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BELBIC BASED HIGH PERFORMANCE IPMSM DRIVE FOR TRACTION

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ABSTRACT

This paper proposes a brain emotional learning based intelligent controller (BELBIC)for Interior Permanent magnet synchronous motor (IPMSM) drives used for traction application. The IPMSM is a suitable motor for traction because of its brushless, wide constant speed-power region and low power-loss operation. The operation of the BELBIC is based on the emotion processing mechanism in the brain. This intelligent control is stimulated by the limbic system of the mammalian brain. Dual feedback and online tuning of emotional controller assures enhanced performance of the drive system. Dual loop adjustable speed drive system is proposed in this paper for traction application. The conventional PI controller controls the speed but does not guarantee the stability of the machine during the load variation. PI controller makes the system unstable by windup action. In this paper novel methods such as the Fuzzy PI controller and BELBIC are proposed to improve stability. Current is controlled by PI controller and speed is controlled by Fuzzy PI controller and BELBIC. Speed and torque performance of the machine is improved by the Fuzzy PI controller and BELBIC compared to conventional PI controller in the IPMSM drive system.
Keywords: *PI, IPMSM, PWM, Fuzzy PI controller and BELBIC*

1. INTRODUCTION

Interior Permanent Magnet Synchronous Motors (IPMSM) fed by PWM inverters are widely used for industrial applications, especially servo drive applications [12],[22] in which constant torque operation is desired. In traction and spindle drives, on the other hand, constant power operation is desired. The inherent advantages of these machines are light weight, small size, simple mechanical construction, easy maintenance, good reliability, and high efficiency. Generally speaking, the applications of the IPMSM drive system [19] include two major areas: the adjustable-speed drive system and the position control system. The adjustable-speed drive system has two control-loops: the current loop and the speed loop. In general, the research has focused on improvement of the performance related to current loop, speed loop, and/or position loop[17].

The IPMSM drive system has been controlled using a PI controller due to its simplicity. Azizur Rahman M et al., 2003 examined IPMSM using PI controller which results in reduced steady state error. However, cannot provide good performance in both transient and load disturbance conditions. Several researchers have investigated the speed controller design of adjustable-speed IPMSM systems to improve their transient responses, load disturbance rejection capability, tracking ability, and robustness (Rebeiro R.S et al.,2012) have analyzed the performance of IPMSM using Fuzzy logic controllers for torque and speed. It improves system performance (Uddin M.N et al., 2004)by reducing ripples in torque but it increases processing time. M. Fazlur Rahman, Md. Enamul Haque Lixin Tang, and Limin Zhong, have studied the problem associated with DTC of IPMSM (Fazlur Rahman 2004). DTC has some smart features such as lesser parameter dependence, no requirement for mechanical rotor position sensor for the inner torque control loop and fast dynamic response. Even though it is difficult [14] to control torque and flux at very low speed, relatively high noise level at low speed and lack of direct current control. Nonlinear control theories [11] provide a systematic approach to control IPMSM. But these methods are complex to implement and very costly. So it is essential to

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implement a simple, effective and low cost system.

BELBIC was introduced [15] as a controller based on the computational model of the limbic system of the mammalian brain. In the past few years this controller has been utilized in control devices[16] and drives [24] for several industrial applications. So Artificial Intelligence based BELBIC is proposed to limit the overshoot and to reduce the settling time. It has the advantage of less processing time.

2. MATHEMATICAL MODEL OF IPMSM

The mathematical model of IPMSM is similar to that of wound rotor synchronous motor [20]. The following assumptions are considered in the model [18],[21]

1. The induced EMF is sinusoidal.
2. Eddy currents and hysteresis losses are negligible.
3. Saturation is neglected.

With these assumptions, the stator d, q axis equations of the IPMSM in the rotor reference frame are [3],[7].

$$U_q=R_s i_q+L_q p i_q+\omega_r L_d i_d+\omega_r \Psi_f \quad (1)$$

$$U_d=R_s i_d+L_d p i_d-\omega_r L_d i_q \quad (2)$$

Also flux linkage equation can be written as [7]

$$\Psi_d=L_d i_d+\Psi_f \quad (3)$$

$$\Psi_q=L_q i_q \quad (4)$$

where,

U_d and U_q are the d, q axis voltages,

i_d, i_q are the d, q axis stator currents,

L_d and L_q are the d, q axis inductances,

Ψ_d and Ψ_q are the d, q axis stator flux linkages,

R_s is the stator winding resistance per phase

ω_r is rotor electrical speed .

