Abstract—This paper presents a high performance switched reluctance motor (SRM) drive based on hybrid observer (HO). The HO estimates the rotor position and speed for wide speed range. In addition, a fuzzy logic current compensator (FLCC) for reducing torque ripple has been presented. In the regions that torque reduces, the FLCC, inject additional current for each phase currents. This drive has been simulated with MATLAB/SIMULINK for nonlinear model of SRM. Simulation results show that proposed drive will estimate the rotor position and speed with high precision for all speeds (near zero speeds up to rated speed). Also, FLCC minimize the torque ripple and reduce speed estimation error, too. This drive has the advantages of robustness, high reliability and without extra hardware, drive performance has been improved.

I. INTRODUCTION

Switched reluctance motor (SRM) drives are new developing adjustable speed motor drives in the last two decades. High reliability, simple structure, high torque to inertia ratio, high torque to power ratio, robust contracture, low cost, high efficiency, high torque in low speed are only a few advantages in SRM, because of these SRM has undergo rapid development in hybrid vehicles, aircrafts, starter/generator systems, washing machines and other automotive applications[1,2].

A sensorless drive decrease cost and increase reliability, which extracts rotor position information indirectly from electric signals of motor terminals, is highly desirable. Several methods of sensorless SRM drives have been published in the last years. However these methods are generally only suitable for either high speed (rated speed) or low speeds (near zero speeds) [3-5]. Sliding mode observer, with its advantages of inherent robustness parameters of uncertainly, computational simplicity, and high stability, provides a powerful approach to implement sensorless schemes [6,7].

In this paper, a HO algorithm acts on nonlinear model of SRM and has been developed to estimate rotor position and speed of SRM with current sliding mode observer (CSMO) and flux linkage sliding mode observer (FSMO) for wide speed range. The CSMO gains in high and FSMO in low speeds has been regulated and these gains will be corrected separately for each observer at wide speed range with concern of estimated errors.

A high level of torque ripple is the major problem of SRM. One way to minimize the torque ripple is to optimize the stator/rotor pole arcs together with the excitation current waveforms. However, if the SRM is already built, the torque ripple minimization can be done by the optimization of the phase current profile [2], [8]. This paper presents a new simple procedure for minimizing the torque ripple via fuzzy logic control of the SRM. This procedure is based on injection of compensation current in each phase by using fuzzy logic current compensator (FLCC).

II. ESTIMATE OF POSITION AND SPEED WITH HO

The block diagram of estimate the position and speed with proposed HO has been shown in Fig.1. It consists of three parts: nonlinear model of SRM, CSMO and FSMO. As well as in this algorithm, a PI controller for speed control has been used.

Fig. 1. Block diagram of estimate position and speed with HO

A. Non-linear model of SRM

To define a HO for SRM drives system, we need first to setup a nonlinear model of the SRM and build the SRM differential equations. All of the dynamic characteristics of the SRM may be found if given sufficient knowledge of the flux linkage and torque for each phase.

The phase flux linkage and instantaneous torque are variable against position and current [5, 6]. Consequently, flux and voltage for each phase of SRM is:

\[ \varphi_j = L_j (I_j, \theta) I_j \]  

(1)
\[ V_j = R_j I_j + \frac{d\varphi_j(I_j, \theta)}{dt} \]  
\[ = R_j I_j + \frac{\partial \varphi_j}{\partial I_j} \frac{dI_j}{dt} + \frac{\partial \varphi_j}{\partial \theta} \frac{d\theta}{dt} \]  
\[ = R_j I_j + L_j \frac{dI_j}{dt} + \frac{\partial \varphi_j}{\partial \theta} \omega \]

where, \( (\partial \varphi_j/\partial \theta) \omega \) is the backward electromotive force (EMF) term and \( (\partial \varphi_j/\partial I_j) \) is the incremental inductance of the \( j^{th} \) phase [2,4]. Finally, the torque of SRM is:

\[ W_c = \frac{1}{2} \varphi(\theta, I) dl \]

\[ T_j = \left[ \frac{\partial W_c(\theta, I_j)}{\partial \theta} \right]_{I_j = \text{const.}} \]

\[ T_e = \sum_{j=0}^{n} T_j \]

where, \( W_c \) is the co-energy and \( T_j \) is the torque of \( j^{th} \) phase. The mathematical motion of the motor by the action of electromagnetic torque \( T_e \) and load torque \( T_l \) is:

\[ T_e - T_l = J \frac{d\omega}{dt} + B \omega \]

