Sensor less Speed Control of 8/6 Switched Reluctance Motor Drive via Hybrid Observer Using ANFIS and Fuzzy-PID

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Abstract:

This paper presents the Speed control of 8/6 Switched Reluctance Motor (SRM) using Adaptive Network-based Fuzzy Inference System (ANFIS) and Fuzzy-PID with Hybrid Observer (HO) algorithm. The HO algorithm gives the optimum value of estimated position angle and speed is taken with the combination of Current Sliding Mode Observer (CSMO) and Flux Sliding Mode Observer (FSMO). The non linear model of 8/6 SRM is modeled with MATLAB Simulink and the parameters of Actual speed, Estimated speed, Error of speed and Torque ripples are measured correspondingly. The results of ANFIS and Fuzzy-PID are compared with wide ranges of speed and the same is presented. The experiments are carried out on a four-phase 8/6 SRM using DSP TMS320LF2407A platform shows the achievability and significance of the developed methods for low, medium and high speed operations.

Index Terms - Current Sliding Mode Observer, Flux Sliding Mode Observer, Hybrid Observer, ANFIS, Fuzzy-PID.

I. INTRODUCTION

An electrical drive is very significant part of any industry for variable speed operation. When compared to AC and DC drives, AC drives are very economical due to the absence of commutator and brushes. Recently, SRM drives have received considerable attention from the researchers and the drive industry due to their various attractive features like variable-speed and variable frequency ac machine drive technology The SRM is an electromagnetic and electro dynamic equipment that converts the electrical energy into mechanical energy. The SRM is singly-excited, doubly-salient machines which develop the electromagnetic torque due to variable reluctance principle. The motor has salient poles on both the stator and rotor but only one member (the stator carries winding). In order to have self-starting capabilities, the rotor of SRM has lesser poles than stator as rotor has no winding. SRM is even more rugged than squirrel cage induction motor. The possible and commonly used configuration are 8/6 (4 phase) and 6/4 (3 phase). The choice of converter topology depends upon application of SRM.One of the main aspects of the research in SRM drives is circuitry

types. The SRM has a torque independent of the direction of the current, $[T\,\alpha\,i^2]$ which can therefore be unidirectional. This permits the use of unipolar devices in the circuitry. This circuitry is having several advantages over the circuitry that is used for ac machines and dc machines drives. In order to identify good performance drive systems, the machine is to be modeled with MATLAB/Simulink. For good dynamic response of the motor with wide ranges of load variation of the systems, we have to adopt suitable algorithms and theorems. The techniques and approaches of robust control, eg: Fuzzy-PID Control using Simulated Annealing Optimization [1], Kharitonov Theorem and Swarm Intelligence [2] ANFIS [3] have been recently drawing more attention from many researchers. The algorithm called HOA is used to find the optimum value of rotor position of switched reluctance motor which was proposed only in 6/4 SRM with fuzzy [4].

In this paper, 8/6 SRM is proposed with HO, CSMO & FSMO is developed and compared with ANFIS & FUZZY –PID in order to estimate the speed, error of speed and torque ripple for wide speed ranges. The HO algorithm estimates rotor position and speed with CSMO in high speeds and FSMO in low speeds. CSMO gains in high speeds and FSMO in low speeds has been regulated and synchronized.

II. SPEED CONTROL WITH THE PROPOSED OBSERVER

The construction of 8/6 i.e 8 stator poles and 6 rotor poles SRM is shown in Fig.1. In conventional method, the position of rotor is determined by using speed sensors. With the introduction of high speed controllers it becomes feasible to control machines without mechanical (speed or position) sensors control i.e. sensorless control.
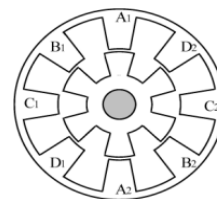

Fig. 1 Construction of 8/6 Switched Reluctance Motor.