The electro mechanical torque is given by

$$T_e=(3/2)(P/2)[\Psi_f i_q-(L_d-L_q)i_d i_q] \quad (5)$$

where P is the number of poles, T_L is the load torque, B is the damping co-efficient, ω_m is the rotor mechanical speed, J is the moment of inertia and p is the differential operator [1].

$$\omega_r=(P/2)\omega_m \quad (6)$$

Where θ_m is the position angle of the rotor.

In order to achieve maximum torque per ampere and maximum efficiency, direct axis current component i_d is forced to be zero [4].

$$T_e=(3/2)(P/2)\Psi_f i_q \quad (7)$$

The d, q variables are obtained from a, b, c variables through the park transform [10].

$$U_q=2/3[U_a\cos\theta+U_b\cos(\theta-2\Pi/3)+U_c\cos(\theta+2\Pi/3)] \quad (8)$$

$$U_d=2/3[U_a\sin\theta+U_b\sin(\theta-2\Pi/3)+U_c\sin(\theta+2\Pi/3)] \quad (9)$$

The a, b, c variables are obtained from the d, q variables through the inverse of the park transform [5],

$$U_a=U_q\cos\theta+U_d\sin\theta \quad (10)$$

$$U_b=U_q\cos(\theta-2\Pi/3)+U_d\sin(\theta-2\Pi/3) \quad (11)$$

$$U_c=U_q\cos(\theta+2\Pi/3)+U_d\sin(\theta+2\Pi/3) \quad (12)$$

3. SIMULATION MODEL OF IPMSM DRIVE

The IPMSM drive system consists of speed loop, current loop, park transformation, PWM inverter and IPMSM motor. Block diagram of IPMSM drive is shown in figure 1.

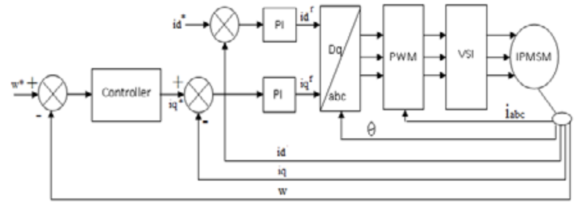

Figure 1: Block Diagram Of IPMSM Drive

Speed loop has three inputs such as reference speed, measured speed and i_q. Its output is reference current of i_q^*.

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Error of reference speed and measured speed is given to the proposed/ PI controller. Output of speed controller is compared with the measured i_q. This error signal produces i_q reference when it passes through PI controller. Current loop has i_d* and i_d as inputs. Its output is reference current i_d. Error of i_d* and i_d is given to the PI controller to produce reference current of i_d. Inverse Park transformation receives the two reference current signals from speed loop and current loop. It converts that current i_d and i_q into i_a , i_b & i_c. The I_{abc} produced by inverse park transformation is the reference current for Pulse Width Modulator.

PWM inverter consists of a Hex bridge IGBT inverter and PWM generator. PWM generator receives reference signal from inverse park transformation. This signal is compared with the carrier signal and produces 3 pulses. These pulses are used to trigger the upper switches in the three arms. The pulse to the upper switch in the arm is inverted and given to the lower switch in the arm. From the inverter three phase voltage is taken out.

4. SPEED CONTROLLER

Set speed of the machine is achieved by optimum tuning of controller in a speed control loop. Performance of IPMSM drive using various controllers are analyzed in this paper. Fuzzy PI and Brain emotional learning based intelligent controller are proposed and compared with the conventional PI controller.

4.1 PIController

The conventional PI controller is the simplest method of feedback control and widely used in industries. Proportional plus Integral Controller increases the speed of response. It produces very low steady state error. This is because derivative action is more sensitive to higher-frequency terms in the inputs.

