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Simulation Design of Blood-pump Intelligent Controller Based on PID-like fuzzy logic Technique

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KEY WORDS

Bearingless brushless, Suspension Control, Fuzzy-PID, PSO, Ventricular assist device.

ABSTRACT

This paper presents a blood pump with a bearingless brushless DC motor, supported by speed, torque, and suspension force controllers. Simulation of the pump motor and its controllers tested by MATLAB/Simulink. Two Proportional plus Integral (PI) controllers are employed for controlling the rotational speed and torque of the motor. For controlling the suspension force a comparative study is presented between the Proportional plus Integral plus Derivative (PID) controller and two inputs PID-like Fuzzy Logic Controller (FLC). A particle swarm optimization technique is used to find the best values for the controller's parameters. The results of the speed and torque controllers exhibit a good time response to reach the desired speed with a short period of time and to decrease the distorting effects of the load torque successfully. Under similar conditions, the PID-like FLC that controls the suspension forces shows a better time response compared to the PID controller. An enhancement in the responses is rated between 18% and 49%, measured using the absolute integral of error criteria on the x and y axes, and in the processing, time rated between 38% and 47%, very high oscillation suppression capability is observed in the PID-like FLC response.

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1. INTRODUCTION

Ventricular Assist Devices (VAD) transplanted successfully for the first time in a patient's body in 1966. It is used either to accomplish the entire heart functions, which is called in this case Biventricular assist device or to assist either the right ventricular or the left ventricular, depending on which side of the heart is damaged more than the other. VADs are distinguished from artificial hearts at which the patient's heart is unable to accomplish any of its functions sufficiently, for that the native heart is removed and replaced by an artificial heart [1]. Both artificial hearts and VAD are

miniature mechanical pumps, designed with special proprieties to work inside the human body temporarily or permanently. Development of heart pumps may be classified into three generations: the first generation: pneumatic pulsatile pumps, which have a pulse similar to the real hearts, it can be of heart pumps may be classified into three generations: the first generation: pneumatic pulsatile pumps, which have a pulse similar to the real hearts, it can be used only in hospitals for several months, the second generation: semi-implantable pulsatile with which patients can be released, this device be used for 1 to 3 years, and finally, the third generation: non-pulsatile pumps that are driven with magnetically levitated motors, it can last for 5 to 10 years [2]. In recent year's new motor type known as bearingless motors employed for the manufacturing of the heart pumps. In bearingless motors, the stator slots have two sets of windings: one for generating the electromagnetic motor torque, while the other is generating the suspension magnetic forces needed to hold the rotor and suspend it without any mechanical contact between the rotor and the stator inner surface. Bearingless motors researches started in the early 1980s in the last century in Europe. Its also called self-bearing motors or combined motor bearing [3]. There are many types of bearingless motors such as Permanent Magnet (PM) motors, synchronous reluctance bearingless motors, bearingless induction motors, homopolar, hybrid, and consequent bearingless motors [4]. PM motors have three types depending on the position of the permanent magnet in the rotor: surface-mounted PM bearingless motors, inset PM bearingless motors, and buried PM bearingless motors. Surface-mounted PM bearingless motors have the advantage of decoupling control of the rotational and bearing forces which means each controller is treated independently [4]. The most common method for designing a bearingless motor is the $P \pm 2$ method, where P is the number of poles of the rotor. The rotational movement of the motor is achieved with a P number of poles while the bearing force is generated with $P \pm 2$ number of poles [5]. At magnetically levitated VADs the PM is fixed on the pump impeller which represents the motor rotor. Suitable controllers need to be designed in order to suspend the impeller efficiently and to prevent it from hitting the internal stator surface.

The motor uses magnetic flux density, produced by the permanent magnet in the air gap between the rotor and the stator, to produce the motor rotating torque and the rotor suspension force. PM Bearingless Brushless DC (BBLDC) motor is extensively used in artificial heart pumps, because of its many important advantages, such as it has low weight and small size, it is distinguished as very high-speed motor, there is no heat generation because there is no material wear, since it is magnetically levitated and there is no mechanical contact and it has zero friction, it has less probability to produce blood trauma, anti-thrombogenicity and have high mechanical reliability [6]. Speed and torque controllers of BBLDC motor are designed like conventional brushless DC motor controllers. Since the motor is part of VAD, motor speed needs to be changeable, according to the patient's needs. Speed controller designed to track the change in the continuously changing reference speed. VADs operate at high speeds (5000 -7000 rpm), combined with high torque (15 -20 mN.m) [7].

The magnetic forces of the bearing part of the BBLDC motor are similar to the forces generated in a conventional magnetic bearing. The transfer function of the radial force current component to the radial rotor displacement in the magnetic bearing is unstable. For stabilizing the rotor suspension magnetic forces, a negative feedback controller is necessary to use [4]. There are many sources of non-linearity in the magnetic bearing system, such as the relationship between the forces generated in the electromagnetic actuator and the winding current and the motor air gap. Another source is the mutual inference between the electromagnetic forces acting in two perpendicular directions, which are generated in three cases: geometry of the actuators, eddy-current effect, and gyroscopic effect. At the same time, design disturbances on the suspension forces have to be included in the controller design, in order to have a good frequency and time domain. Such disturbances are: influence of delay caused by many reasons and cause a serious problem in the magnetic suspension system, unbalanced mechanical forces, eccentric displacement, and synchronized displacement suppression [4]. Many researchers suggested a PI controller for the speed and torque controller, but for the rotor or impeller suspension control, some researchers used the PID controller for the bearing forces control without consideration of the nonlinearity and disturbance sources in the implementation of the controller. Zad et al [8], a PID controller is employed for controlling the position and suspension of the rotor, the results show a good response for suspending the rotor without any mechanical contact, and good response due to the existence of a load force subjected on the rotor, which pushes the rotor away from its reference position with an amount of displacement proportional to the applied force. It is believed that almost 90% of controllers currently functioning use PID controllers. The main