A. Non Linear Model of SRM:

To illustrate a hybrid observer for SRM drives system, we need to establish a nonlinear model of the SRM with differential equations. The dynamic characteristics of the SRM may be found if sufficient knowledge of the flux linkage and torque for each phase [5-9]. The relationship between flux and voltage for each phases of SRM is derived in eqn. (1), (2) & (3).

$$\varphi_n = L_n(I_n, \theta)I_n \qquad n = 1, 2, 3, 4. \qquad (1)$$

$$V_n = R_n I_n + \frac{d\varphi_n(I_n, \theta)}{dt} \qquad (2)$$

$$= R_n I_n + \frac{d\varphi_n(I_n, \theta)}{dt}$$

$$= R_n I_n + \frac{\partial\varphi_n}{\partial I_n} \cdot \frac{dI_n}{dt} + \frac{\partial\varphi_n}{\partial\theta} \cdot \frac{d\theta}{dt}$$

$$V_n = R_n I_n + L_n \frac{dI_n}{dt} + \frac{\partial\varphi_n}{\partial\theta} \cdot \omega \qquad (3)$$

where,

$\frac{\partial\theta}{\partial t} = \omega$, $\frac{\partial\varphi_n}{\partial\theta} \cdot \omega$ is the Backward Electro Motive Force (EMF)

$\frac{\partial\varphi_n}{\partial I_n}$ is the incremental inductance of the nth phase

The torque of nth phase SRM is

$$W_C = \int_0^I \varphi(\theta, I) dI \qquad (4)$$

$$T_n = \left(\frac{\partial W_C(\theta, I_n)}{\partial\theta}\right) I_n = \text{Constant} \qquad (5)$$

where,

W_C is the co-energy and T_n is the torque of nth phase. From the eqn. (4) & (5), the mathematical motion of the motor by the action of Electromagnetic torque T_e and load torque T_L is determined as

$$T_e = \sum_{n=0}^m T_n \qquad (6)$$

$$T_e - T_L = J\frac{d_\omega}{d_t} + B\omega \qquad (7)$$

From the eqn. (6) & (7), the equation of motion can be expressed as:

$$\frac{\partial\theta}{\partial t} = \omega \text{ Or } \theta = \omega$$

where,

J is the moment of inertia of the rotor and the load of the SRM, B denotes the friction factor, ω is the angular speed and t is the time.

B. Estimate of Speed and Actual Speed with Hybrid Observer

The block diagram of hybrid observer is consists of three parts: Nonlinear model of 8/6 SRM, CSMO and FSMO is shown in the Fig 2. From the above block diagram, the combination of CSMO and FSMO is called HO. In addition to this algorithm, a PID controller is used to get robust performance in a wide range of operating conditions.
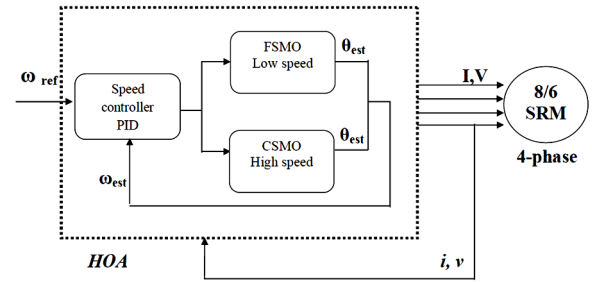

Fig. 2 Block diagram of HO

C. Current Sliding Mode Observer (CSMO)

The speed and rotor position of CSMO for SRM is constructed based on the following steps:
1. Construct the non linear model of 8/6 SRM, the estimated current is measured with the reference current.
2. The actual current is measure directly with same reference current.
3. The comparator is used to find the estimation speed and position of the rotor with the difference between actual and estimated current [10].
The block diagram describe to estimate the position and speed with CSMO is shown in Fig. 3
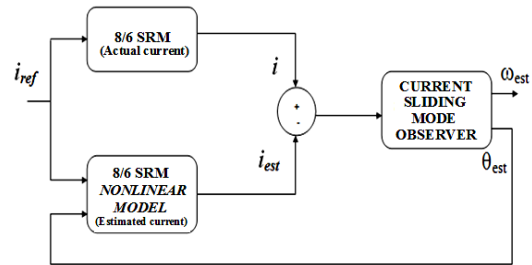