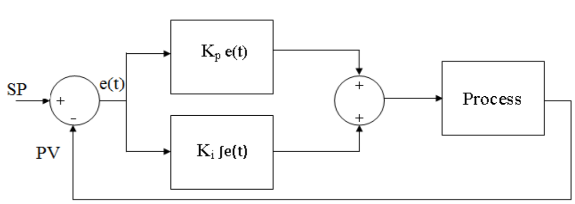

Figure 2: Block Diagram Of PI Controller

Figure 2 shows the block diagram of PI controller. In this paper Speed error (e (t)) is taken as input to PI controller and output is taken into the system. General equation of the PI controller is

$$u(t) = k_p\, e(t) + k_i \int e(t) \qquad (13)$$

$$e(t) = SP - PV \qquad (14)$$

e (t) is the error of actual measured value (***PV***) from the set-point (***SP***). k_p is proportional gain, k_i is the integral gain and u(t) is the controller output.

In this paper Ziegler Nichols' method of tuning is implemented to find the optimum value of K_p & K_i values. In an IPMSM drive PI controller is used in both loops such as speed loop and current loop. It is an optimum controller for the current loop. In case of speed loop it produces the high overshoot, long settling time and drop in speed while change in load.

4.2 Fuzzy PI Controller

The fixed value of Kp and K_i in a PI controller produces the high overshoot, settling time and speed drop during a change in load. Online tuning of K_p and K_i in a PI controller can conquer this problem. It necessitates the Fuzzy PI controller for online tuning of K_p and K_i.

In a Fuzzy PI controller Fuzzy logic module is considered as an auto tuning module for parameters K_p and K_i in PI controller. The Fuzzy PI controller is considered the major contribution of this research [9] ,[11],[21]. The fuzzy inference of fuzzy PI controller is based on the fuzzy associative matrices. The calculation of the speed of the controller is very quick, which can satisfy the rapid need of the controlled object. The block diagram of control system is shown in Figure 3.

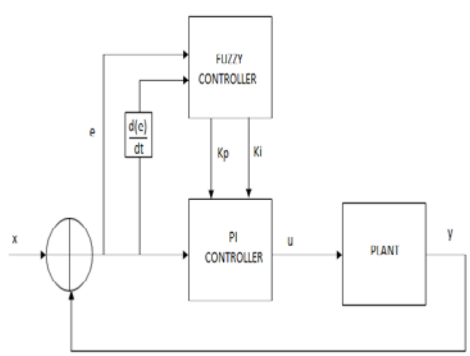

Figure. 3: Fuzzy PI Controller Block Diagram

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The control algorithm of traditional PI controller can be described as

$u(k) = k_p e(k) + k_i \int e(k)$

where, k_p is the proportional gain, k_i is the integral gain and e (k) is the speed error.

The design algorithm of Fuzzy PI controller in this paper is to adjust the k_p and k_i parameters online through fuzzy inference based on the current speed error e and error change rate ec to make the control object attain the good dynamic and static performances.

Speed error e and error change rate ec are used as fuzzy input and the proportional factor k_p the integral factor k_i are used as fuzzy outputs. The degree of truth of E and EC are configured as 5 degrees, all defined as {NB, NS,ZO, PS, PB}, where NB, NS, ZO, PS and PB represent negative big, negative small, zero, positive small and positive big respectively.

The degree of truth of KP and KI configured as 4 degrees, are defined as {Z, S, M, B}, where Z, S, M and B represent zero, small, medium and big. The membership functions of E, EC, KP and KI are triangular distribution functions. The membership functions for each variable are shown in Figure 4, Figure 5 and Figure 6 respectively.

