

Real- time implementation of parallel type fuzzy- PID controller for effective control of hybrid Pole self bearing Switched reluctance motor

R.S.R. Krishnam Naidu^{1*}, U. Salma²

¹Department of EEE, GITAM University, Visakhapatnam.

²Associate Professor, Department of EEE, GITAM University, Visakhapatnam

*Corresponding author E-mail: naidueee06@gmail.com

Abstract

This paper presents a hybrid intelligent and design in a real time for the rapid prototyping of a robust fuzzy controller along with conventional Proportional– Integral and Derivative (PID) controller that allows quick insight of these integrated designs. The design procedure of the parallel fuzzy PID and its combination with the traditional PID in a universal control scheme are extended. The structural design of the parallel fuzzy PID controller is composed of three fuzzy sub controllers which are connected in parallel. These parallel sub controllers are assembled to get the proposed parallel fuzzy type PID controller. The hybrid fuzzy PID gains are expressed in the error domain. Hence, the structural design presents an alternative to control schemes employed so far. This hybrid intelligent controller is formulated and executed in real world hardware for position as well as speed control of a Hybrid Pole Self Bearing Switched Reluctance Motor (HPSBSRM) drive system. The design of the parallel fuzzy PID controller, implementation and finally analysis all are carried out using MATLAB/Simulink environment. Software results concluded that the novel hybrid intelligent parallel fuzzy PID controller generates better control action when compared to traditional PID controller, predominantly in system nonlinearities and in external load variations.

Keywords: Classical PID control, hybrid intelligent parallel fuzzy PID controller, hybrid pole bearing less switched reluctance motor, real time implementation, MATLAB/Simulink.

1. Introduction

With the beginning of digital signal processors (DSPs), digital skill has impacted significantly on the motion control engineering. The accessibility of sophisticated languages has permitted the beginning of software design methodologies and testing procedures. A new combination of neural fuzzy controller has been tested for reference tracking positions with robustness has been found in [1-4]. An evolutionary algorithm (EA) based fuzzy –PID type adaptable controller has been introduced for a PMSM drive in real time can be found in [5-6]. Brain-emotional-learning-based intelligent controller has been adopted and implemented for induction motor drives in a real-time platform in [7], the working of this controller is mainly based on the input data of sensors and emotional cues. A single neuron artificial neural network has been proposed to interior permanent magnet synchronous motor (IPMSM) [8] it doesn't require offline training and wide knowledge of the motor behavior of various drive systems. A direct model reference intelligent rule based controller has been applied to a highly nonlinear system with the requirement of a little knowledge on the overall system and its variable parameter values [9]. Design of Fuzzy PID Controller in a parallel combination and is implemented for Brushless Motor Drives for high performance [10]. Implementation of new hybrid type controller for electric drive control has been found in [11]. Adaption of fuzzy PID controller is introduced in [12- 14] by merging the fuzzy rule based system with the PID controller to get better performance. Self tuning mechanism of PID controller has been applied for controlling the position and shaping in actuators

and simulations for this self tuned fuzzy PID controller on the servo motor presented in [16-17]. For the bearing less SRM, the design of hybrid stator and enhancement of electromagnetic forces has been presented in [18-21].

Due to the absence of proper tuning methods for conventional PID gains, researchers have been focused on design and implementation of widespread and easy methods in order to tuning the controller gains. In literature only a few papers addressed the problems in motion control industry even though it is a serious issue. Consequently, a designer required an integrated design from initial stage of code generation to develop satisfactory control system. Hence this paper presented a hybrid type integrated rapid prototype control of a robust parallel fuzzy PID controller using a MATLAB/Simulink environment. This hybrid fuzzy PID controller is obtained by integrating three parallel fuzzy sub controllers.

The fuzzy PID gains are obtained from the parallel assembled sub controllers and are realized from the intelligent knowledge based fuzzy inference; hence each individual sub controller engenders the control signal. The feedback signals are generated to tune the gains in online in terms of human knowledge based fuzzy inference system. The process of tuning is proposed for hybrid intelligent controllers in order to achieve good dynamic as well as steady state performance.

This tuning mechanism for the fuzzy PID gains is implemented such that control signal obtained at fuzzy inference is always less than the saturation limit. Matlab/Simulink results have been presented the proposed hybrid intelligent parallel fuzzy PID controller offers much enhanced performance on position as well as speed than the conventional PID control.

As the currents drawn by the converters are reduced by this proposed controller, the losses are reduced as result efficiency has been improved.

2. 12/14 self bearing switched reluctance motor

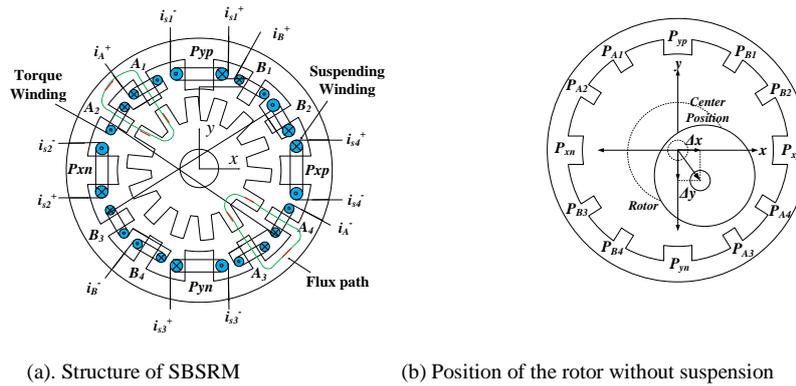


Fig.1: structure of the SBSRM and position of the rotor without suspension

A 12/14 SBSRM and its structure is shown in Fig.1 (a). SBSRM has eight torque pole (A1 to A4 which are in series connection to form A-Phase winding and B1 to B4 which are in series connection to form B-Phase winding as shown in fig.1), 4 radial force poles (Ps1, Ps2, Ps3 and Ps4) on stator, 4 radial force poles (Ps1, Ps2, Ps3 and Ps4), are independently connected in x and y directions and 14 poles on rotor. The generated torque shows the independent nature with the generated radial force, hence torque and suspension forces can be controlled independently. As shown in fig.1(a), this motor used higher portion of stator poles for generating torque, hence improve power density, and decrease the requirement of magneto motive force (MMF) and also decrease the iron and copper losses (core losses). Fig.2. shows the Prototype of SBSRM. Table-I shows the dimensions of the SBSRM. Fig.6 depicts the real-time hardware control mechanism of both torque and axial force controlling of the SBSRM. X* and Y* are the command displacement signals, the values of command displacements are zero, it means that rotor is being in center position. These command displacement signals have been compared with the signals which are coming from two displacement sensors, one is placed in X-direction and another one is placed in Y direction. The sensitivity of the displacement sensors is 5V/mm. the error signals are given to the conventional PID controller. The output of the PID controllers are Fx* and Fy*, these are the command forces need to bring the rotor to center position. These command forces are converted into command currents and compared with suspension currents. The error current signals are given to the PWM logic block and generate PWM signals to the 4- phase asymmetric converter. This 4-phase converter suspends the rotor to the center position according the generated PWM signals. Now encoder giving the position information of the rotor, from this position speed is calculated using speed estimator block and this speed is compared with the speed command W* (reference speed). The error speed is given to the PI controller and generates command current im* and is compare with the motor torque currents (IA and IB) and this signal is given to the PWM block to generate the PWM signals to 2-phase asymmetric converter. This 2-phase converter drives the rotor according to the generated PWM signals. The total radial or suspending force generated by a HPSBSRM expressed as in equation (1)