drawbacks of the PID controller are that its parameters are immutable in the entire control process, it cannot deal with the presence of the motor disturbances effectively, its limited accuracy, the response has a high oscillation and sensitivity to noise [9]. Some researches took the effect of the disturbances and the coupling effects between the torque windings and levitation windings building a nonlinear controller. Grabner et al [10] presented a novel radial position and motor torque control algorithm for a BBLDC motor, based on the theory of feedback linearization. Li et al [11] coupling relationship between motor torque and rotor suspension forces is analyzed, and fuzzy adaptive control theory is applied to control speed and suspension. An adaptive PI speed and PI suspension controllers are introduced by Diao et al [12], at which an improved bacterial foraging algorithm is proposed and applied to the speed PI controller and the suspension PID controller for online parameter optimization. During the design of the controllers, some design parameters will appear, which influences the dynamic performance of the system. Try-and-error procedure for selecting these parameters is tedious and does not lead to the best solution in terms of better dynamic performance. For that purpose, different optimization techniques have been presented, such as the Ziegler-Nichols method, genetic algorithm, Particle Swarm Optimization (PSO), and ant colony optimization. PSO algorithm is very popular for optimizing the controller's parameters. It can optimize the problem with a given fitness function in a shorter period of time and strong controller parameters [13]. In this paper, two PI controllers are proposed to control the rotational speed and electromagnetic torque of the BBLDC motor. For controlling the suspension force, a comparative study is presented between PID controller and two inputs PID-like Fuzzy Logic Controller (FLC), for a miniature blood pump with four-motor poles and two bearing poles, this comparative study took into account the existence of the disturbance forces, and how it affects the suspension of the rotor, to take a comprehensive look at whether the controller can keep the rotor suspended without touching the inner stator surface or not. The PSO optimization technique is used to obtain the best values for the controller's parameters. The computer simulations are carried out to minimize the objective function defined as the error Integral multiplied by the Absolute value of Error (IAE).

2. RELATED WORKS

Most of the recent researches deal with the blood pump that adopted the third generation of the blood pump, which replace the mechanical bearing with a magnetic one. Either a separate magnetic bearing is used or a bearingless motor. The papers study either the speed controller or the bearing controller because the simulation model of the bearingless motor with both systems is complex and required a good knowledge in control techniques, power electronics, and electrical machines. Osa et al [14] introduced a bearingless motor for a miniature blood pump, the pump is small enough for pediatric heart diseases, the study introduces a centrifugal pump with dual stators, 7500 rpm speed, and 5 Degrees of Freedom (DOF) magnetic bearings. It investigates the basic magnetic suspension performance by using PID controllers. Meng et al [15] introduce an axial flow blood pump with a two compact radial magnetic bearing with 5 DOF. The used motor is a brushless motor that delivers a high speed, up to 10000 rpm. It investigates the performance of the magnetic bearing under PID controllers, which shows that the rotor is suspended successfully in the rest and at maximum speed. Synchronous motor for the third generation blood pumps is proposed by Morales et al [16], it focuses on controlling the speed of the motor and introduces a field-oriented control algorithm for this purpose. The speed range is between 1000 – 4000rpm, it also presents an algorithm to enhance the resolution of Hall effect sensors used to measure the rotor angular position. You et al [17] present a nonlinear controller for an axial flow pump, with a single DOF magnetic bearing. The controller is composed of a starting controller and variable gains PID controller and proved that the used controllers provide an enhancement in the performance as compared to the fixed gains controllers.

3. MOTOR STRUCTURE

The proposed BBLDC motor has two sets of windings in the single slot: one for the motor electromagnetic torque generation, and the other for rotor levitation force generation. The non-salient surface-mounted PM rotor type motor is proposed, which means the control of the two parts of the motor can be handled separately, which is known as decoupling control [5]. Figure 1 shows a cross-section of the PM bearingless motor [18].

I. Principle of electromagnetic torque generation

The electromagnetic torque is generated when the motor windings are excited. The principle of torque generation in the proposed BBLDC motor is the same as that in conventional three-phase brushless DC motor. In three-phase brushless DC motor with Field oriented control system, motor currents are transformed from the three-phase static reference frame to the two rotating Direct-Quadrature (d – q) reference frame by using Park transformation [4]:

$$\begin{bmatrix} i_{md} \\ i_{mq} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (1)$$

, where i_{md} and i_{mq} are the currents in the d – q reference, and i_u , i_v , and i_w are the currents in the three-phase static reference.

If v_{md} is the voltage applied to the series-connected d-axis, and v_{mq} for the q axis, then the voltage and current relationship can be written as [4]:

$$\begin{bmatrix} V_{md} \\ V_{mq} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_d & L_{dq} \\ L_q & L_{qd} \end{bmatrix} + \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ w\lambda_m \end{bmatrix} \quad (2)$$

, where R_s is the resistance of the torque windings, L_d and L_q are the self-inductance for the d- and q-axes, respectively, L_{dq} and L_{qd} are the mutual inductances between d and q, and q and d axes, respectively, ω is the angular velocity, and λ_m is the flux linkage caused by the stator magnetic. The elector magnetic torque is [4]:

$$T_r = p \left((L_d - L_q) i_{md} \cdot i_{mq} + \lambda_m \cdot i_{mq} \right) \quad (3)$$

For non-salient-pole rotors with the permanent magnet mounted in the surface of the rotor, there is no reluctance torque generation so a modification rises in Eq. (3) at which the first term (the reluctance torque) is zero and $T_r = \lambda_m i_{mq}$ [4].