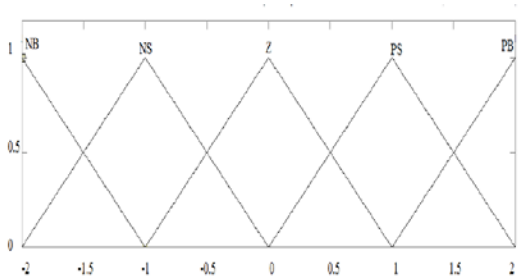

Figure 4: Fuzzy Membership Functions Of E And EC

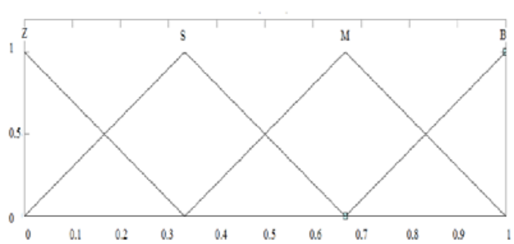

Figure 5: Fuzzy Membership Functions Of KP

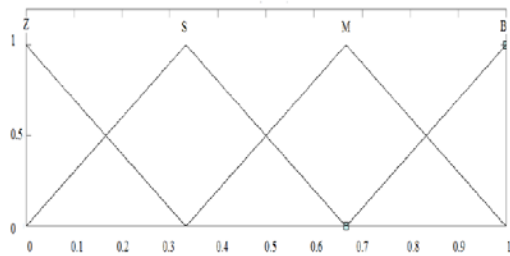

Figure.6: Fuzzy Membership Functions Of KI

The principle of designing fuzzy rules is that the output of the controller can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized as table I and table II according to the expert experiment in the PMSM servo system and simulation analysis of the system. The Mamdani inference method is used as the fuzzy inference mode. The inference can be written as

"IF E is NS AND EC is PS THEN KP is S, KI is M". KP and KI are written the same as 25 fuzzy condition statements. The MIN - MAX method of fuzzification is applied. The weighted average method is adopted for defuzzification.

TABLE 1: The Control Rules For K_p

e	NB	NS	ZO	PS	PB
NB	Z	Z	Z	Z	Z
NS	M	M	M	M	M
ZO	B	B	Z	B	B
PS	S	M	M	M	M
PB	Z	S	B	B	B

TABLE 2 : The Control Rules For K_i

E	NB	NS	ZO	PS	PB
NB	B	B	B	B	M
NS	M	B	S	S	S
ZO	M	B	Z	S	B
PS	S	S	S	S	S
PB	M	B	B	M	B

The fuzzy PI controller reduces the overshoot, settling time and drop in speed during load change. Even though it produces some overshoot which should be reduced to improve the

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performance of drive, it necessitates the simple and effective artificial intelligent controller.

4.3 BELBIC Controller

To enhance the speed performance a controller with less processing time, easy and effective control BELBIC is proposed in this paper. It is proposed to reduce the overshoot, settling time and drop in speed during change. It can be achieved by proposing BELBIC because it is a dual feedback controller. PI and Fuzzy PI are single feedback controllers.
BELBIC receives speed error of machine as one of the feedbacks and the BLEBIC output as another feedback. It results in accurate tuning of controller based on the present state.

BELBIC is based on the architecture of the "Limbic System" of the human brain. The limbic system is responsible for the emotional learning in human beings. Figure 7 shows the block diagram of BELBIC controller.[27]

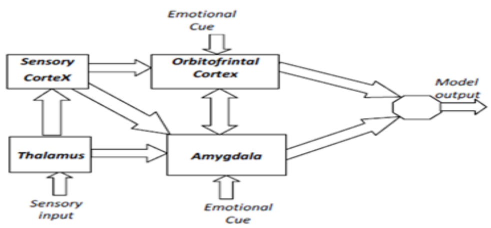

Figure 7: Block Diagram Of BELBIC

BELBIC is a simple composition of the Amygdala and Orbitofrontal cortex in the brain. A simple limbic system of the brain is shown in Figure 8.

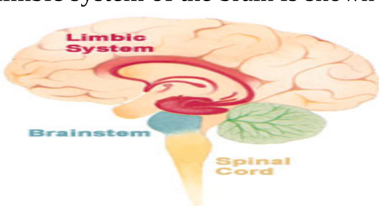

Figure 8: Limbic System Of Brain

Pre-processing on sensory input signals such as noise reduction or filtering can be done in Thalamus. The emotional evaluation of stimulus signal is carrying out through the Amygdala, which is a small part in the medial temporal lobe in the brain. As a result, this emotional mechanism is utilized as a basis of emotional states and reactions.