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix} \begin{bmatrix} i_x^2 \\ i_y^2 \end{bmatrix} \quad (1)$$

Here

$$K_x = \frac{\mu_0 N^2 L_{stk} r}{4l_{G12}^2} (\beta_r + K_f) \quad (2)$$

$$K_y = \frac{\mu_0 N^2 L_{stk} r \theta'}{4l_{G12}^2} (\beta_r + K_f) \quad (3)$$

$$\begin{bmatrix} \dot{i}_x^{*2} \\ \dot{i}_y^{*2} \end{bmatrix} = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix} \begin{bmatrix} F_x^* \\ F_y^* \end{bmatrix} \quad (4)$$

where, μ_0 is the absolute permeability of the medium (air), N is the coil turns in number, L_{stk} is the length of stack, r is the rotor radius, g is the air gap length, K_f is a fringing constant of inductance, β_r is the radial stator pole arc length. The currents for the respective poles (4) can be calculated from the force calculation (1). i_x^* and i_y^* are the command currents and F_x^* and F_y^* are the command forces.

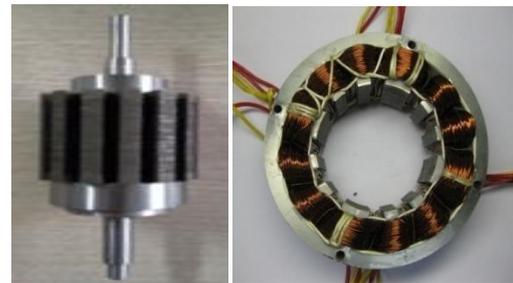


Fig.2: Prototype of SBSRM

The proposed hybrid intelligent fuzzy PID controller connected in parallel with three fuzzy sub-controllers. The gains of the controller values are update in online. Fig. 7 illustrates the structural design of the proposed hybrid intelligent parallel fuzzy PID controller and its combination with the traditional PID controller. Each individual fuzzy sub controller has error (result of actual speed subtracted from set speed) and change in error (the delayed feedback control signal Du) as two inputs and a corresponding fuzzy variable as an output. The delayed control signal Du can be represented in three independent control input signals as. DUP, DUI, DUD, for each corresponding fuzzy sub controllers. The rotor speed error treated as one fuzzy variable and is represented with seven fuzzy sets like, three positive sets PL, PM and PS, one zero set ZE and three negative sets named NL, NM and NS. An output control signal decision can be generated based on this input fuzzy sets information for speed and position error signal. In the same manner each individual delayed signal has been generated by integrating the overlapped fuzzy. Each individual sets having their own

membership function (Triangular MF has been considered in this paper, since the dynamics of the system has not been effected by the shape of the membership function and for simplicity of programming) for the speed as well as for position error. Inputs for the fuzzy membership functions are depicted in Figs. 8 and fig.9. FKP, FKI, and FKD are the outputs of the fuzzy control decisions of the each individual sub controller and are directly taken from the fuzzy knowledge and the fuzzy inference base. The singleton shapes have been considered for each fuzzy output membership function. Fig.10 illustrates the membership functions considered for each fuzzy response. Weighted average de-fuzzification has been utilized to process the output membership functions Fig. 3 illustrates the distribution of flux of the 12/14 type SBSRM and from this figure it can be observed that the drawback of long flux path can be avoided and forming short flux path. Which results decrease in stator MMF and leads to lessen the stator as well as rotor core losses. Hence efficiency has been increased.

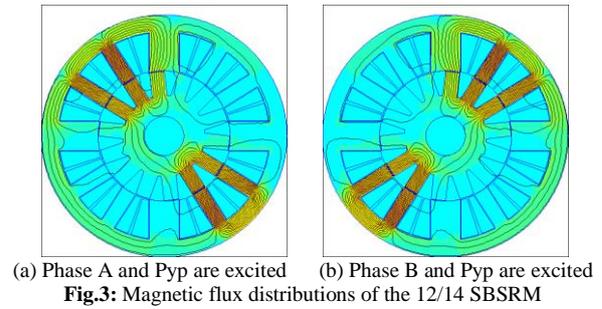


Fig. 3: Magnetic flux distributions of the 12/14 SBSRM

Fig. 4 depicts the inductance characteristics of both torque and suspension windings. Rotor position has been taken in terms of per unit (PU). One PU gives one rotor pole (26 degrees in mechanical). From this figure it can be noticed that torque winding inductance has been varying with respect to rotor position and suspension winding inductance is remains constant with respect to the rotor position. Hence the torque generated by the suspension winding has no influence on torque generated by the torque winding. These types of characteristics know as decoupling characteristics.

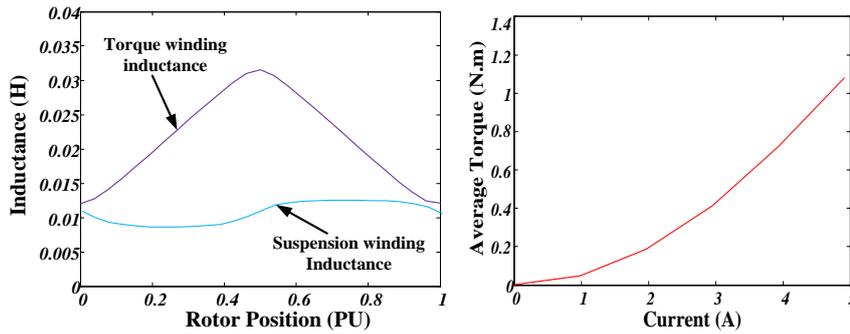


Fig.4: Inductance profiles of torque and suspension windings. Fig.5: Average torque of 12/14 SBSRM

Fig. 5 depicts the average torque generated by the 12/14 SBSRM. This average torque is larger than the previous structures

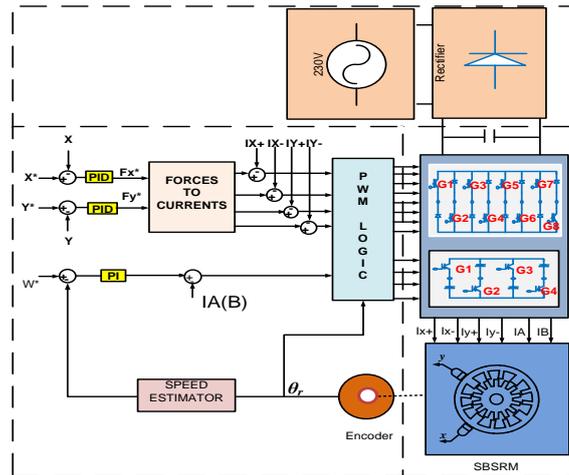


Fig.6: Control scheme of SBSRM

Table I: DIMENSIONS OF SBSRM

| Parameter | SBSRM | |
|-------------------------------|--------------------|------------|
| stator poles | 12 | |
| rotor poles | 14 | |
| Arc angle | Stator torque pole | 12.85(deg) |
| | Stator axial pole | 25.7 (deg) |
| | Rotor pole | 12.85(deg) |
| Length | Axial stack | 40(mm) |
| | Air gap | 0.3(mm) |
| Diameter | Outer stator | 112 (mm) |
| | Inner stator | 60.2 (mm) |
| Yoke thickness of rotor (mm) | 7.7(mm) | |
| No. of winding turns per pole | Torque | 80 |
| | Axial force | 100 |

3. Proposed fuzzy PID controller

After assigning the fuzzy sets to input variables of each individual fuzzy sub controller the next step is to determine the IF- THEN inference rules. The formulation of fuzzy rules are depends on the product of number of input fuzzy sets. In this case the input variables used for speed error consists of seven fuzzy sets and also input variables used for delayed control signal having seven fuzzy sets. Hence a total number of forty-nine rules are required. The forty nine fuzzy rules have been written on the basis of practical knowledge of the hybrid pole bearing less switched reluctance motor drive.