II. Principle of suspension force generation

The principle of suspension in force generation is similar to that of the conventional magnetic bearing [18]. When one winding-set of the suspension windings is excited, the electromagnetic forces responsible for the rotor generation are generated. Figure 2 shows the variation of the suspension force direction, due to the rotor rotation [4]. It shows four-pole motor for the rotational movement and a 2 pole bearing system for the suspension force. The relationship between flux linkage and the currents in the torque and suspension windings is described as [4]:

$$\begin{bmatrix} \lambda_{md} \\ \lambda_{mq} \\ \lambda_{sd} \\ \lambda_{sq} \end{bmatrix} = \begin{bmatrix} L_d & 0 & M'_d i & -M'_d j \\ 0 & L_q & M'_q j & M'_q i \\ M'_d i & M'_q j & L_s & 0 \\ -M'_q i & M'_d j & 0 & L_s \end{bmatrix} \begin{bmatrix} i_{md} \\ i_{mq} \\ i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \lambda'_m \\ 0 \\ \lambda'_{mi} \\ -\lambda'_{mj} \end{bmatrix} \quad (4)$$

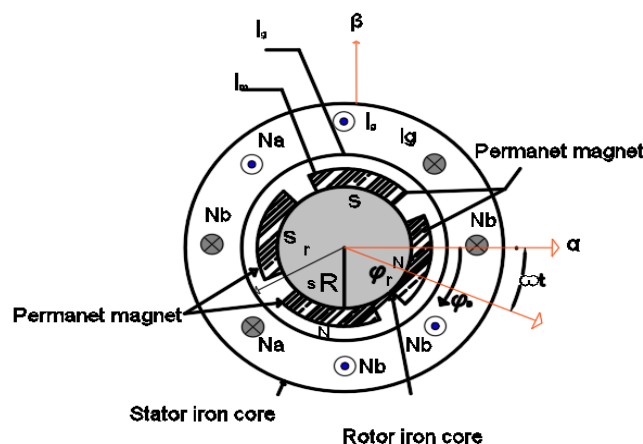


Figure 1: Cross-section of PM type bearingless motor [14].

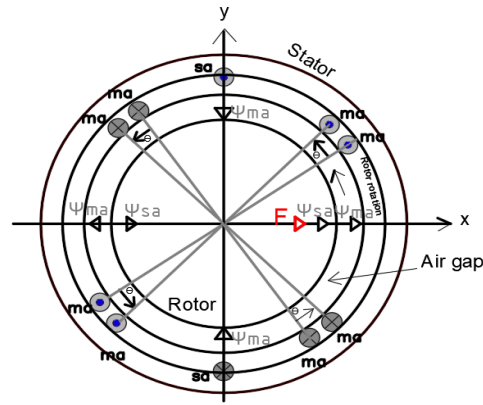


Figure 2: Variation of the suspension force direction due to the rotor rotation [4].

, where λ_{md} and λ_{mq} are flux linkages produced by the torque windings, λ_{sd} and λ_{sq} are the flux linkages produced by the suspension windings suspension d- and q- axes windings, and λ'_m , M'_d , and M'_q are the suspension force constants.

In a non-salient cylindrical rotor with a quiet thick permanent magnet, the permanent magnet flux linkage is very big as compared with the flux linkages of the q – axis torque current. Due to that, and from Eq. (4), the suspension force is [4]:

$$\begin{bmatrix} F_i \\ F_j \end{bmatrix} = M' I_p \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (5)$$

, where M' is the derivative of the mutual inductance between the torque and suspension windings, I_p represents the permanent magnet current, and θ is the angle of the rotation of the rotor.

4. CONTROL STRATEGY OF TORQUE AND SUSPENSION FORCE

Figure.3 shows the block diagram of the BBLDC motor control system. The motor and its control system are accomplished with the aid of MATLAB/Simulink. Two independent control systems have to be simulated: one for the rotational speed, while the other is for the rotor suspension and position. Three Hall-effect sensors are connected to the stator inner surface for measuring the angular position of the rotor, which is necessary to select the appropriate phase winding that needs to be excited [11]. Another two Hall sensors are measuring the amount of displacement that the rotor moved from its reference position, caused by magnetic bearing non-linearity and disturbances, resulted from manufacturing imperfections or a sudden strong movement in the patient's body caused by a hard fall or another reason. In the conventional PID controller, three gains need to be assigned (K_p , K_i , and K_d), and for the used PID-like FLC, four scaling factors are present (N_1 , N_2 , N_3 , and N_4).

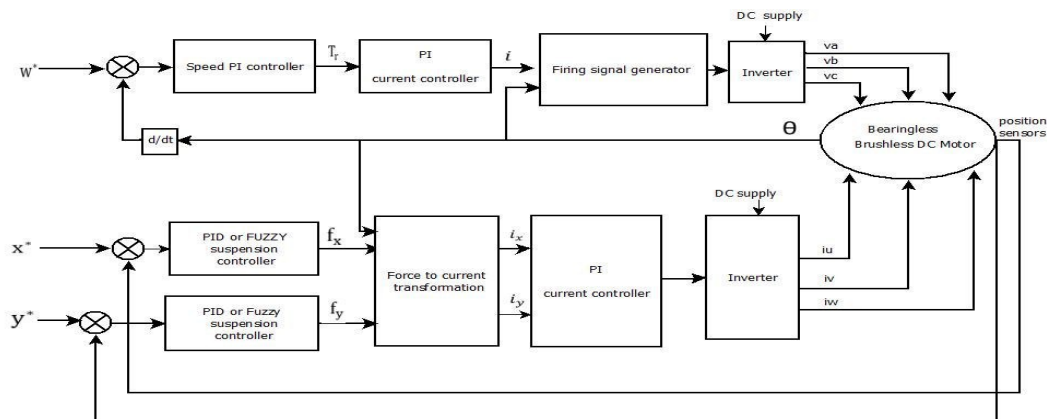


Figure 3: Block diagram of the BBLDC motor controlled

The controller's performance depends on choosing the best value of these parameters using the PSO technique, the main objective is to get the best values for each case that minimizes IAE criteria.

I. Speed and Torque control

The rotary part of the BBLDC motor contains a conventional brushless DC motor, inverter, Pulse Width Modulation (PWM), speed PI controller, and torque PI controller. VAD needs to be designed to work with variable speeds because operating at a constant speed may lead to long term complications or may operate in an undesired support mode; such as excessive pumping in the patients' body during rest when the patient needs much less blood [19]. A possible solution to such a problem is applying a variable speed rotary VAD. The BLDC motor speed is compared with reference speed signal, an error signal is produced and employed to modulate the duty cycle, which specifies the firing signals for a six switches inverter, which is responsible for delivering appropriate voltage to the motor. The motor will be with a high rate of turning on and off. The switching frequency is usually between 20-50 kHz, where the higher frequency will give low variation in current and also smoother torque [19]. The current sensor is employed to measure the three-phase currents, from the measured currents a DC link current is calculated, which is compared with the reference current and the resulted error is fed to a current or torque controller. The output of the current controller is fed to the PWM block to compare it with a triangular wave with high frequency, from where the comparator output is a low or high signal. The improvement in rotary blood pumps requires the implementation of an automatic, adaptive, and robust control system able to adjust pump speed according to the changes in the patient's state. In industry, the PI controller is widely used, due to its simple structure and easy design. The PI speed controller is represented by [19]:

$$u_m(t) = K_{pm}e(t) + K_{im} \int e(t)dt \quad (6)$$

, where $u_m(t)$ is the output of the controller, $e(t)$ represents the error signal between the desired speed and the measured one, and K_{pm} and K_{im} are the proportional and integral gains of the PI controller respectively.

