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 α i] 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).

\[
\begin{align*}
\phi_n &= L_n (I_n (t_0) I_n \quad n = 1, 2, 3, 4. \quad (1) \\
V_n &= R_n I_n + \frac{d\phi_n (I_n, t_0)}{dt} \quad (2) \\
V_n &= R_n I_n + \frac{d\phi_n (I_n, t_0)}{dt} + \frac{d\phi_n}{dt} \quad (3)
\end{align*}
\]

where,
\[
\frac{d\theta}{dt} = \omega, \quad \frac{\partial \phi_n}{\partial \theta} \quad \omega \text{ is the Backward Electro Motive Force (EMF)}
\]
\[
\frac{\partial \phi_n}{\partial \theta} \quad \text{is the incremental inductance of the } n \text{th phase}
\]

The torque of the n th phase SRM is
\[
W_C = \int \phi (\theta, t) dI \quad (4)
\]
\[
T_e = \left( \frac{\partial W_C (\theta_n)}{\partial \theta_n} \right) I_n = \text{Constant} \quad (5)
\]

where,
\[W_C \text{ is the co-energy and } T_e \text{ is the torque of } n \text{th phase.}
\]

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
\[
T_e = \sum_{n=0}^{n} T_n \quad (6)
\]
\[
T_e - T_L = J \ddot{\omega} + B \dot{\omega} \quad (7)
\]

From the eqn. (6) & (7), the equation of motion can be expressed as:
\[
\frac{\partial \theta}{\partial t} = \omega \quad \text{Or } \theta = \omega
\]

where, \(J\) is the moment of inertia of the rotor and the load of the SRM, \(B\) denotes the friction factor, \(\omega\) 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.

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. 2 Block diagram of HO](image)

![Fig. 3 Block diagram of CSMO](image)
position of the rotor and \( \omega \) 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](image)

The Phase flux linkage of \( n^{th} \) phase is estimated using the terminal voltage and phase current as follows,

\[
\lambda_n(t) = \int_{t_0}^{t} (V_n(t) - i_{n1}(t) \cdot r_n) dt
\]  (13)

where, \( V_n, i_n \) and \( r_n \) are voltage, current and resistance of \( n^{th} \) phase.

The flux linkage value is used to obtain the \( n^{th} \) phase flux linkage and is given as follows,

\[
Z(i_n, \theta) = i_n w_n(\theta)
\]  (14)

\[
W_n(\theta) = \cos(N_r \theta) - \frac{(k-1)2\pi}{N_{ph}}
\]  (15)

\[
\lambda_n = \lambda_z Z(i_n, \theta) + \frac{2i_n \theta^2}{z}
\]  (16)

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

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

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

\[
\theta_{est} = \omega_{est} + \alpha_{ref} \text{sgn}(e_\lambda)
\]  (18)

\[
\omega_{est} = \alpha_{sp} \text{sgn}(e_\lambda)
\]  (19)

Where, \( \alpha_{ref} \) and \( \alpha_{sp} \) are the CSMO gains respectively.

Eqns. (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](image)

![Fig. 6 Flow chart of Hybrid Observer](image)
HO Gains of $\alpha_{q}$, $\alpha_{w}$ for high and $\alpha_{q}$, $\alpha_{w}$ for low speeds regulated and will be corrected with $\varepsilon_{q}$, $\varepsilon_{w}$ and $\omega_{q}$, $\omega_{w}$ for all speeds. Also, speed and position errors $\varepsilon_{q}(k)$, $\varepsilon_{w}(k)$ will be compared with last step $\varepsilon_{q}(k-1)$, $\varepsilon_{w}(k-1)$ 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 $7 \times 7$ (49) rules is used to find the optimum value of position angle of 8/6 SRM.

![Fig.7 Structure block of ANFIS](image)

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).

![Fig. 8 (a), (b) & (c) Membership functions plot.](image)

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].

<table>
<thead>
<tr>
<th>E</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
<th>Z</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
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<tr>
<td>$e_{E}$</td>
<td>PMS</td>
<td>PLS</td>
<td>PLS</td>
<td>PLS</td>
<td>PLS</td>
<td>PLS</td>
<td>PLS</td>
</tr>
<tr>
<td>PM</td>
<td>PHS</td>
<td>PMS</td>
<td>PLS</td>
<td>PHS</td>
<td>PVS</td>
<td>PVS</td>
<td>PHS</td>
</tr>
<tr>
<td>PB</td>
<td>PVHS</td>
<td>PHS</td>
<td>PUS</td>
<td>PHS</td>
<td>PUS</td>
<td>PUS</td>
<td>PUS</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>PMS</td>
<td>PLS</td>
</tr>
<tr>
<td>NB</td>
<td>PVHS</td>
<td>PHS</td>
<td>PUS</td>
<td>PUS</td>
<td>PUS</td>
<td>PUS</td>
<td>PUS</td>
</tr>
<tr>
<td>NM</td>
<td>PHS</td>
<td>PLS</td>
<td>PLS</td>
<td>PHS</td>
<td>PHS</td>
<td>PHS</td>
<td>PHS</td>
</tr>
<tr>
<td>NS</td>
<td>PMS</td>
<td>PLS</td>
<td>PLS</td>
<td>PVHS</td>
<td>PVHS</td>
<td>PHS</td>
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</tr>
</tbody>
</table>

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 $\omega=15$ 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.

![Fig. 9 (a) Actual speed and Estimation speed.](image)
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 it 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).

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 $\omega$=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.

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

Fig. 11 (a) & (b) Simulation results of HO & Fuzzy-PID.

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Set speed (RPM)</th>
<th>Speed estimation error (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANFIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSMO</td>
<td>15</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>2.8</td>
</tr>
<tr>
<td>FSMO</td>
<td>15</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>3.0</td>
</tr>
<tr>
<td>HO</td>
<td>15</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>1.8</td>
</tr>
<tr>
<td>FUZZY-PID</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSMO</td>
<td>15</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>4.4</td>
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<td></td>
<td>1500</td>
<td>3.0</td>
</tr>
<tr>
<td>FSMO</td>
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<td>1.1</td>
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<tr>
<td></td>
<td>500</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>3.5</td>
</tr>
<tr>
<td>HO</td>
<td>15</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>2.3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Method</th>
<th>Mode</th>
<th>Set speed (RPM)</th>
<th>Speed Estimation error (RPM)</th>
<th>A Torque (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANFIS</td>
<td>HO</td>
<td>15</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500</td>
<td>1.8</td>
<td>0.8</td>
</tr>
<tr>
<td>FUZZY-PID</td>
<td>HO</td>
<td>15</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1500</td>
<td>2.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

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

**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.
REFERENCES