General fuzzy rule structure is as follows:

Rule (1): IF error is $F_j 1$, and D_u is $F_j 2$ THEN f is $Cl 1$, for $j = 1, \dots, 3, l = 1, \dots, 3$.
 Rule (2): IF error is $F_j 1$, and D_u is $F_j 2$ THEN f is $Cl 2$, for $j = 1, \dots, 3, l = 1, \dots, 3$.
 Rule (3): IF error is $F_j 1$, and D_u is $F_j 2$ THEN f is $Cl 3$, for $j = 1, \dots, 3, l = 1, \dots, 3$.
 Rule (k): IF error is $F_j 1$, and D_u is $F_j 2$ THEN f is $Cl k$ for $j = 1, \dots, 3, l = 1, \dots, 3, k = 1, \dots, 9$.

Min operator has implemented the fuzzy operation called "intersection" which estimate the combination of the rule antecedents the above represented fuzzy rule has strength. This rule strength usually stands for the degree of membership of the output variable for a particular rule. The strength of the rule symbolized with ξ_i, j of a exacting rule and is defined in equation (1)

Rule structure for selecting the suspension poles:

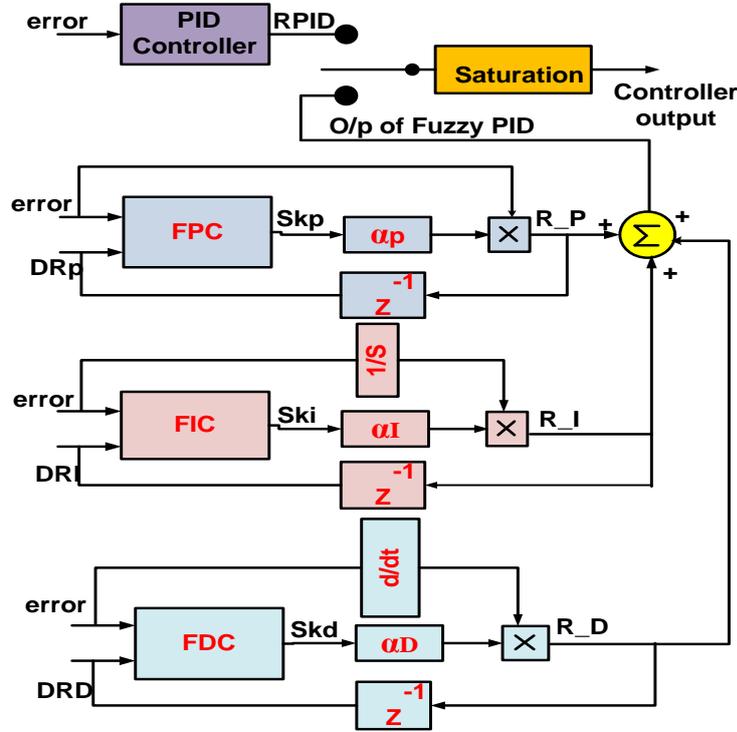


Fig.7: Implementation of the hybrid fuzzy PID controller.

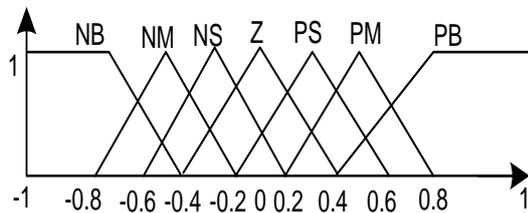


Fig.8: Membership functions for speed error.

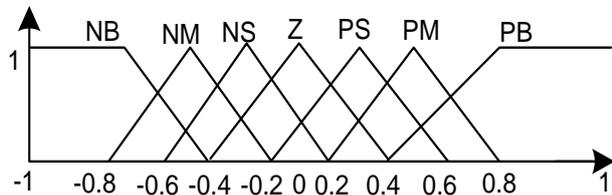


Fig.9: Membership functions for the delayed control signals.

Finally these multiple outputs can be decoding to generate actual or crisp value as an output control signal by using de fuzzification interface. This paper presents the center-average defuzzifier. The crisp output control signals of each individual fuzzy sub controller is given by

$$f(error, D_R) = \frac{\sum_{l=1}^9 \mu O^l \left(\min_{i=1,2} (\mu S_i^l (error, D_R)) \right)}{\sum_{l=1}^9 \left(\min_{i=1,2} (\mu S_i^l (error, D_R)) \right)} \quad (6)$$

Equation (6) can be written as equation (7)

$$f(error, D_R) = \theta^T \xi (error, D_R) = \xi^T (error, D_R) \Phi \quad (7)$$

Where,

Φ = Degree of output membership ($\mu O_1, \dots, \mu O_9$)

Where 'i' is related to fuzzy variable of speed as well as position error and 'j' is related to fuzzy variable, delayed control signal [PL, PM, PS, ZE, NL, NM, NS]. The fuzzy logic system uses the suitable designed knowledge base to estimate the given fuzzy rules by an expert and constructs an output for each rule accordingly.

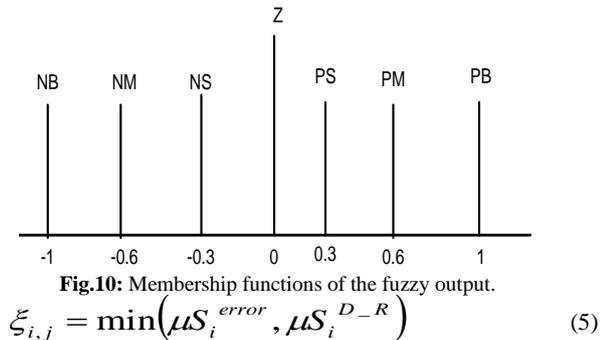


Fig.10: Membership functions of the fuzzy output.

$$\xi_{i,j} = \min(\mu S_i^{error}, \mu S_i^{D-R}) \quad (5)$$

$$\xi^l(error, D_R) = \frac{\min_{i=1,2}(\mu_{S_i^l}(error, D_R))}{\sum_{l=1}^9 \left(\min_{i=1,2}(\mu_{S_i^l}(error, D_R)) \right)} \quad (8)$$

The derived output of fuzzy PID can be composed as equation (5)

$$Out\ of\ fuzzy\ PID(K) = R_P(K) + R_I(K) + R_D(K) \quad (9)$$

The control signals of the fuzzy P, fuzzy I and fuzzy D sub controllers are given below in equation (10), (11) and (14) respectively

$$P(K) = S_p(error, D_R_p) G_p * error(k) \quad (10)$$

$$P(K) = f_i(error, D_U_i) G_i \sum_{i=0}^K error(i) \Delta t, \quad k = 0, 1, 2, \dots \quad (11)$$

$$D(K) = S_D(error, D_R_D) G_D \frac{\delta e(k)}{\Delta t} \quad (12)$$

Where,

αP = Scaling factor to the delayed proportional control signal,

αI = Scaling factor to the delayed integral control signal

αD = Scaling factor to the delayed derivative control signal.