Fig. 3 Block diagram of CSMO

The differential equation of nonlinear model of 8/6 SRM, CSMO for rotor position and speed can derived as follows,

$$S(t) = i_n - i_{n\,est} \qquad (8)$$

$$S_{cont} = S_{sgn} * \sum_{n=1}^m S(t) \qquad (9)$$

where, $S(t)$ is the difference of nth phase of real current (i_n) and estimated current ($i_{n\,est}$)

From the eqn. (8) & (9), the differential equations of CSMO are:

$$\theta_{est} = \omega_{est} + \alpha_{\theta C} \cdot S_{cont} \qquad (10)$$

$$\omega_{est} = T_{est} + \alpha_{\omega C} \cdot S_{cont} \qquad (11)$$

where,

$\alpha_{\theta C}$ and $\alpha_{\omega C}$ are the CSMO gains respectively.

From the eqn. (10) & (11), the estimation error is determined with difference of actual and estimated value is shown in eqn (12).

$$e_\theta = \theta_{est} - \theta, \qquad e_\omega = \omega_{est} - \omega \qquad (12)$$

where,

θ_{est} is the estimated value of position of the rotor, ω_{est} is the estimated speed, θ is the actual value of

position of the rotor and ω is the actual value of speed.

D. Flux linkage Sliding Mode Observer (FSMO)

The speed and rotor position of FSMO for SRM is constructed based on the following steps:

1. The actual flux is determined with the quantities of estimated angle with n[th] phase current.

2. The estimated flux is determined with the quantities of voltage and current of same n[th] phase.

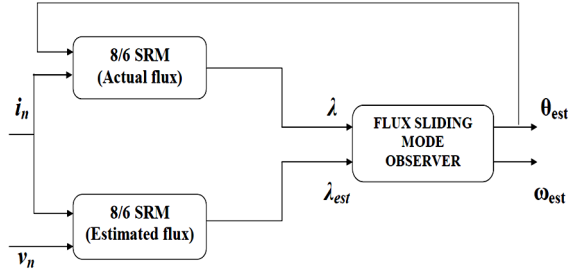The block diagram of estimate the position and speed with FSMO is shown in Fig. 4

Fig. 4 Block diagram of FSMO

The Phase flux linkage of nth phase is estimated using the terminal voltage and phase current as follows,

$$\lambda_{n\,est}(t) = \int_{t0}^{t} (V_n(\tau) - i_{n(\tau)} \cdot r_n) d\tau \qquad (13)$$

where,
V_n, i_n and r_n are voltage, current and resistance of nth phase.
The flux linkage value is used to obtain the nth phase flux linkage and is given as follows,

$$Z(i_n, \theta) = i_n \, w_n(\theta) \qquad (14)$$

$$W_n(\theta) = \cos(N_r \cdot \theta_{est} - \frac{(k-1)2\pi}{N_{ph}}) \qquad (15)$$

$$\lambda_n = \lambda_s \cdot Z(i_n, \theta) \cdot (1 + \frac{Z(i_n, \theta)^2}{2}) \qquad (16)$$

where,
N_r is the numbers of rotor poles, N_{ph} is the number of phases, θ_{est} is the estimated position and λ_s is the saturated flux linkage. Accordingly, flux linkage error is given by:

$$e_\lambda = \sum_{n=1}^{N_{ph}} \frac{dW_n(\theta)}{d\theta} \cdot (\lambda_n - \lambda_{n\,est}) \, |\theta = \theta_{est} \qquad (17)$$

From the eqn. (13-17), the differential equations of FSMO become:

$$\theta_{est} = \omega_{est.} + \alpha_{\theta F} sgn(e_\lambda) \qquad (18)$$

$$\omega_{est} = \alpha_{\omega F} sgn(e_\lambda) \qquad (19)$$

Where,
$\alpha_{\theta F}$ and $\alpha_{\omega F}$ are the CSMO gains respectively.
eqn. (18) & (19) are estimated value of position and speed.