II. Position control

The position of the rotor in x and y direction is detected by the two Hall-effect sensors. The measured positions are compared with the reference signals of x and y, to generate error current produce effective torque because of the direct signals that are passed to the position controller. The amount of force needed to keep the rotor suspended depends on the amplitude and direction of the suspension winding excitation current, which depends on the rotor angular position given by the Hall sensors. Figure 4 shows the principle of the suspension force generation. During angular positions, 0° to 15° and 45° to 60° , the suspension windings sv1 and sv2 are excited on the v plane. As well, at the angular position from 15° to 30° and 60° to 75° , the suspension windings su1 and su2 are excited in u plane.

Also, in the angular position during 30° to 45° and the angular position 75° to 90° , the suspension windings sw1 and sw2 are excited in the w plane [4]. The position controllers realized in this study are the PID controller and PID-like FLC. PID controllers give output in the time domain which is defined as [19]:

$$u_s(t) = K_{ps}e(t) + K_{is} \int e(t)dt + K_{ds} \frac{d}{dt}e(t) \quad (7)$$

, where $u_s(t)$ is the output of the controller, $e(t)$ represents the error signal between the desired position and the measured one, and K_{ps} , K_{is} , and K_{ds} are the proportional, integral, derivative gains of the PID controller respectively.

The best gains of the PID controller need to be found in the presence of the magnetic bearing disturbances such as the influence of delay, which is caused by many reasons associated with design malefactions and causes serious problems to the motor [4]. Figure 5 shows the interference principle in two perpendicular axes, where K_i is current stiffness, G_p : is the plant transfer function, K_s is the sensor gain, $K_x = -\sin\theta_{re}$, and $K_y = \sin\theta_{re}$, where θ_{re} is the angle error of the rotor direction [4]. There are many other sources of disturbances such as unbalance force, eccentric displacement, and synchronized displacement. To achieve better response and to assure that the rotor is suspended and not touching the stator inner surface, the Fuzzy PID controller can be used. The PID-like FLC are usually classified based on the number of inputs to the controller. Two and three-input fuzzy controllers are the most common

structures. Figure 6 shows the structure of the PID-like FLC. This structure has two inputs, which make it more efficient for real-time implementation [19]. The structure is a PD like FLC + PI controller, but for simplicity, it is named as PID-like FLC. The inference method utilized for the designed PD-like FLC is the Mamdani method. Figure 7 shows the membership functions for the position error (e), change of error (ec), and the output (u). The rule-base table is designed based on the expected response of the system to a particular input to the system, depending on past experiences of the system behavior [19]. Five linguistic variables for the membership functions are defined as Negative Big (NB), Negative Small (NS), Zero (ZO), Positive Small (PS), and Positive Big (PB). Table I, lists tabular representation of the PID-like FLC rule base.

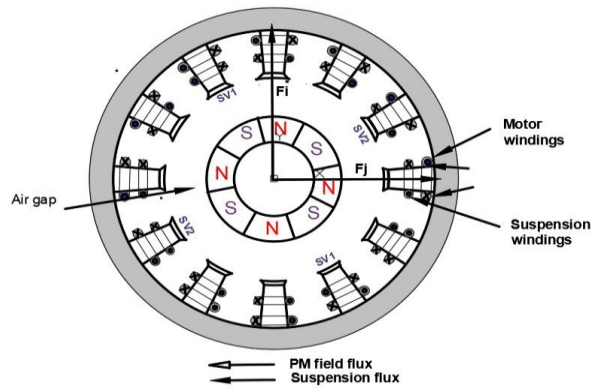


Figure 4: Principle of suspension force generation of the BBLDC motor [5].

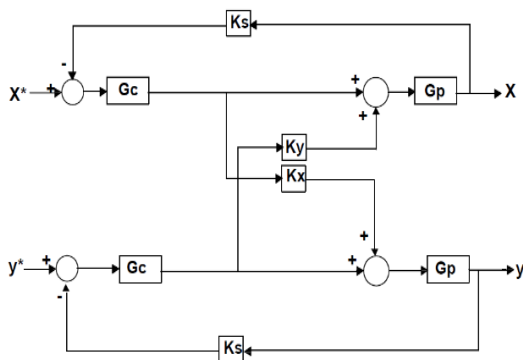


Figure 5: Magnetic suspension inference in two axes.

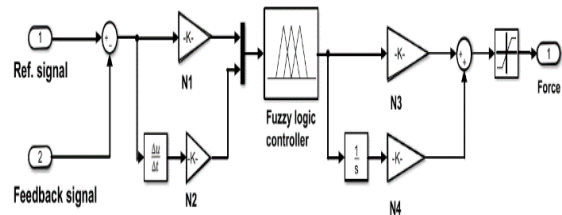


Figure 6: Basic structure of the PID-like FLC position controller

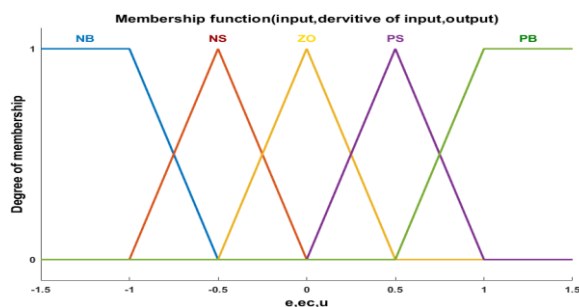


Figure 7: Membership functions e , ec , and u , of the PID-like FLC

TABLE I: PID -like FLC rules table

$\frac{ec}{e}$	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PM
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

III. PSO technique

The main purpose of optimization techniques is to optimize a function to achieve the best results or the best performance. PSO is one of the most popular optimization techniques. It was introduced in 1995 by Russell, Eberhart, and James Kennedy [19].