FKP, FKI and FKD = Tuning parameters provided by the output of each fuzzy inference mechanism.

On the basis of trial and error method, these scaling factors are calculated. as a result, the three noticeable outputs of the each sub controllers can be expressed as

$$Fuzzy_K_C = f_C(error, D_U_p) \quad ; \quad C = P, I, D$$

Where,

C = P for proportional controller, 'I' for integral controller, 'D' for derivative controller

Equation (9) shows the final output of fuzzy PID controller with Saturation.

$$u(k) = \begin{cases} S_{max}(k) & S_{SPID}(k) > u_{max}(k) \\ S_{SPID}(k) & S_{min}(k) \leq S_{SPID}(k) \leq S_{max}(k) \\ S_{min}(k) & S_{SPID}(k) < S_{min}(k) \end{cases} \quad (13)$$

Where,

Smin and Smax = Minimum and Maximum permitted inputs to the proposed drive system.

4. Rapid control prototyping

The Real time input- output (RTIO) board and MATLAB/ Simulink successfully formed a rapid control environment shown in Fig.11, in which controller has been designed using Simulink environment rather than programming control languages. The reference signals for X-directional displacement, Y-Directional displacement and speed are shown in fig.11. These reference signal blocks can be dragged from the Simulink environment. These three reference signals are amplified using gain blocks and compared with the actual outputs of the proposed SBSRM. Comparators are designed to compare reference and actual signals and to generate the error signal to the proposed controller. Each fuzzy Sub controller shown in fig. 11 has been performed independently to control the overall tracking goal. Classical PID controller output is compared with the output of fuzzy PID controller. This fuzzy PID controller in X-displacement has three individual sub controllers and the output of these sub controllers are summed to get overall controller output and then compared with conventional PID controller. This process is similar in Y-directional displacement and speed. Once the controller is designed using Simulink's block diagram, the feedback signals can be given to the controller and the controller taken care the feedback signals and generates the pulse width modulation (PWM) signals according to the controlling algorithm. These generated PWM signals can be given to the driver circuit to drive the IGBT's.

Using this RTIO, one can skip the process of generating the C-code form the Simulink building blocks, hence every change in Simulink controller algorithm shows the instantaneous effect on real-time hardware. The designer's are very much sufficient basic knowledge in MTLAB/Simulink for designing the controller. The sampling frequency of 10 kHz is used. Using this RTIO environment, designers can well carry out MATLAB/simulations, develop both conventional as well as intelligent control laws and can easily evaluate the simulated response, easily developed the controllers to the real-time environment.

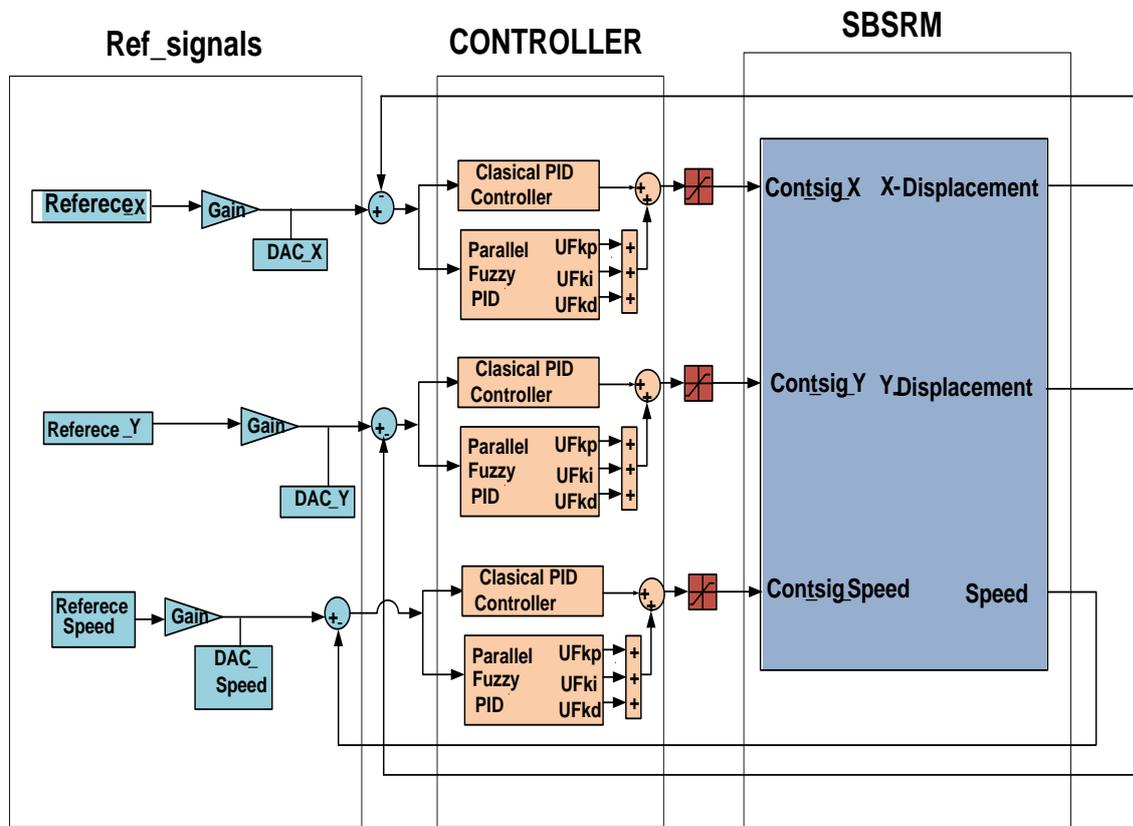


Fig.11: Rapid prototype control of proposed SBSRM

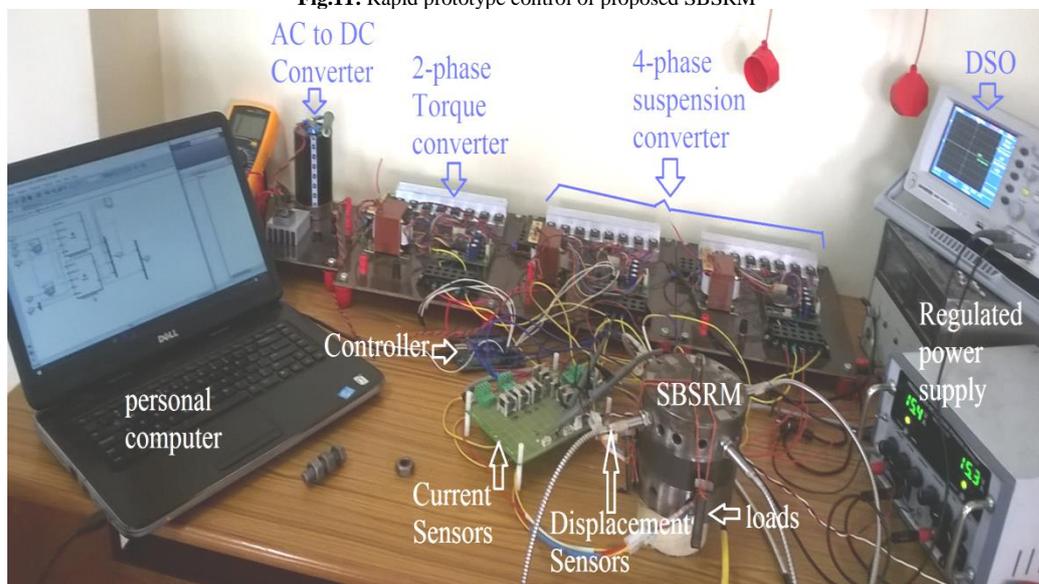


Fig.12: Photograph of the experimental apparatus

5. Hardware system description

The hardware Set up is shown in fig.12. this setup consists of Real time input- output (RTIO) board, personal computer (PC), an AC to DC converter for, which provides DC power supply to the torque winding asymmetric converter, (0-230V) separate regulated power supply for suspending winding radial force converter, a driver circuit to drive the both torque and suspending converters, a novel structured self bearing switched reluctance motor (SBSRM) with X- directional loading arrangement is shown in hardware setup. The DSP control board forms closed loop operation with proper feedbacks from encoder and displacement sensors for the effective controlling of SBSRM with loading and external disturbances. The acquired feedback signals are computed and generates error signal for the proposed controller and this controller will calculate the error information and responds in an intelligent manner with