E. Hybrid Observer (HO)

The combination of CSMO and FSMO is said as Hybrid Observer. Each of the CSMO and the FSMO observers need current and voltage sensors for estimate of rotor position, speed and speed error. The block diagram and flowchart of the HO is shown in Fig. 5 & 6 respectively. The HO, estimates speed and the rotor position for all of high and low speeds by combination of CSMO and FSMO, and match the outputs using PID controller. The HO has an advantage of Automatic switch from CSMO to FSMO or vice versa is performed with proper synchronizing of angle position of rotor and speed [11-15].
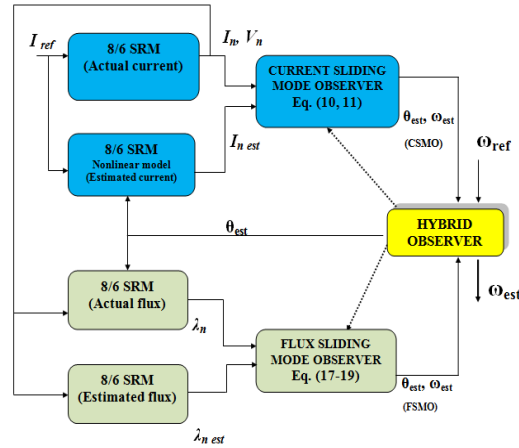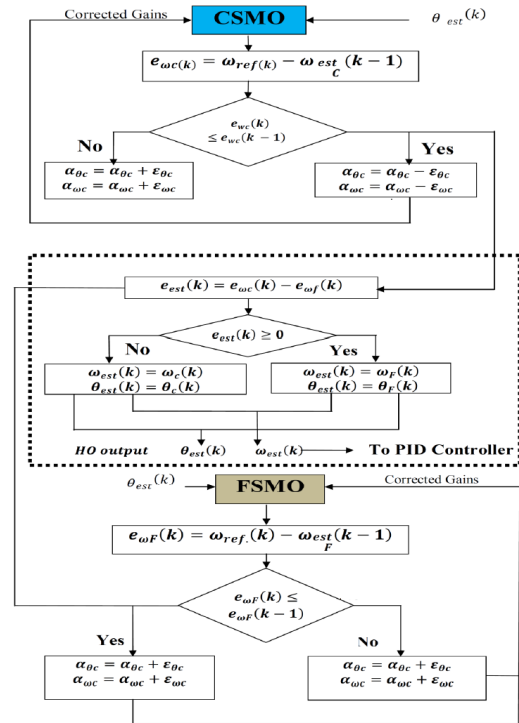

Fig. 5 Block diagram of Hybrid Observer

Fig. 6 Flow chart of Hybrid Observer

HO Gains of $\alpha_{\theta c}, \alpha_{\omega c}$ for high and $\alpha_{\theta f}, \alpha_{\omega f}$ for low speeds regulated and will be corrected with $\varepsilon_{\theta c}, \varepsilon_{\omega c}$ and $\alpha_{\theta f}, \omega_{\theta f}$ for all speeds. Also, speed and position errors $e_{\omega}(k), e_{\theta}(k)$ will be compared with last step $e_{\omega}(k-1), e_{\theta}(k-1)$ separately for every observer (CSMO and FSMO) and the better one is selected.