At first, Sensory Input signals are going into Thalamus for pre-processing on them. In this paper speed error is considered as Sensory input. Then Amygdala and Sensory Cortex will receive their processed form and their outputs will be computed by Amygdala and Orbitofrontal based on the Emotional Signal received from the environment. Final output is the subtraction of the Amygdala and Orbitofrontal Cortex. One of the Amygdala's inputs is called Thalamic connection and calculated as the maximum overall Sensory Input S as in equation (15). This specific input is not projected into the Orbitofrontal part and cannot by itself be inhibited and therefore it differs from other Amygdalas' inputs.

$$A_{th}=i_{max}S_i \tag{15}$$

Every input is multiplied by a soft weight V in each A node in Amygdala to give the output of the node. The O nodes behaviors produce their output signal by applying a weight W to the input signals as well as A nodes. To adjust the Vi difference between the reinforcement signal rew and the activation of the A nodes is been made use. For tuning the learning rate the parameter is used and it is set to a constant value. As shown in equation (16) Amygdala learning rule is an example of simple associative learning system, although this weight adjusting rule is almost monotonic. For instance, Vi can just be increased.

$$\Delta_i vi = \alpha(s_i i \max(o, rew - \textstyle\sum A_i j)) \tag{16}$$

α Is the learning step in the Amygdala. The reason of this adjusting limitation is that after training of emotional reaction, the result of this training should be permanent, and it is handled through the Orbitofrontal part when it is inappropriate [6]. Subtraction of reinforcing signal from previous output E makes the signal of reinforcement for O nodes. To put it in another way, comparison of desired and actual reinforcement signals in nodes O inhibits the model output. The learning equation of the Orbitofrontal Cortex is drawn in Eq. (17).

$$s_i \textstyle\sum(o_j - rew) \tag{17}$$

The amygdala and Orbit frontal learning rules are much alike, but the Orbitofrontal weight W can be changed in both ways to increase and decrease as needed to track the proper inhibition. And rule of β in this formula is similar to the α ones. Simulation model of BELBIC is shown in

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figure 9.

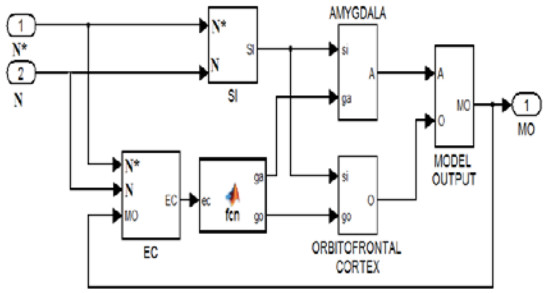

Figure 9: Simulation Model Of BELBIC

Mathematics the Linear Model of BEL Controller is represented by Following Simplified Equations

$$A = G_A.SI \quad (18)$$

$$O = G_{OC}.SI \quad (19)$$

$$(dG_A A)/dT = \alpha \mathbf{SI}(ES - A) \quad (20)$$

$$\frac{dG_{OC}}{dT} = \beta.\mathbf{SI}(A - OC - ES) \quad (21)$$

$$MO = A - OC \quad (22)$$

where MO is Model Output, SI is Sensory Input, ES is Emotional Sensor, A is Amygdala Output, O is Orbitofrontal Cortex, α is Learning rate of Amygdala, P is Learning rate of Orbitofrontal cortex, G_A is Gain for Amygdala , G_{OC} is Gain for Orbitofrontal Cortex. Based on the above equations mathematical model of BELBIC is formed. Since BELBIC is purely formed by the arithmetic equations it is ease to implement and consumes less processing time

5. SIMULATION RESULTS AND DISCUSSIONS

IPMSM dive is simulated using MATLAB/Simulink. IPMSM dive is analyzed using conventional PI controller. Then the same system is analyzed with Fuzzy PI controller and BELBIC. For the analysis load changes during run time. Reference speed and load are same for all PI, Fuzzy PI controller and BELBIC.