reference to the given rule based data. This entire controller algorithm is placed in Simulink environment and Interfacing with 28377 DSP board. The motor is 280V, 3A, 400W, four phase suspension and two phase motor. PWM controlling algorithm is placed in personal computer. Generated Pulses are amplified with driver circuit and given to the torque and radial for converters. For torque winding converter DC power supply is given form the AC to DC rectifier and for suspension converter DC power supply is given form the Regulated power supply, with can deliver maximum of 10A. ACS 712 current sensors are used to measure the feedback currents form torque and suspension winding and these currents can be shown in digital oscilloscope (DSO).

6. Results and discussion

Case1: suspending the rotor to the center position



Fig.13 (a) shows the rotor eccentricity displacement in X-Direction and 10(b) shows the rotor eccentricity displacement in Y- Direction when the suspension control algorithm is applied, eccentric errors in the two directions can be rapidly reduced to zero, which means that the rotor can be kept in the center position. Fig.14 shows Suspending force winding currents (i_{xp} , i_{xn} , i_{yp} and i_{yn}), from suspension winding currents it is cleared that the windings in negative x-directional and positive y-directional windings only drawing the current to bring the rotor to the center position. The currents in positive X-directional and negative Y-directional windings are zero. It means that the de-centered rotor has been centered by means of energizing the respective stator suspension poles. From fig.14 it is also obvious that the proposed controller exhibits better performance than the conventional controller. The

suspension currents drawn by the PID controller is 2A in both X and Y- Displacements and also having ripples. The suspension currents drawn by the proposed controller is 1A in both X and Y-suspension windings and has no current ripples. Hence copper losses are reduced hence efficiency is being improved. Fig.15 shows the comparison of the Suspension forces (F_x & F_y) in X and Y- Directions with Proposed parallel fuzzy PID controller. The load of 10N has been applied in X and Y- Directions. From the Suspension forces it is cleared that the proposed controller generates more force than the conventional controller in both negative x-directional and positive y-directional windings to bring the rotor to the center position. Consequently the respective suspension winding currents drawn by the coverer is less.

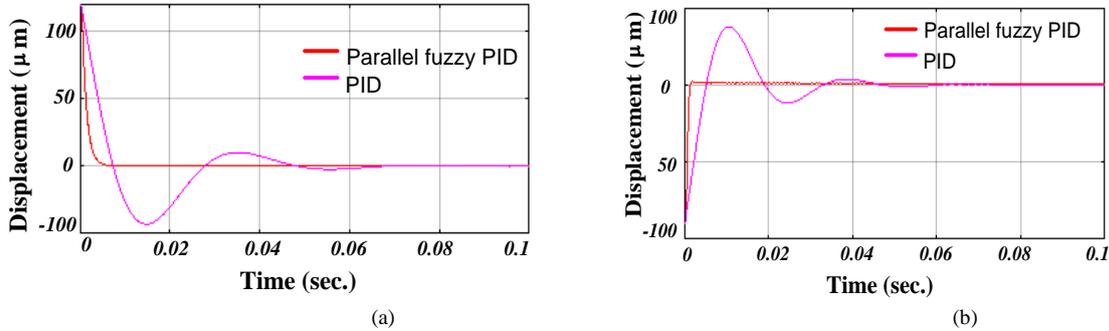


Fig.13: Rotor eccentricity displacement in (a) x- Displacement, (b) Y- Displacement at suspending condition

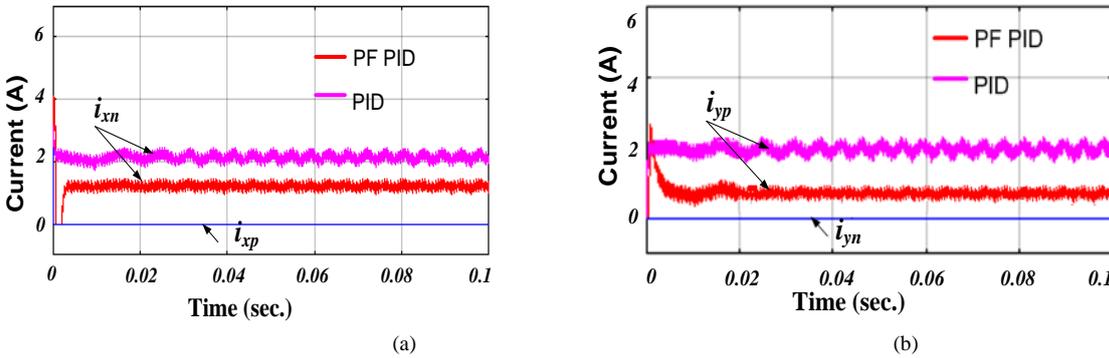


Fig.14: Suspending force winding currents (a) negative x-directional pole (b) positive y-directional pole at suspending condition

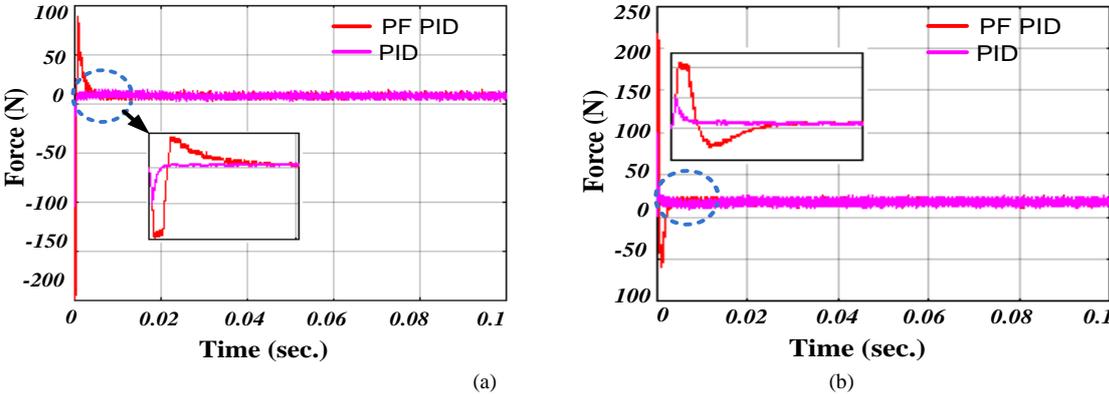


Fig.15: Suspending force at suspending condition (a) X-Direction (b) Y-Direction

Case2: Accelerating the rotor to the desired speed

Initially there are no torque winding currents for the SBSRM (in case 1). In this case load (N-m) has been placed on the shaft, and hence torque winding currents are taken from the 2-phase asymmetric converter to reach the desired or set speed as shown in fig.16. Motor starts rotate and can reach the set speed value in a faster rate with the parallel fuzzy PID controller when comparing with the conventional PID controller and also exhibits no ripples in speed during steady state period. Fig.16. shows comparison of A-phase and B-phase winding currents with proposed controller, here noticed that magnitude of phase winding currents are less after reaching the motor to a set speed with the proposed controller and hence the losses in the converter can be reduced and rating of the device can also be reduced in order to save the converter cost.