III. ADAPTIVE NEURO FUZZY INFERENCE SYSTEM VERSUS FUZZY-PID

A. Adaptive Neuro Fuzzy Inference System (ANFIS)

ANFIS is a kind of artificial neural network based on the Takagi-Sugeno type fuzzy logic inference systems. Artificial neural network is used to determine the optimal values of model parameters of fuzzy inference system. In training the neural network, a hybrid algorithm containing widely used back-propagation learning method and the least squares method was used. For this purpose ANFIS allows to determine the rule base and the membership functions by using the data sets [16-20].

Fig.7 illustrate the Fuzzy inference system structure which shows that 7 x 7 (49) rules is used to find the optimum value of position angle of 8/6 SRM.
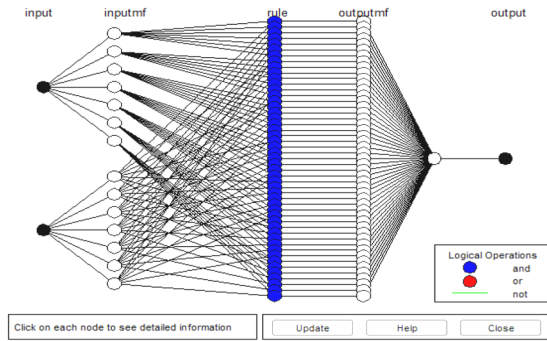

Fig.7 Structure block of ANFIS

B. Fuzzy Logic Controller (FLC)-PID

The FLC is a mathematical system that analyzes the input values in terms of logical variables, mostly if-then rules are used. To improve the performance of the systems, the FLC-PID is used. The input variables are speed error (E) and change in speed error (e) and the output variables are position angle (u). Show the membership functions of E, e and u in Fig 8 (a), (b) &(c).
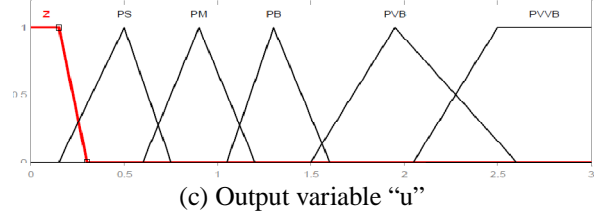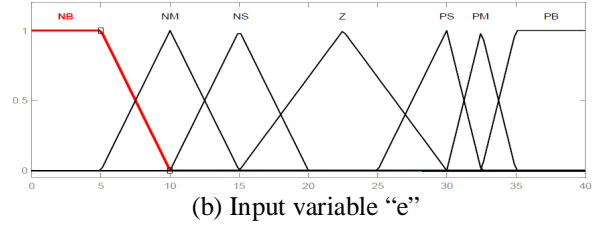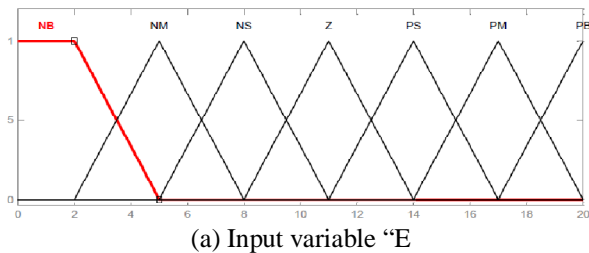

(a) Input variable "E

(b) Input variable "e"

(c) Output variable "u"

Fig. 8 (a), (b) & (c) Membership functions plot.

