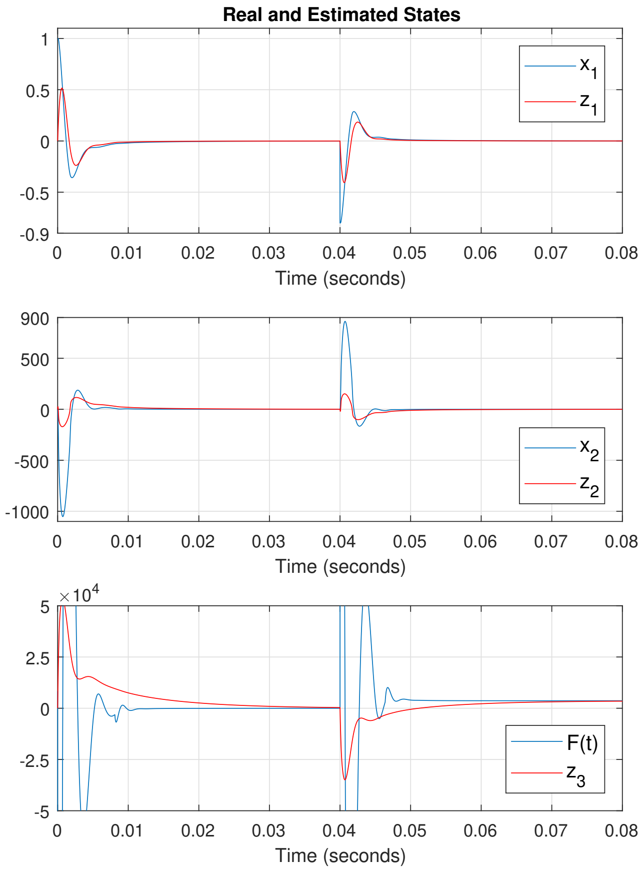

Fig. 10. Performance of the extended state observer.

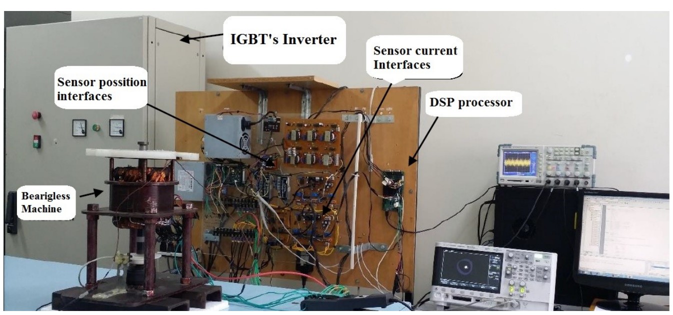

Fig. 11. Experimental setup.

Fuzzy- ADRC has good dynamic and static performance for BIM. This work studied the application of an ADRC fuzzy controller to a simulated radial position control system of an induction machine without bearings with split winding. The results proved the efficiency of the controller in keeping the rotor in the desired position. Future work aims to apply this controller to an experimental system whose dynamics are subject to a higher number of disturbances and uncertainties.

REFERENCES

[1] D. Gerada, A. Mebarki, N. L. Brown, C. Gerada, A. Cavagnino, and A. Boglietti, "High-speed electrical machines: Technologies, trends, and developments," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 6, pp. 2946–2959, 2013.

[2] T. Wellerdieck, P. Peralta, T. Nussbaumer, and J. W. Kolar, "Contributions to an ultra-high temperature (250 c/500 f) bearingless pump," in *2015 18th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, 2015, pp. 1158–1164.

[3] M. N. Recheis, B. Schweighofer, P. Fulmek, and H. Wegleiter, "Selection of magnetic materials for bearingless high-speed mobile flywheel energy storage systems," *IEEE Transactions on Magnetics*, vol. 50, no. 4, pp. 1–4, 2014.

[4] N. Kurita, T. Ishikawa, N. Saito, T. Masuzawa, and D. L. Timms, "A double-sided stator type axial bearingless motor development for total artificial heart," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1516–1523, 2018.

[5] A. O. Salazar and R. Stephan, "A bearingless method for induction machines," *IEEE Transactions on Magnetics*, vol. 29, no. 6, pp. 2965–2967, 1993.

[6] K. Li, G. Cheng, X. Sun, D. Zhao, and Z. Yang, "Direct torque and suspension force control for bearingless induction motors based on active disturbance rejection control scheme," *IEEE Access*, vol. 7, pp. 86 989–87 001, 2019.

[7] Z. Yang, J. Ji, X. Sun, H. Zhu, and Q. Zhao, "Active disturbance rejection control for bearingless induction motor based on hyperbolic tangent tracking differentiator," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2019.

[8] M. Ran, Q. Wang, C. Dong, and L. Xie, "Active disturbance rejection control for uncertain time-delay nonlinear systems," *Automatica*, vol. 112, p. 108692, 2020.

[9] Z. Gao, "A new fuzzy active-disturbance rejection controller applied in pmsm position servo system," in *Proceedings 17th International Conference on Electrical Machines and Systems (ICEMS), China*, vol. 1, 2014, pp. 2055–2059.

[10] "Radial position control of a bearingless machine with active disturbance rejection control, author=Da Silva, Werbet L. Almeida and Andrés O. Salazar and Ronaldo José N. Cabral Neto and Elmer R. L. Villarreal, booktitle=XXVII International Conference on Electronics, Electrical Engineering and computings (IEEE-INTERCON 2020), Peru, volume=1, pages=1–4, year=2020."

[11] F. E. C. Souza, "Otimização da estrutura de acionamento para o controle de posição radial de um motor de indução trifásico sem mancais com enrolamento dividido," 2018.

[12] A. Chiba, T. Fukao, O. Ichikawa, M. Oshima, M. Takemoto, and D. G. Dorrell, *Magnetic bearings and bearingless drives*, 2005.

[13] D. Huang, D. Min, Y. Jian, and Y. Li, "Current-cycle iterative learning control for high-precision position tracking of piezoelectric actuator system via active disturbance rejection control for hysteresis compensation," *IEEE Transactions on Industrial Electronics*, 2019.

[14] J. Li, Y. Xia, X. Qi, and Z. Gao, "On the necessity, scheme, and basis of the linear–nonlinear switching in active disturbance rejection control," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 1425–1435, 2016.

[15] J. Han, "From pid to active disturbance rejection control," *IEEE transactions on Industrial Electronics*, vol. 56, no. 3, pp. 900–906, 2009.

[16] Z. Gao, "Scaling and bandwidth-parameterization based controller tuning," in *Proceedings of the American control conference*, vol. 6, 2006, pp. 4989–4996.

[17] M. G. Simoes and I. S. Shaw, *Fuzzy Control and Modelling*. Editora Blucher, Brazil (in Portuguese), 2007.

[18] E. A. D. F. Nunes, A. O. Salazar, E. R. L. Villarreal, F. E. C. Souza, L. P. D. J. S. B. Lopes, and J. C. C. Luque, "Proposal of a fuzzy controller for radial position in a bearingless induction motor," *IEEE ACCESS*, vol. 7, pp. 114 808–114 816, 2019.