Fig.17. shows the comparison of shaft torque with proposed controller, as we know that the generated torque in the SBSRM is proportional to the phase winding currents and hence the generated torque is at starting is about 0.8 N.m, which is same as that of the conventional PID controller but at the steady state condition the torque generated by the proposed controller generates optimized torque for the same load. Fig.18 shows that shaft displacements at both suspending and rotating conditions applied simultaneously. As we know that both suspension and torque controlling are completely individual to each other hence the injection of torque winding currents in case (ii) has not been showing any affect on the suspension winding currents, even though little fluctuations can be observed, the shaft is still in center position. These fluctuations are now reduced with the proposed controller as shown in the fig.19.

The forces generated to bring the rotor shaft to the center position are shown in fig.20, it can be noticed that with the proposed

controller the suspension force generated is more at the time of starting to bring the rotor to the center position quickly.

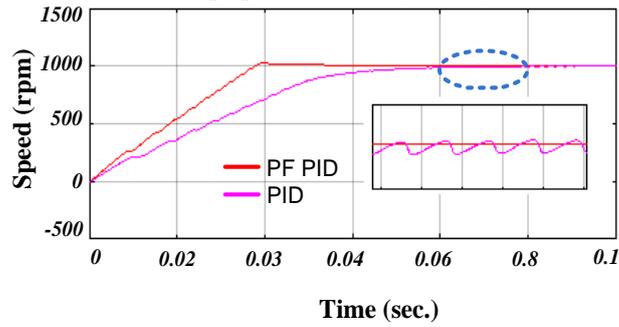


Fig.16: Comparison of speeds with proposed controller

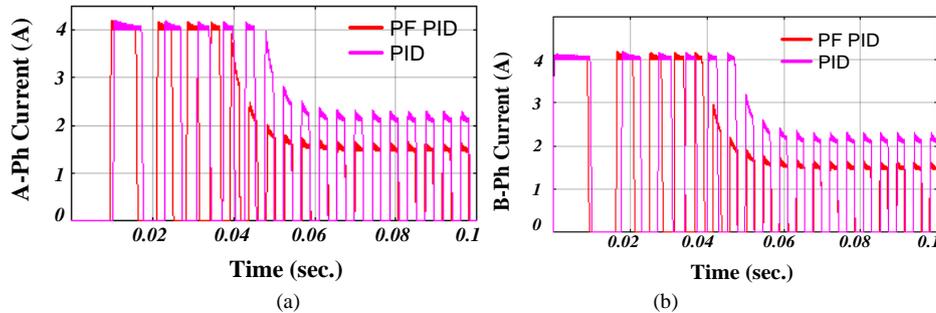


Fig.17: Comparison of phase winding currents with proposed controller (a) A-Phase winding current, (b) B-Phase winding current.

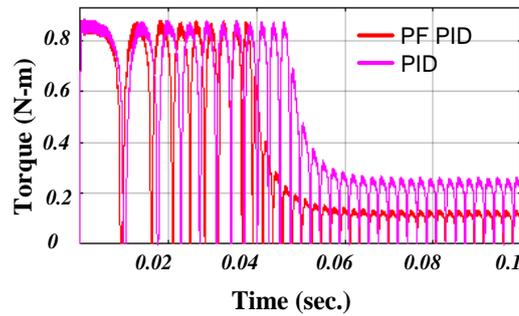


Fig.18: Comparison of shaft torque with proposed controller

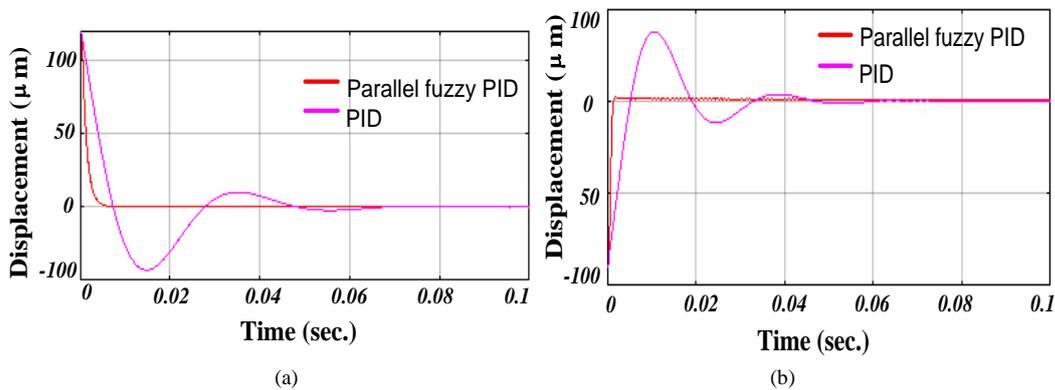


Fig.19: Shaft displacements at both suspending and rotating condition

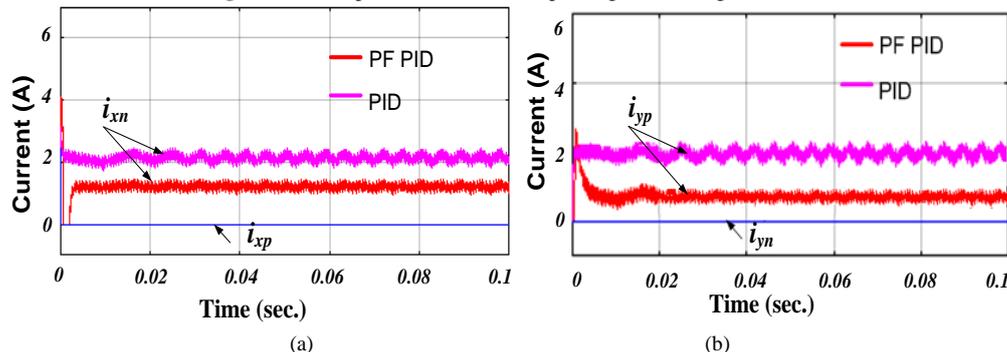


Fig. 20: Suspending force winding currents at suspending and rotating condition (a) negative x-directional pole (b) positive y-directional pole at suspending condition

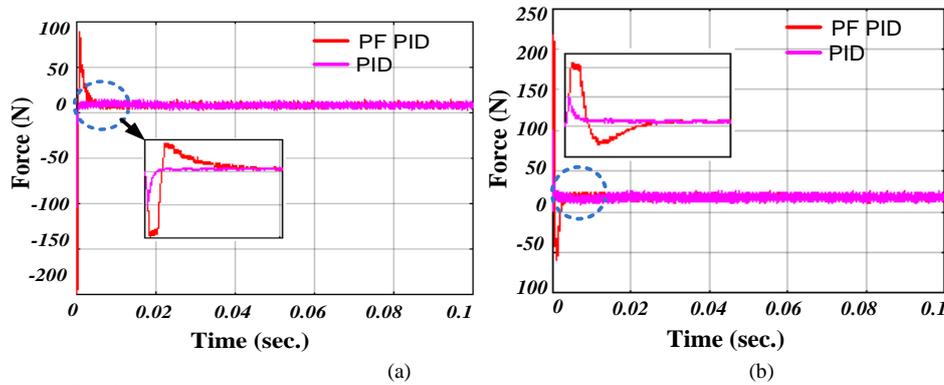


Fig. 21: Suspending force at suspending and rotating condition (a) X-Direction (b) Y-Direction