PSO technique is a stylized representation of the movement in a bird flock when it's searching for food, as a first step meeting location is set. Then all the birds spread in different directions, to cover a wide area of search. When one of the birds finds the food, it returns to the meeting location to inform the rest of the birds. All other birds will fly to the specified location. In PSO technique birds are referred to as particles. Each particle has a specific position, velocity, and weight. Particle position and speed are updated continuously until it reaches the best performance according to Eqs. (8) and (9) [25].

$$v_{t+1} = w \cdot v_t + c_1 \cdot \text{rand}(p_{\text{best}} - x_i) + c_2 \cdot \text{rand}(G_{\text{best}} - x_i) \quad (8)$$

$$x_{i+1} = x_i + v_{t+1} \quad (9)$$

, where v_{t+1} , x_{t+1} are the velocity and position updated values, v_t , x_t is the position present values, w is the weighting gain, c_1 , c_2 are the learning factors, p_{best} are the best parameters values, G_{best} is the best-optimized value.

The fitness function depends basically on the calculated error between the reference and the measured values. Error-values are usually very small performance indices and usually used to create the fitness function. Many equations calculate the performance indices such as the Integral of Square Error (ISE), Integral of the Absolute value of the Error (IAE), and Integral of the Time multiplied by the Absolute value of the Error (ITAE). The selection of performance indices depends on the type of desired response [19]. Here, IAE is used, since it doesn't add weight to the error. It tends to produce a slower response than ISE systems, but with less oscillation. The parameters used in the PSO technique affect the optimization operation. Here, the learning factors c_1 and c_2 are assigned according to the condition " $c_1 + c_2 \leq 4$ ". While the inertia weight is designed to be updated as [19]:

$$w_{t+1} = w_t * w_{\text{damp}} \quad (10)$$

, where (w_{t+1}) is the initial inertia weight, and (w_{damp}) is the damping ratio.

5. SIMULATION AND RESULTS

Figure 8, shows the MATLAB/Simulink simulation model of the BBLDC motor-controlled system. Table II lists the parameters for the used blood pump [8]. For the simulation of BBLDC motor, two parts must be simulated and tested. The first part tracks and delivers the desired speed by employing a speed controller. For ensuring the motor can withstand different torque loads with efficiency a torque or current controller is designed. The second part is used to suspend the rotor and it includes two Hall position sensors to track the rotor position and prevent it from touching the surrounding inner stator surface. Since it is difficult to find the best performance for the motor by finding the controller's parameters manually, the PSO algorithm is used to find the best values of the parameters.

1. Speed and Torque controllers

PSO technique is used to find the best gains for the PI speed controller (K_{pm} , K_{im}), and the torque PI controller gains (K_{pT} , K_{iT}), for both controllers a single fitness function is used and the optimization process is performed for both controllers at the same time with 9500 rpm desired speed. The fitness function is designed to minimize the IAE of the speedy response, decrease the speed overshoot, and to regulate the current to supply a suitable amount of current proportional to the load torque by minimizing IAE between the reference torque and the measured one, it can be represented as:

$$F_{\text{motor}} = \text{minimize}(c \int_0^\infty |e_1| dt + m \int_0^\infty |e_2| dt) \quad (11)$$

, where c and m are weightings factors, and they are chosen as positive values, so that $+m = 1$, e_1 : is the error measured from the speed response, and e_2 : the error of the torque response. A maximum of 30 iterations is used. With 20 particle sizes, the values of c_1 and c_2 are kept constant = 2; Changing the PSO parameters has an obvious effect on the calculated gains and the IAE criteria. In order to have a better understanding of the effects of changing PSO parameters, different values are assigned to the weighting factors (c and m). Table III lists different PSO weighting factors, the best calculated gains, and IAE criteria calculated in each case. Figure 9 shows the cost function for the calculated cost functions in Table III. In order to test the BBLDC motor speed and torque responses the best results from Table III calculated by the PSO technique are adopted, at which $c=0.2$, $m=0.8$, and $G_{\text{best}} = 8.62$.

BBLDC motor reference speed set to change at specific speeds (7000-9000-10000-9000-7000) rpm, with 51 mN.m at 0.04 sec.

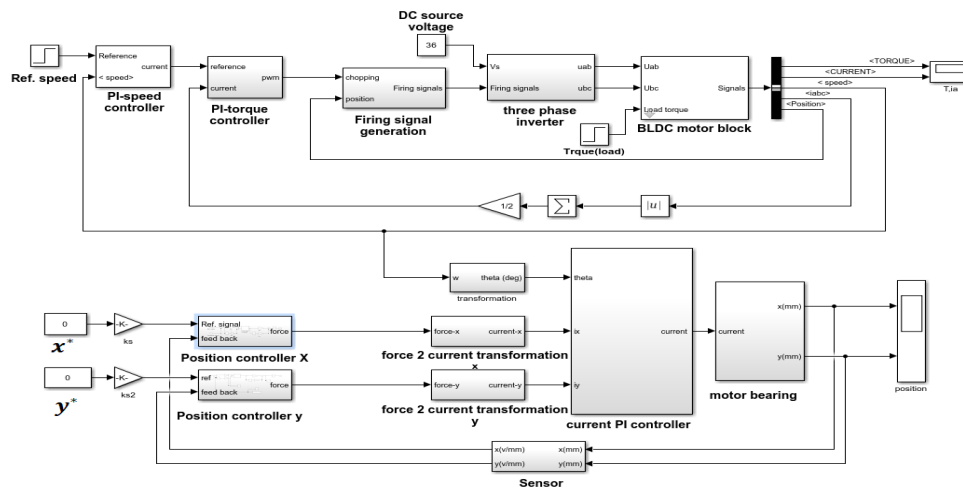


Figure 8: MATLAB/ Simulink simulation model of the BBLDC motor.

TABLE II: The parameters of the blood pump [11].