The equation of motion can be expressed as:

\[ \frac{d\theta}{dt} = \omega \quad \text{or} \quad \dot{\theta} = \omega \]

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. According to these equations and experimentally measured characteristics, the representation of dynamic mathematical nonlinear model of SRM is illustrated as Fig. 2.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Representation of dynamic mathematical nonlinear model of 3-phase SRM}
\end{figure}

**B. Current Sliding Mode Observer (CSMO)**

A speed and rotor position CSMO for SRM is constructed based on the following steps [6]:

1) The phase voltages and currents are measured;

2) A nonlinear model of motor is simulated with the same the measured voltage as inputs, the phase currents are estimated;

3) The difference between the actual phase currents and the estimated currents are used by the CSMO to estimate rotor speed and position. Block diagram of CSMO shown in Fig. 3.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Block diagram of CSMO}
\end{figure}

According to the system differential equations derived from the nonlinear model of SRM, a CSMO for rotor position and speed can be defined as follows,

\[ S(t) = i_j - i_{j \text{est.}} \]  
\[ S_{\text{cont.}} = \text{sgn.} \sum_{j=1}^{n} S(t) \]

Differential equations of CSMO are:

\[ \dot{\theta}_{\text{est.}} = \omega_{\text{est.}} + \alpha_{\theta \text{C}} S_{\text{cont.}} \]

\[ \dot{\omega}_{\text{est.}} = T_{\text{est.}} + \alpha_{\omega \text{C}} S_{\text{cont.}} \]

The estimation error is defined as follows,

\[ e_\theta = \theta_{\text{est.}} - \theta, e_\omega = \omega_{\text{est.}} - \omega \]

Consequently, by subtracting Eq. (10) from (7) and Eq. (11) from (6), we get the error dynamics,

\[ \dot{e}_\theta = e_\theta - \alpha_{\theta \text{C}} S_{\text{cont.}} \]  
\[ \dot{e}_\omega = \left[ \frac{T_{\text{est.}} - T_l}{J} \right]_{\text{est.}} - \alpha_{\omega \text{C}} S_{\text{cont.}} \]

By appropriately choosing the two CSMO gains \( \alpha_{\theta \text{C}}, \alpha_{\omega \text{C}} \) can make,

\[ e_\theta e_\theta(0) \Rightarrow (e_\theta \Rightarrow 0) \Rightarrow (\theta_{\text{est.}} \Rightarrow \theta) \]

\[ e_\omega e_\omega(0) \Rightarrow (e_\omega \Rightarrow 0) \Rightarrow (\omega_{\text{est.}} \Rightarrow \omega) \]
C. Flux linkage Sliding Mode Observer (FSMO)

The FSMO system is driven by the differential between the actual flux linkage and flux linkage estimator output [7]. This provides a continuous position and speed information, based on the two measured quantities, voltage and current. Fig. 4 shows the block diagram of FSMO based model.