7. Experimental Results

Fig.21. Shows that X-directional and Y-directional displacements for suspension algorithm alone, it can be observed that these displacements have been settled at zero positions. Fig. 22(a) shows that displacements with PID controller when suspension load is decreased suddenly form 2N to 1N, it can be observed that conventional PID controller is showing unstable performance. Fig. 22(b) shows displacements with proposed parallel fuzzy controller, it can be observed that proposed controller exhibits stable operation when comparing with the conventional PID controller when the suspension load is suddenly decreased from 2N to 1N. Fig. 24 (a) shows that the speed of the SBSRM with the conventional PID controller, it can be seen that it has been settled to the desired speed with more oscillations and settled after four time divisions. Fig. 24(b) shows the A-Phase and B-Phase torque winding currents with PID controller, it can observed that initially torque winding

currents are more nearly 4A at the time of starting and later on settled to the lower currents after motor reached to the set speed. Up to five time divisions these huge currents has been carried out hence device gets heated up. Fig. 25(a) shows the speed with the parallel fuzzy PID controller, it can be observed that the speed is exhibiting less ripples and also has settled to a command speed in a short duration. Fig.25(b) shows the A-Phase and B-Phase torque winding currents with parallel fuzzy PID controller, it can observed that magnitude of starting currents are reduced from 4A to 2A and later on settled to the lower currents nearly to 1A after motor reached to the command speed. As the speed has settled in a faster rate with proposed controller, the torque winding currents also has been settled quickly to the lower values immediately after motor reaches to the command speed. Hence the IGBT device is no longer carry large currents for longer duration and the possibility of device getting heated up is reduced. Hence one can go for lower ratings of the device and cost can be reduced and efficiency also can be improved.

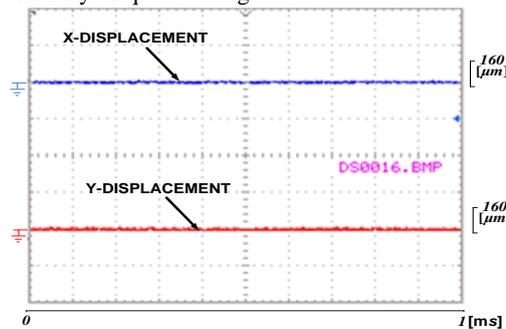


Fig.22: Displacements settled at zero positions without rotor rotation

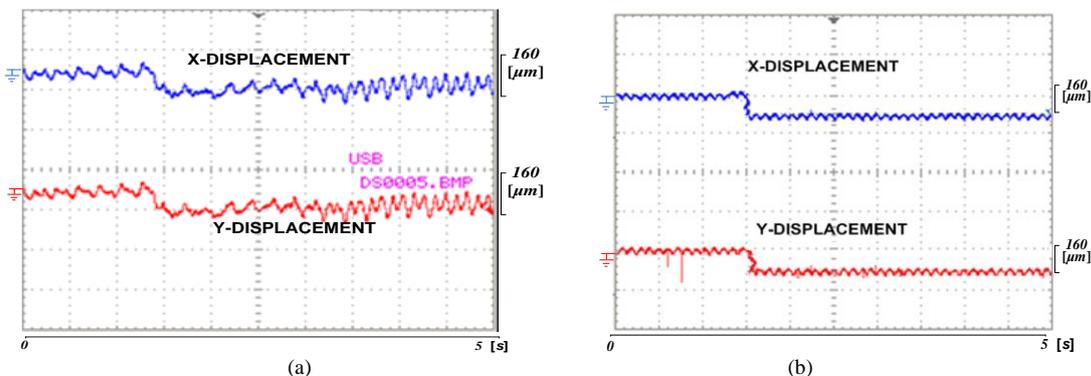


Fig.23: Displacements (a) With PID controller (b) With proposed controller. When suspension load is decreased suddenly form 2N to 1N

Fig.25: (a) Speed with Parallel Fuzzy PID Controller. (b). Torque Winding currents with Fuzzy controller

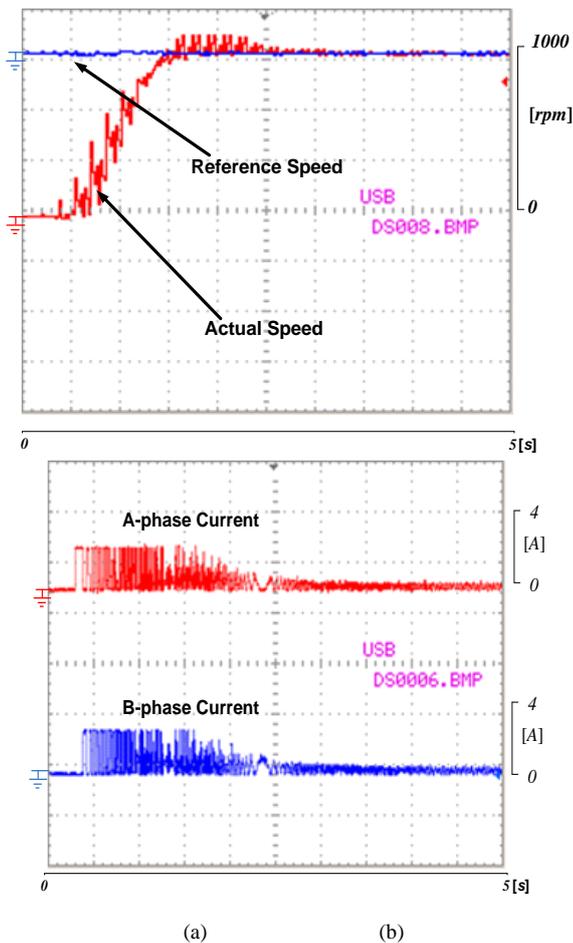
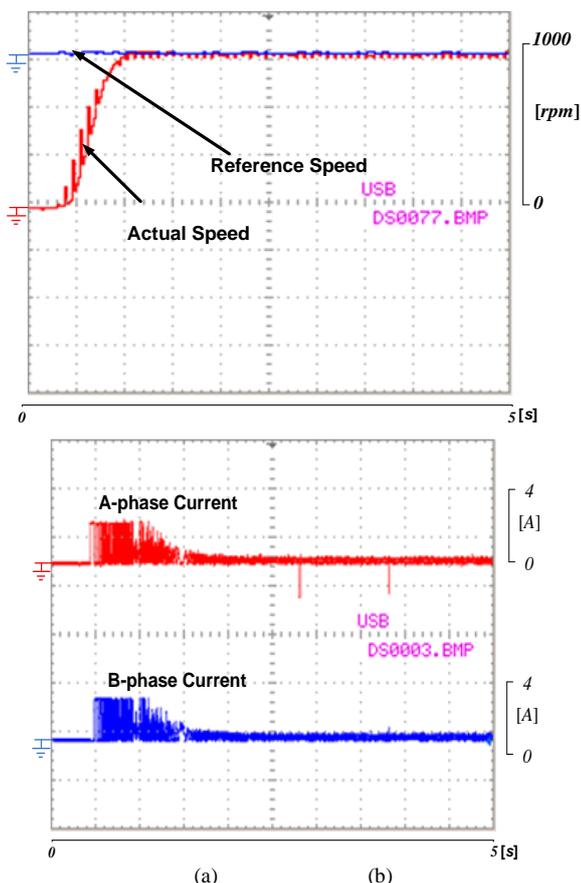