TABLE I
FUZZY RULE BASE

| e\E	PS	PM	PB	Z	NB	NM	NS
PS	PMS	PLS	PLS	PMS	PHS	PHS	PMS
PM	PHS	PMS	PMS	PHS	PVHS	PVHS	PHS
PB	PVHS	PHS	PHS	PUHS	PUHS	PUHS	PUHS
Z	Z	Z	Z	Z	PMS	PLS	PLS
NB	PVHS	PHS	PM	PUHS	PUHS	PUHS	PUHS
NM	PHS	PLS	PLS	PHS	PUHS	PUHS	PUHS
NS	PMS	PLS	PLS	PMS	PVHS	PVHS	PHS

The membership function has seven fuzzy set and thus formed (7x7) 49 rule base, i.e Positive Small (PS), Positive Medium (PM) and Positive Big (PB), Negative Small (NS), Negative Medium (NM), Negative Big (NB) and Zero (Z).These rules is used to find the optimum value of position angle of 8/6 SRM is tabulated in TABLE I [21-23].
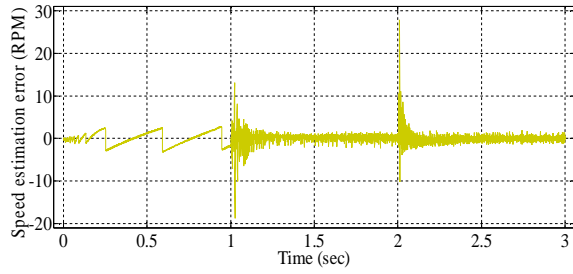
IV. SIMULATION RESULTS

A. Current Sliding Mode Observer (CSMO)
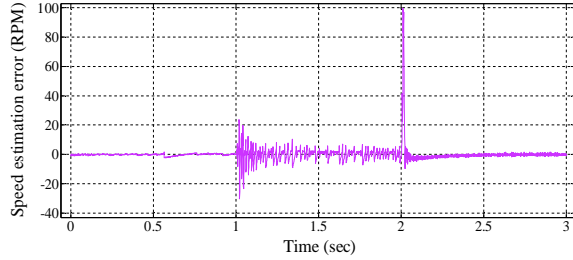
Fig.9 (a) the actual speed and estimated speed are verified and Fig.9 (b) & (c) show the CSMO simulation results for ω=15 RPM, 500 RPM and 1500 RPM for both ANFIS and Fuzzy-PID. These results show that Speed estimation error is found for both the cases. These simulation results demonstrate that CSMO are not suitable for low speeds (15 RPM) drives.
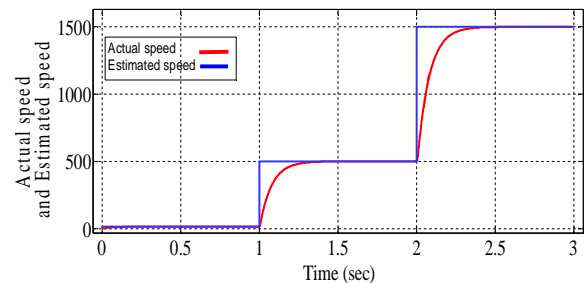
(a) Actual speed and Estimation speed.
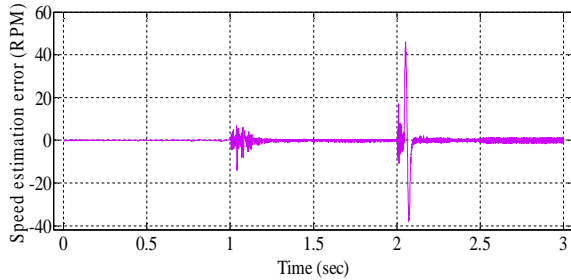
(b) Speed estimation error in CSMO (ANFIS)

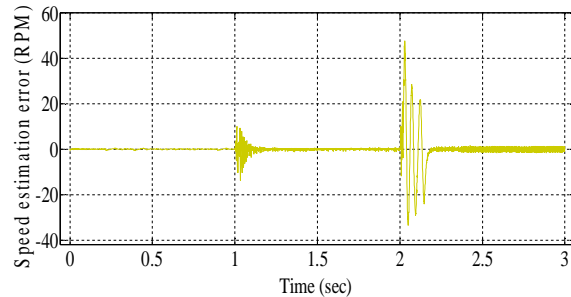(c) Speed estimation error in CSMO (Fuzzy-PID)