The simulation model of IPMSM drive is shown in figure 10

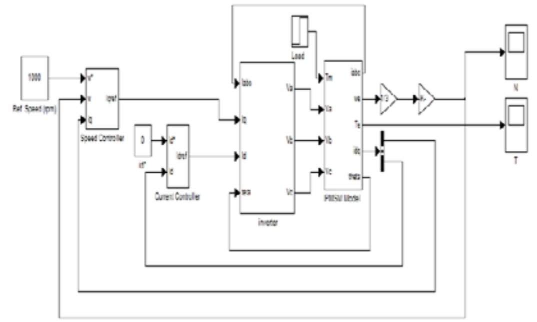

Figure 10: Simulation Model Of Ipmsm Drive

The parameters of IPMSM used in this simulation model are given in table 3,

Table 3 :Ipmsm Parameters

Parameters		Value
Stator Resistance	Rs	1.4 Ω
Direct axis inductance	L_d	6.6 mH
Quadrature axis inductance	L_q	0.0116H
Moment of Inertia	J	0.00176 $Kg.m^2$
Rotor flux linkage	φ_f	0.1546 Wb
Number of poles	P	6

The results of IPMSM drive system using a conventional PI controller for speed is shown in figure 11 and figure 12.

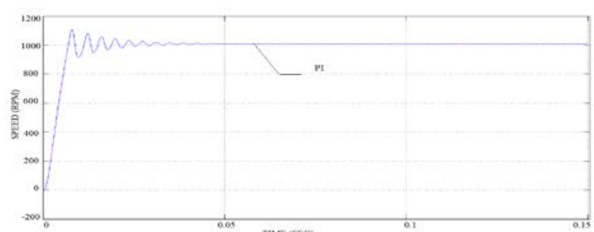

Figure 11: Speed Response Of IPMSM Drive Using PI Controller.

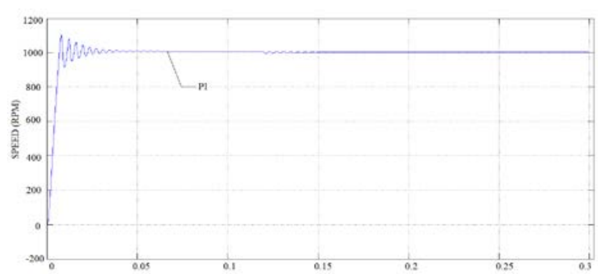

Figure 12 : Speed Response Of IPMSM Drive Using A PI Controller With Change In Load

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The results of IPMSM drive system using proposed Fuzzy PI controller for speed is shown in figure 13 and figure 14.

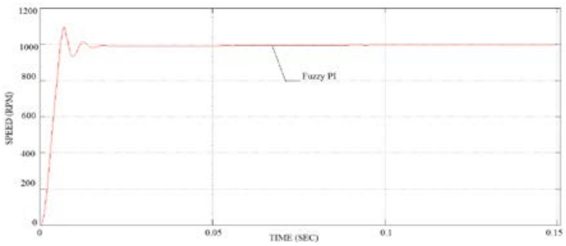

Figure 13: Speed response of IPMSM drive using a Fuzzy PI controller.

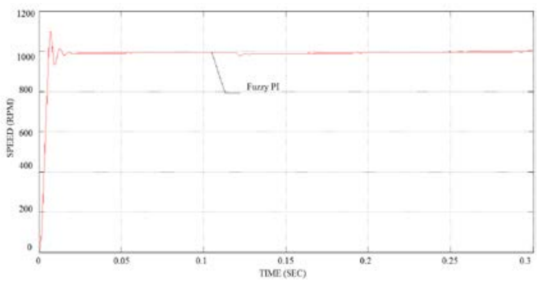

Figure 14: Speed Response Of IPMSM Drive Using A Fuzzy PI Controller With Change In Load.

The results of IPMSM drive system using the proposed Emotional controller for speed is shown in figure 15 and figure 16.