Quantity	Value
Axial length of the rotor	12.5 mm
Axial length of the PM	7 mm
Thickness of the PM	3 mm
Outer diameter of the rotor	28 mm
Outer diameter of the stator	70 mm
Air gap length	0.75 mm
Back-electro motive force constant	0.0147 V.sec/rad
Hall sensors sensitivity	5 mV/Gauss
No. of suspension force windings	80
No. of torque windings	40
Remnant flux density	1.38 T
Average torque	38 mN.m
No-load speed	24000 rpm

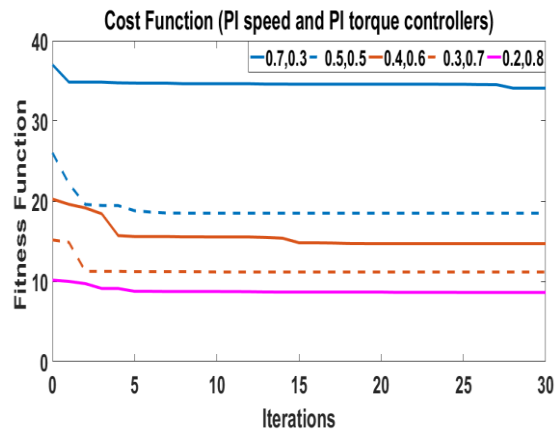
$$F_{\text{motor}} = \text{minimize}(c \int_0^\infty |e_1| dt + m \int_0^\infty |e_1| dt) \quad (12)$$

, where c and m are weighting factors, and they are chosen as positive values, so that $+m = 1$, $e1$: is the error measured from the speedy response, and $e2$: the error of the torque response.

A maximum of 30 iterations is used. With 20 particle sizes, the values of c_1 and c_2 are kept constant = 2; Changing the PSO parameters has an obvious effect on the calculated gains and the IAE criteria. In order to have a better understanding of the effects of changing PSO parameters, different values are assigned to the weighting factors (c and m). Table III lists different PSO weighting factors, the best calculated gains, and IAE criteria calculated in each case. Figure 9 shows the cost function for the calculated cost functions in Table III. In order to test the BBLDC motor speed and torque responses the best results from Table III calculated by the PSO technique are adopted, at which $c = 0.2$, $m = 0.8$, and $G_{best} = 8.62$. BBLDC motor reference speed set to change at specific speeds (7000-9000-10000-9000-7000) rpm, with 51 mN.m at 0.04 Sec. Speed, torque, and currents performances are shown in Figure 10. It is observed that the torque controlled by the PI controller contained ripples at the time of change in load which is caused by the electronic commutation implemented in BLDC motors.

TABLE III: The PSO weighting factors and the calculated best values for each case

cm	G_{best}	Speed controller parameters	Torque controller parameter
0.7	34.09	$K_{pm}=9.16$	$K_{pT}=439.35$
0.3		$K_{im}=0.044$	$K_{iT}=7.93$
0.5	18.50	$K_{pm}=1.40$	$K_{pT}=301.17$
0.5		$K_{im}=1.25*10^{-7}$	$K_{iT}=700$
0.4	14.09	$K_{pm}=1.31$	$K_{pT}=499.99$
0.6		$K_{im}=0.059$	$K_{iT}=699.99$
0.3	11.16	$K_{pm}=1.32$	$K_{pT}=499.84$
0.7		$K_{im}=0.098$	$K_{iT}=638.18$
0.2	8.62	$K_{pm}=1.38$	$K_{pT}=61.7$
0.8		$K_{im}=0.38$	$K_{iT}=376.81$

**Figure 9: Cost functions found by the PSO optimization technique.**

It can be seen that the motor first starts with high torque reaches 100 mN.m, which causes high current consumption up to 4 A. After 0.01Sec torque and current consumption decreases to be almost zero because there is no torque load subjected to the motor. When the torque increased to 51mN.m, the motor current consumption is also increased to 2.5 A. Results proved that the PI controlled system is capable of delivering the required pump speed successfully.

II. Position Controller

The simulation of the position controller is accomplished by comparing the performance of the PID controller and PID-like FLC to produce the proper magnetic forces for the rotor suspension. The two controllers assumed to face eccentricity at the x and y axes at the start point. The displacement in the x-axis is -0.6 mm and the y-axis is -0.4 mm. A disturbance force (inference in two perpendicular axes) is subjected to the rotor. Figure 8 shows that double feedback lines are used. The outer loop (PID or PID-like FLC) is used for controlling the rotor position, while the inner loop (PI) is employed for controlling the amount and direction of the current for suspending the rotor. The PSO optimization technique is used to optimize the gain parameters for the PID controller (K_{ps} , K_{is} , K_{ds}), PI current controller gains (K_{psc} , K_{isc}), and PID-like FLC scaling factors ($N1$, $N2$, $N3$, and $N4$). For both PID and PID-like FLC maximum 30 iterations are used, particle size is 20, $c1$, and $c2$ both have the same value= 2, and w_{t+1} and w_{damp} are kept constants with the values 0.4 and 0.85, respectively. The fitness function designed to include the IAE calculated from the position responsibilities and the IAE calculated from the current response as:

$$F_{motor} = \text{minimize} (l \int_0^{\infty} |e_x| dt + n \int_0^{\infty} |e_y| dt + f \int_0^{\infty} |e_{crrt}| dt) \quad (13)$$

, where l , n , and f are weighting factors, and they are chosen as positive values with the condition: $l + n + f = 1$, e_x : is the error measured from the suspension controller of the x-axis, e_y : is the error

measured from the suspension controller of the y-axis, while e_{crnt} is the error measured from the current controller.