The phase flux linkage of \( j \)th phase is estimated using the terminal voltage and phase current as follows,

\[
\lambda_{\text{est}}(\tau) = \int_{t_0}^{t} (V_j(\tau) - i_j(\tau) r_j) d\tau
\]

where, \( v_j, i_j \) and \( r_j \) are the voltage, current and resistance of \( j \)th phase. A reasonably accurate but simplified flux linkage model is used to obtain the phase flux linkage and is given as follows,

\[
Z(i_j, \theta) = i_j W_j(\theta)
\]

\[
W_j(\theta) = \cos(N_r \theta_{\text{est}}) - \frac{(n-1)2\pi}{N_{ph}}
\]

\[
\lambda_j = \lambda_s Z(i_j, \theta_{\text{est}}) (1 + \frac{Z(i_j, \theta)^2}{2})
\]

where, \( N_r \) is the number of rotor poles, and \( N_{ph} \) is the number of phases, \( \theta_{\text{est}} \) is the estimated position and \( \lambda_s \) is the saturated flux linkage. Consequently, flux linkage error is:

\[
e_{\lambda} = \sum_{j=1}^{N_{ph}} \frac{dW_j(\theta)}{d\theta} \frac{(\lambda_j - \lambda_{\text{est}})}{\theta = \theta_{\text{est}}}
\]

and differential equations of FSMO are:

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

\[
\omega_{\text{est}} = \alpha_{\omega} \text{ sgn}(e_{\omega})
\]

By appropriately choosing the two FSMO gains \( \alpha_{\omega} \), \( \alpha_{\omega} \) can make,

\[
e_{\lambda} = 0 \Rightarrow \theta_{\text{est}} = \theta \& \omega_{\text{est}} = \omega
\]

III. Hybrid Observer (HO)

Each of the CSMO and the FSMO observers need current and voltage sensors for estimate of rotor position and speed. This similarity is important reason to combine of CSMO and FSMO. The block diagram of the HO is shown in Fig. 5. This observer, estimates the rotor position and speed for all of high and low speeds by CSMO and FSMO, and synchronize the outputs. The flowchart of proposed algorithm is shown in Fig. 6. This algorithm has the advantage of automatically switching from CSMO to FSMO only after real time synchronizing of position and speed data between CSMO and FSMO. Gains of \( \alpha_{\omega} \), \( \alpha_{\omega} \) for high and \( \alpha_{\omega} \), \( \alpha_{\omega} \) for low speeds are regulated and will be corrected on line with \( e_{\omega} \), \( e_{\omega} \) and \( e_{\omega} \), \( e_{\omega} \) by using hybrid algorithm for all speeds. As well as, speed and position errors \( e_{\omega}(k), e_{\omega}(k) \) will be compared with last step \( e_{\omega}(k-1), e_{\omega}(k-1) \) separately for every observer (CSMO and FSMO) and the better one is selected.

IV. Fuzzy Logic Torque Ripple Minimization

We know SRM torque ripple is basic reason of acoustic noise generation. Therefore, torque ripple minimization decrease mechanical stress, undesired effects on bearing and increase estimation precision in sensorless SRM drive[2], [8]. In this simple procedure, nonlinear SRM torque characteristics are defined to A-G regions (Fig. 7). Each of regions \( 5^\circ \) has been selected because in these regions, nonlinear torque behavior can be linear assumed. SRM torque in region D almost is constant but in other regions by using FLCC torque reduction will be compensated. The A-G regions of nonlinear SRM torque have been shown in table 1.
The block diagram of fuzzy logic torque ripple minimization for each phase shown in Fig. 8 and FLCC shown in Fig. 9. Fuzzy logic rules in FLCC are determined for all speeds (near zero speeds up to rated speed). FLCC acts on the reference current when $0 \leq \theta \leq 15^\circ$ and $30^\circ < \theta \leq 45^\circ$ (A-C, E-G regions). Consequently, new reference current is:

$$I_{ref, new} = I_{ref} + I_{Comp}$$

(22)