Fig. 9 (a), (b) & (c) Simulation results of CSMO at
15 RPM, 500 RPM &1500 RPM

B. *Flux linkage Sliding Mode Observer (FSMO)*

Fig.10(a)&(b).Illustrate the FSMO simulation results for ω=15 RPM, 500 RPM and 1500 RPM for both ANFIS and Fuzzy-PID. These results show that Speed estimation error is found for both the cases. These simulation results demonstrate that FSMO are not suitable for high speeds (1500 RPM) drives.
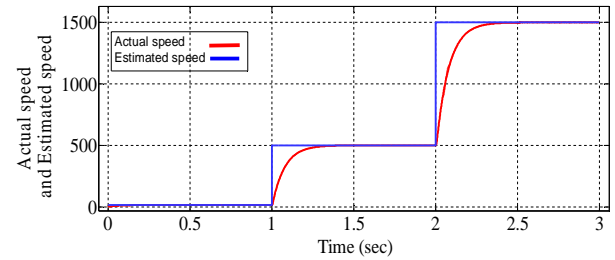

(a) Speed estimation error in FSMO (ANFIS)

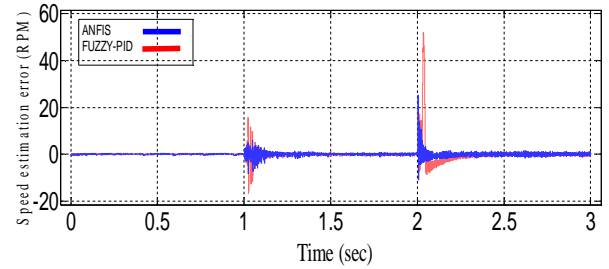

(b) Speed estimation error in FSMO (Fuzzy-PID)

Fig. 10 (a) & (b) Simulation results of FSMO at
15 RPM, 500 RPM &1500 RPM

C. *Hybrid Observer (HO)*

The combination of CSMO and FSMO is called Hybrid observer. The CSMO and FSMO need current and voltage sensors to measure the estimation of rotor position and speed. This connection makes to combine CSMO and FSMO. The advantage of this HO is used for automatic switching from CSMO to FSMO after the real time synchronizing of position and speed data between CSMO and FSMO. Fig.11(a) the actual speed and estimated speed are verified and Fig.11 (b) it is clear that, the HO speed estimation errors are smaller in ANFIS when compared to Fuzzy-PID and it has good performance for wide speed range. (15 RPM, 500 RPM and 1500 RPM).

(a) Actual speed and Estimation speed.

(b) Speed estimation error of ANFIS &
Fuzzy-PID.

Fig. 11 (a) & (b) Simulation results of HO at
15 RPM, 500 RPM &1500 RPM

It is found that superior operation is being performed by the ANFIS for different speed ranges at the sample period of 2.572 to 2.592 sec as shown in Fig.12. It is clearly shows that torque ripples are minimized in HO with ANFIS technique when compared to Fuzzy-PID.
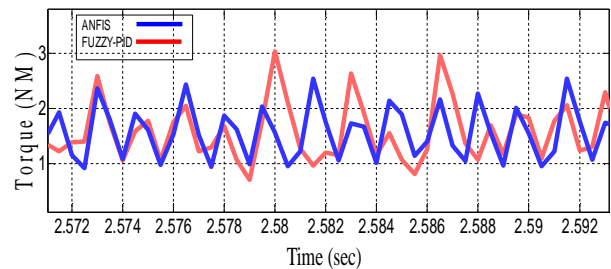

Fig. 12 Torque ripple in HO using ANFIS and
Fuzzy-PID

The comparison table is made for speed estimation error and torque ripple values are listed in TABLE II and TABLE III respectively.