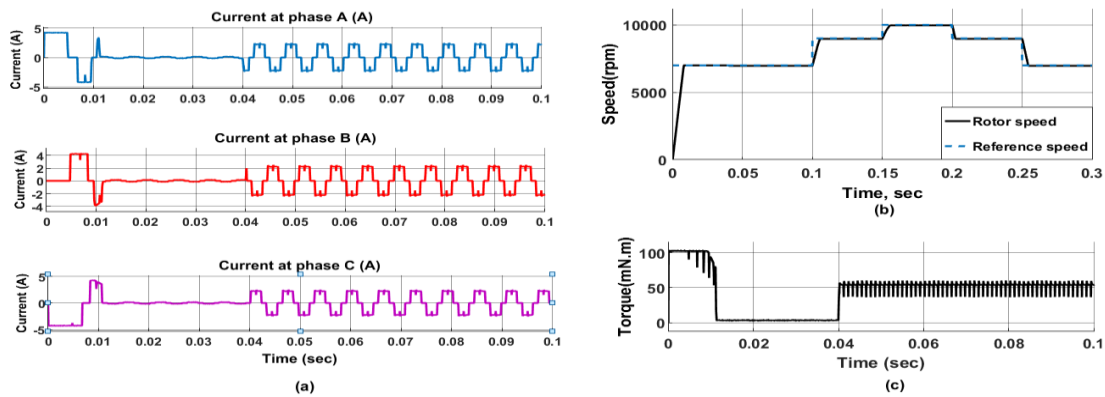


Figure 10: Responses of the PI current and PI speed controllers of BBLDC Motor, a) current in three phases, b) Motor speed response, and c) Motor torque.

Different values of the weighting factors (l , n , and f) give different best values for the controller's parameters and the optimized fitness values. In Tables IV and V, different values of l , n , and f , are tested to give different parameter values for the PID and PID-like FLC, respectively. The results show that different weighting factors give different values for the optimized IAE and parameter values each time. Figure 11.a shows the cost function of the PID controller for each case of Table IV while Figure 11.b shows the cost function of the PID-like FLC for each case of Table V in this Figure the values of the cost functions concentrates between 0.001 and 0.1, so to note the details clearly, the y-axis is plotted on a log axis. For testing the system responses, the values of the parameters that give the best IAE are chosen as: for the PID controller $l=0.4$, $n=0.4$, and $f=0.2$, and for the PID-like FLC are $l=0.4$, $n=0.4$, and $f=0.2$. For analyzing the response of the BBLDC motor under the PID controller and PID-like FLC two cases are considered without and with force disturbance.

A. Without Force disturbance

Figure 12 shows the performance of the BBLDC motor with a PID controller and PID-like FLC without applying disturbance. The motor is set for a reference speed of 9800 rpm. The comparison made in Table VI between PID and PID-like FLC responses at the x and y axes demonstrate that the PID-like FLC shows a better response, and suspend the motor more effectively than the PID controller. PID-like FLC shows a considerable enhancement,

TABLE IV: The best values found by the PSO in the PID controller.

l, n, f	G_{best}	Position controller parameter (PID)	Current controller parameters
0.1,0.1,0.8	0.2103	$K_{ps}=0.089, K_{is}=366.53, K_{ds}=0$	$K_{psc}=22.37, K_{isc}=141.06$
0.2,0.2,0.6	0.1643	$K_{ps}=0.024, K_{is}=110.63, K_{ds}=66.37$	$K_{psc}=80.32, K_{isc}=71.19$
0.3,0.2,0.5	0.1425	$K_{ps}=0.037, K_{is}=141.49, K_{ds}=21.61$	$K_{psc}=52.22, K_{isc}=109.61$
0.3,0.3,0.3	0.0737	$K_{ps}=0.0866, K_{is}=390.42, K_{ds}=113.55$	$K_{psc}=11.90, K_{isc}=145.68$
0.4,0.4,0.2	0.0489	$K_{ps}=0.111, K_{is}=424.49, K_{ds}=125.60$	$K_{psc}=4.177, K_{isc}=173.41$

TABLE V: The best values found by the PSO for the PID-like FLC.

L, n, f	G_{best}	Position controller parameter (PID-like FLC)	Current controller parameters
0.1,0.1,0.8	0.0635	$N1=6.75, N2=0.0006, N3=24.87, N4=51.85$	$K_{psc}=8.41, K_{isc}=146.63$
0.3,0.2,0.5	0.0430	$N1=11.46, N2=6.32 \times 10^{-4}, N3=28.45, N4=83.46$	$K_{psc}=166.48, K_{isc}=148.51$
0.2,0.2,0.6	0.0307	$N1=12.08, N2=0.0014, N3=16.16, N4=99.64$	$K_{psc}=4.76, K_{isc}=0.134$
0.3,0.3,0.3	0.0285	$N1=11.71, N2=0.0008, N3=35.79, N4=62.38$	$K_{psc}=45.51, K_{isc}=84.96$
0.4,0.4,0.2	0.0217	$N1=19.91, N2=0.0011, N3=34.65, N4=44.47$	$K_{psc}=60.82, K_{isc}=76.91$

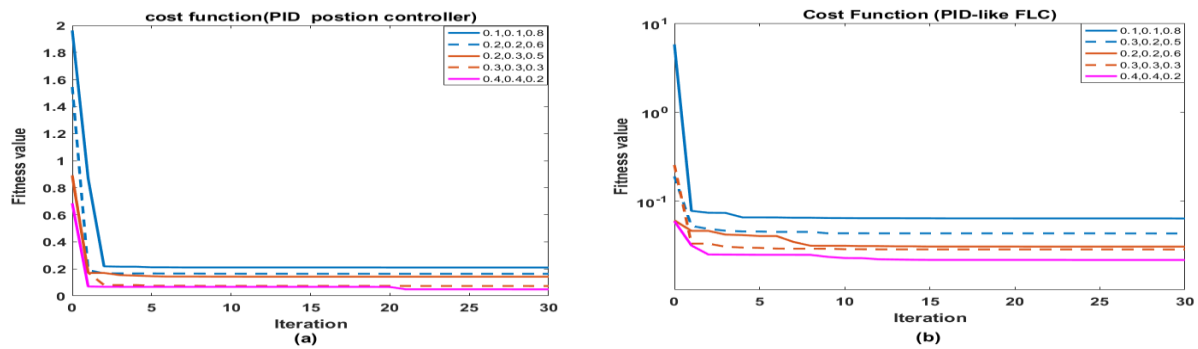


Figure 11: The cost function of the position controllers, (a) for the PID controller, (b) for the PID-like FLC.