Fig.24: (a) Speed with PID controller. (b) Torque winding currents with PID controller



8. Conclusion

A robust fuzzy PID controller in a parallel structure has been developed in real-time to Hybrid Pole Self Bearing Switched Reluctance Motor and described in detail in this paper. The integrated fuzzy with conventional PID controller has been put into practice and tested practically. Results have proved with an excellent unique tracking performance with proposed fuzzy integrating PID controller and established the usefulness of this controller in motor drive with uncertainties of rotor displacement parameters in both X-direction and Y-direction respectively. The effectiveness of the proposed controller has been shown in results by comparing with the conventional PID controller and has been proved that it is efficient. The practical implementation has been based on RTIO (Real Time input output) and MATLAB/Simulink environment. The combination of RTIO and MATLAB/Simulink/RTW created an effective rapid prototype control environment. In this paper the designer has mainly focused on designing of controller for speed as well as for position controlling of the HPSBSRM.

References

- [1] Faa-Jeng L, Kai-Jie Y, I-Fan S, & Jin-Kuan C, "Intelligent position control of permanent magnet synchronous motor using recurrent fuzzy neural cerebellar model articulation network", *IET Electric Power Appl.*, Vol.9, No.3, (2015), pp.248 – 264.
- [2] Chih-Min L & Hsin-Yi L, "Intelligent Control Using the Wavelet Fuzzy CMAC Backstopping Control System for Two-Axis Linear Piezoelectric Ceramic Motor Drive Systems", *IEEE Transactions on Fuzzy Systems*, Vol.22, No.4, (2014), pp.791 – 802.
- [3] Fayez F & El-Sousy M, "Intelligent Optimal Recurrent Wavelet Elman Neural Network Control System for Permanent-Magnet Synchronous Motor Servo Drive", *IEEE Transactions on Industrial Informatics*, Vol.9, No.4, (2013), pp.1986 -2003.
- [4] El-Sousy FFM, "Robust wavelet-neural-network sliding-mode control system for permanent magnet synchronous motor drive", *IET Electric Power Applications*, Vol.5, No.1, (2011), pp.113-132.
- [5] Han Ho C, Hong Min Y & Yong K, "Implementation of Evolutionary Fuzzy PID Speed Controller for PM Synchronous Motor", *IEEE Transactions on Industrial Informatics*, Vol.11, No.2, (2015), pp.540 – 547.
- [6] Fayez FM, El-Sousy K & Abuhasel A, "Self-Organizing Recurrent Fuzzy Wavelet Neural Network-Based Mixed H2/H ∞ Adaptive Tracking Control for Uncertain Two-Axis Motion Control System", *IEEE Transactions on Industry Applications*, Vol.52, No.6, (2016), pp.5139 – 5155.
- [7] Markadeh GR, Ehsan D, Caro L & Azizur Rahman M, "Speed and Flux Control of Induction Motors Using Emotional Intelligent Controller", *IEEE Trans. Ind. Appl.*, Vol.47, No.3, (2011), pp.1126 – 1135.
- [8] Casey BB & Azizur Rahman M, "Intelligent Speed Control of Interior Permanent Magnet Motor Drives Using a Single Untrained Artificial Neuron", *IEEE Trans. Ind. Appl.*, Vol.49, No.4, (2013), pp.1836 – 1843.
- [9] Mojtaba Ahmadi K, Yesim O, Okay K & Huijun G, "Direct Model Reference Adaptive Fuzzy Control of Networked SISO Nonlinear Systems", *IEEE/ASME Trans. Mechatronics*, Vol.21, No.14, (2016), pp.205 – 213.
- [10] Ahmed R, Marcel J, Castro S & Abdul RO, "Design and Implementation of Parallel Fuzzy PID Controller for High-Performance Brushless Motor Drives: An Integrated Environment for Rapid Control Prototyping", *IEEE Transactions on Industry Applications*, Vol.44, No.4, (2008), pp.1090 – 1098.
- [11] Cheng M, Sun Q & Zhou E, "New self-tuning fuzzy PI control of a novel doubly salient permanent-magnet motor drive", *IEEE Trans. Ind. Electron.*, Vol.53, No.3, (2006), pp.814-821.
- [12] Lee CD, Chuang CW & Kao CC, "Apply Fuzzy PID Rule to PDA Based Control of Position Control of Slider Crank Mechanisms", *Proceedings of IEEE International Conference on Cybernetics and*



- Intelligent Systems and Robotics, Automation and Mechatronics*, (2004), pp.508-513.
- [13] Kha NB & Ahn KK, "Position Control of Shape Memory Alloy Actuators by Using Self Tuning Fuzzy PID Controller", *Proceedings of IEEE International Conference on Industrial Electronics and Applications*, (2006).
- [14] Huang X & Shi L, "Simulation on a Fuzzy-PID Position Controller on The CNC Servo System", *Proceedings of the IEEE Sixth International Conference on Intelligent Systems Design and Applications*, (2006), pp.105- 309.
- [15] Lee CD, Chuang CW & Kao CC, "Apply Fuzzy PID Rule to PDA Based Control of Position Control of Slider Crank Mechanisms", *IEEE Conference on Cybernetics and Intelligent Systems*, Vol.1, (2004), pp.508-513.
- [16] Kha NB & Ahn KK, "Position Control of Shape Memory Alloy Actuators by Using Self Tuning Fuzzy PID Controller", *Proceedings of IEEE International Conference on Industrial Electronics and Applications*, (2006).
- [17] Huang X & Shi L, "Simulation on a Fuzzy-PID Position Controller on The CNC Servo System", *Proceedings of the IEEE Sixth International Conference on Intelligent Systems Design and Applications*, (2006), pp.105-309.
- [18] Morrison CR, Siebert MW, Ho EJ, "Electromagnetic Forces in a Hybrid Magnetic-Bearing Switched-Reluctance Motor", *IEEE Transactions on Magnetics*, Vol.44, No.12, (2008), pp.4626 - 4638.
- [19] Huijun W, Dong-Hee L, Tae-Hub P & Jin-Woo A, "Hybrid stator-pole switched reluctance motor to improve radial force for bearing less application", *Energy Conversion and Management*, Vol.52, No.2, (2011), pp.1371-1376.
- [20] Wang H, Wang Y, Liu X, Abn JW, "Design of novel bearing less switched reluctance motor", *IET Electric Power Applications*, Vol.6, No.2, (2012), pp.73-81.
- [21] Wang H, Liu J, Bao J & Xue B, "A Novel Bearing less Switched Reluctance Motor with Biased Permanent Magnet", *IEEE Transactions on Industrial Electronics*, Vol.61, No.12, (2014), pp.6947-6955.
- [22] Boumediène A, "Intelligent PID DC Motor Speed Control Alteration Parameters Using Particle Swarm Optimization", *Artificial Intelligence Resources in Control and Automation Engineering*, (2012), pp.3-14.