TABLE II
COMPARISON TABLE OF CSMO, FSMO AND HO WITH ANFIS AND FUZZY-PID

	Mode	Set speed (RPM)	Speed estimation error (RPM)
ANFIS	CSMO	15	4.0
		500	3.4
		1500	2.8
	FSMO	15	1.0
		500	1.9
		1500	3.0
	HO	**15**	**0.7**
		500	**0.9**
		1500	**1.8**
	Mode	Set speed (RPM)	Speed estimation error (RPM)
FUZZY-PID	CSMO	15	6.0
		500	4.4
		1500	3.0
	FSMO	15	1.1
		500	2.2
		1500	3.5
	HO	**15**	**0.9**
		500	**1.2**
		1500	**2.3**

TABLE III
SIMULATION RESULTS (TORQUE RIPPLE) OF HO WITH ANFIS AND FUZZY-PID

Method	Mode	Set speed (RPM)	Speed Estimation error (RPM)	Δ Torque (NM)
ANFIS	HO	15	0.7	0.5
		500	0.9	0.9
		1500	**1.8**	**0.8**
FUZZY-PID	HO	15	0.9	0.7
		500	1.2	1.4
		1500	**2.3**	**1.7**

V. EXPERIMENTAL DISCUSSION

In order to validate the Hybrid observer algorithms, significant experimental results are endowed with three parts of SRM drive. (i) Controller (ii) Power Converter and (iii) Electric Motor [24-28].
Controller: The controller generates PWM signal to the converter and hence forms the heart of the Variable Speed Drives (VSDs).
Power Converter: Two switches per phase inverter, IGBT gate drive circuits, Hall Effect current sensors, Electric Motor: It is connected directly/indirectly to the load.
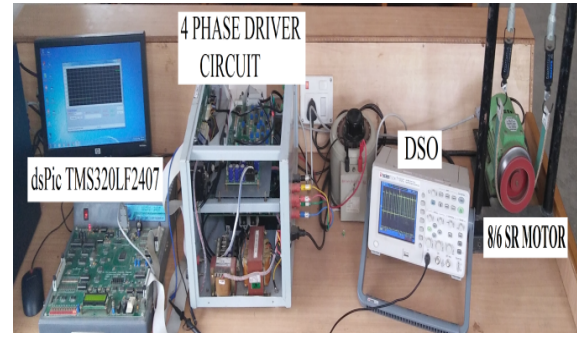The experimental view of 8/6 SRM with inverter driver circuit is shown in Fig.13

Fig. 13 Photograph of the experimental setup

APPENDIX: EXPERIMENTAL SRM DRIVE

MOTOR RATINGS:

N_s= 8, N_r= 6
Voltage: 350V
Maximum current: 30A
No. of phases: 4
Speed: 1500 RPM
Stator resistance (Ohms) =3.1
Inertia (kg .m^2) = 0.0089
L_{min} = 10mH, L_{max} = 110mH

PROCESSOR:

Controller: TMS320LF2407A
Emulation: IEEE standard 1149.1 test access port to on-chip scan-based emulation logic
Speed: 25-ns (40MIPLS) instruction cycle time, with most instructions single cycle
Crystal Frequency: 10MHz
Clock Frequency: 40 MHz
Timer: On-chip timer can be used
Interrupts: 6
Serial: RS232C Serial Interface using on-chip

VI. CONCLUSION

In this paper, Hybrid Observer Algorithm is validated using ANFIS and Fuzzy-PID. The voltage and current are measured from 8/6 SR motor terminals to estimate the rotor position and speed. In addition, the torque ripple minimization is also observed and compared for both the optimization techniques. It effectively reduces the torque ripple for all speeds in ANFIS when compared to Fuzzy-PID. Simulation results show that CSMO are suitable only for low and FSMO for high speed. The Hybrid Observer has good performance for low, medium as well as high speed applications. The proposed system was designed, implemented and proved through DSP controller TMS320LF2407A and its effectiveness in error reduction was validated.

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