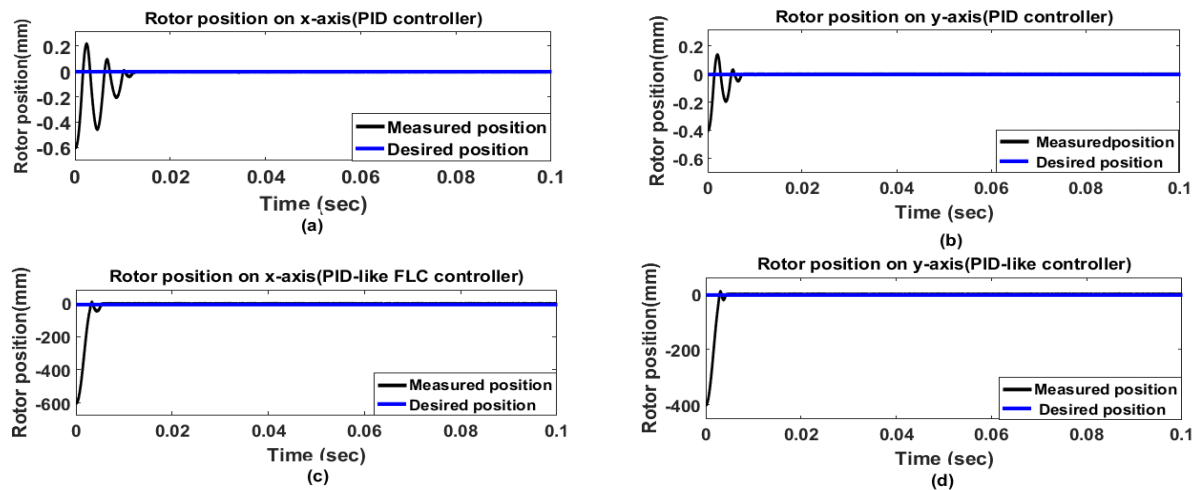


Figure 12: The response of the position controller, a) Response of the PID controller at the x-axis, b) Response of the PID controller at the y-axis, c) Response of the FLC at the x-axis, and d) Response of the FLC at the y-axis.

TABLE VI: Comparison between the two position controllers' responses

	PID Controller		PID-like FLC		Improvement%	
	x-axis	y-axis	x-axis	y-axis	x-axis	y-axis
Settling time (msec)	13	10.6	7.5	5.6	38.46	47.17
Overshoot (mm)	0.21	0.12	0.004	0.02	98.10	83.33
Undershoot (mm)	0.45	0.21	0.009	0.02	98.00	90.48
IAE for 0.1 sec	0.0148	0.0054	0.0075	0.00635	49.32	17.59

It can suppress the oscillation noticed in the response of the PID controller. Also, a noticeable enhancement occurred in the settling time to reach 38.46% at the x-axis, and 47.17% at the y-axis. IAE criteria used to measure the error in the position of the x and y axes, the results show an improvement in the PID-like FLC results as compared with the PID control about 49.32%, 17.59% at the x and y axes, respectively.

B. With force disturbance

When the effect of the inference between two perpendicular axes is introduced to the controllers, it is observed that the PID controller became unable to give correct controlling signals to produce a proper rotor suspension force, and the controller fails to handle the rotor. On the other hand, PID-like FLC manages to handle the effects of the disturbances, unfortunately, it shows an oscillation in the output signal before reaching the desired positions on the x and y axes, as shown in Figure 13.

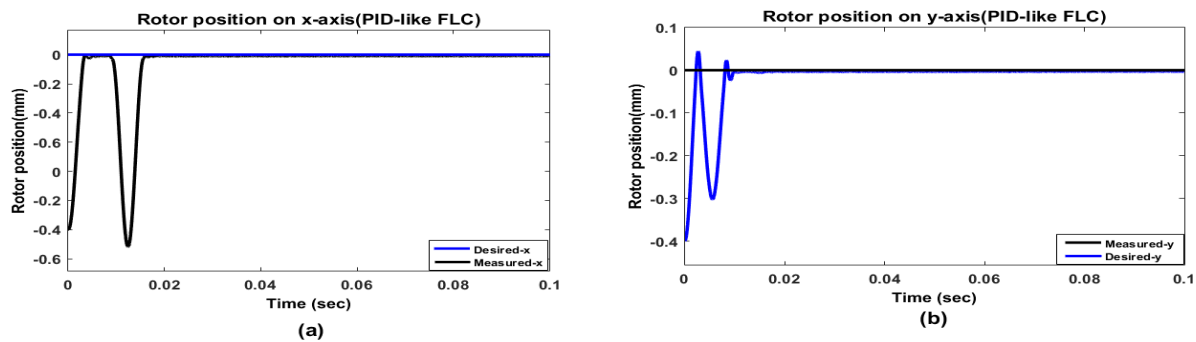


Figure 13: The response of the position controller under disturbance effect, A) Response of the PID-like FLC controller at x-axis) Response of the PID-like FLC at the y-axis

6. CONCLUSION

In this paper, a bearingless brushless DC motor for the heart pump has been simulated. The mathematical models of the rotary system and the suspension forces are illustrated. The controllers used Radial force winding current to produce suitable rotor suspension forces and to assure that the rotor is suspended without any contact with the stator inner surface. The model is simulated using MATLAB/Simulink. The simulated result verified the effectiveness of the proposed speed PI controller, which is found suitable to support variable motor speeds in a good time and the torque controller shows a good response to withstand the maximum load torque. Two force controllers have been tested to control the rotor position, PID controller, and PID-like FLC. Under similar conditions, the PID-like FLC shows a better response compared to the PID controller. When an inference between x- and y-axes is introduced to the design, the PID controller failed to control the suspension magnetic forces. Once a disturbance is introduced the controller lost its capability of controlling the system, there are other types of disturbances that may exhibit in the magnetic bearing system, and also the coupling between the motor and bearings may have major negative effects on the system. A linear controller cannot deal with the disturbances and the coupling effectively. Without disturbance, the measured enhancement is rated between 18% and 43%, measured by using the IAE criteria on the x and y axes. It showed a superior enhancement in the oscillation suppression, it almost canceled the oscillation observed at the beginning of the motor work. Also, a considerable enhancement in the settling time is achieved, it's rated between 38% and 47%. In this paper, all the controller's parameters are found by employing the PSO technique, to find the best values for the controller's parameters. PSO manages to produce an optimized result to achieve the best responses for the BBLDC motor system.

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