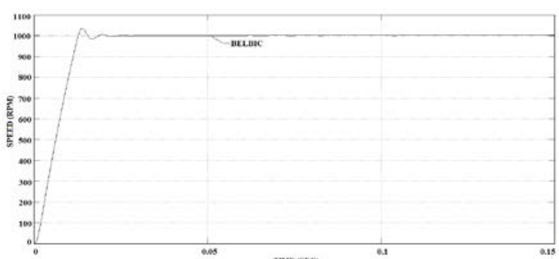

Figure 15: Speed Response Of IPMSM Drive Using BLEBIC.

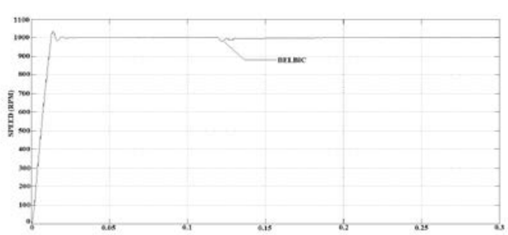

Figure 16: Speed Response Of IPMSM Drive Using BLEBIC With Change In Load.

Comparison of speed response of IPMSM drive using PI, Fuzzy PI and BLEBIC controller is shown in figure 17.

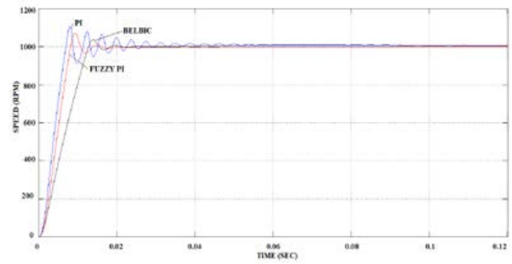

Figure 17: Comparison Of Speed Response Of IPMSM Drive Using PI, Fuzzy PI And BLEBIC Controller

Speed response of IPMSM drive using BLEBIC at various speed references such as rated speed, above rated speed and below rated speed is shown in figure 18.

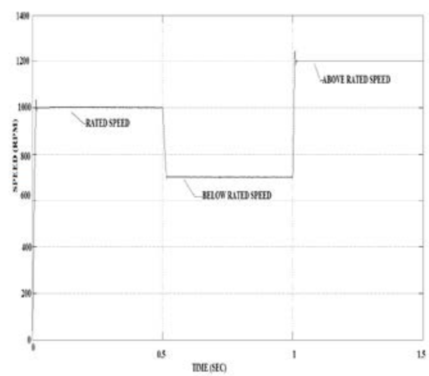

Figure 18: Speed Response Of IPMSM Drive Using BLEBIC At Various Speed References

The comparison of controller performance for speed $\omega_m =$ 1000 RPM using PI, Fuzzy PI and BLEBIC controller are tabulated in Table 4.

TABLE 4: Comparison Of Controller Performance

Controller	Peak overshoot %	Steady state error %	Speed drop during load %	Settling time after load Sec
PI	11	0.6	0.4	0.04
Fuzzy PI	7	0.3	0.2	0.02
BLEBIC	3.5	0.1	0.18	0.018

6. CONCLUSION

The essential characteristics of traction motor are accurate speed and stability during load change. In this paper three types of controllers PI, Fuzzy PI and BLEBIC are used as speed controllers in the IPMSM control and simulated in Matlab / Simulink. The performance of the system is analyzed with all three controllers and compared. From the simulation results it is clear that system performance is improved by Fuzzy PI and BLEBIC controller. The Fuzzy PI controller improves speed response compared to conventional PI controller in terms of overshoot, steady state error, drooping speed during load change and settling time after load change.

BLEBIC controller is better than PI and Fuzzy PI controller in terms of stability. It quickly settles in speed after load change compared to other two controllers. Meantime BLEBIC controller produces the same response for rated speed, above rated speed and below rated speed of the machine. Simulation results show the robust performance of BELBIC against the disturbance. The BLEBIC controller based IPMSM drive is suitable for traction to operate in a wide speed range and frequent load changing condition.

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