<table>
<thead>
<tr>
<th>Position (degree)</th>
<th>Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 \leq \theta &lt; 5$</td>
<td>A</td>
</tr>
<tr>
<td>$5 \leq \theta &lt; 10$</td>
<td>B</td>
</tr>
<tr>
<td>$10 \leq \theta &lt; 15$</td>
<td>C</td>
</tr>
<tr>
<td>$15 \leq \theta &lt; 30$</td>
<td>D</td>
</tr>
<tr>
<td>$30 \leq \theta &lt; 35$</td>
<td>E</td>
</tr>
<tr>
<td>$35 \leq \theta &lt; 40$</td>
<td>F</td>
</tr>
<tr>
<td>$40 \leq \theta &lt; 45$</td>
<td>G</td>
</tr>
</tbody>
</table>

In FLCC (Fig. 9), fuzzy rules act on reference current (with seven member function for 0-20 Amp.) and angular position (with seven member function for $0-45^\circ$) as inputs and compensated current (with six member function for 0-3 Amp.) as output. In the regions of A, B and F, G torque reduces at the large scale and for torque ripple minimization, fuzzy rules PVB or PVVB but in the C and E regions torque reduces by far slowly, consequently fuzzy rules PB and PVB have been determined.

In addition, fuzzy logic rules for maximum compensation in near zero speeds up to rated speed has been used. As well, in upper the rated speed, fuzzy logic rules for compensation current is limited to PB because high ripple in current will damage the SRM.
V. SIMULATION RESULTS

The proposed method is simulated by MATLAB/SIMULINK, where the parameters of SRM are $I_{min} = 8 mH$, $I_{max} = 60 mH$, $\beta_r = \beta_s = 30 \degree$, $\omega = 1500 rpm$.

$V = -150 - 0 - 150 \vee \& I = 10 A$, $\Delta I = 0.2$.

The number of rotor teeth $N_r = 4$, the number of stator teeth $N_s = 6$, the number of phases $N_{ph} = 3$, and the resistance of the windings $R = 1.32$. In these simulations, alignment angle between phases $7\degree$ has been selected.

Fig. 10 illustrates the HO simulation results without FLCC for $\omega = 50, 100, 500, 1000, 1500 rpm$. These results show the speed, estimated speed, speed estimation error and position estimation error, respectively. In Fig. 10, speed estimation error and position estimation error for rated speed range are the 8 rpm and 2.8 rad.

Fig. 11 shows the 3-phase currents and total torque without FLCC at rated speed ($\omega = 1500 rpm$). In this Figure reference current, minimum torque and maximum torque

Fig. 10. Simulation results of HO at 50, 100, 500, 1000, 1500 rpm without FLCC.

Fig. 11. Simulation results of HO at 1500 rpm without FLCC.

Fig. 12. Simulation results of HO at 50, 100, 500, 1000, 1500 rpm with FLCC.
are 10A, 1.5N.m and 3.5N.m ($\Delta T = T_{\text{max}} - T_{\text{min}} = 2N.m$), respectively.

Fig. 12 illustrates the HO simulation results with FLCC for $\omega = 50,100,500,1000,1500 \text{ rpm}$. In this Figure, speed estimation error and position estimation error for rated speed are the 2 rpm and 0.104 rad, respectively.

Finally, Fig. 13 shows the 3-phase currents and total torque with FLCC at rated speed ($\omega = 1500 \text{ rpm}$). In this Figure, minimum torque and maximum torque are 2.95N.m and 3.5N.m ($\Delta T = T_{\text{max}} - T_{\text{min}} = 0.55N.m$), respectively. As well, 3-phase currents have been varied for torque ripple reduction. Simulation results of HO with FLCC for wide speed range are listed in Table 2. In this table, it is clear that the speed estimation error, position estimation errors and torque ripple has been reduced, effectively.

![Fig. 13. Simulation results of HO at 1500 rpm with FLCC.](image)

### TABLE 2

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Speed estimation error (rpm)</th>
<th>Position estimation error (rad)</th>
<th>$\Delta T$ (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.05</td>
<td>0.015</td>
<td>0.14</td>
</tr>
<tr>
<td>100</td>
<td>2.1</td>
<td>0.033</td>
<td>0.2</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>0.108</td>
<td>0.4</td>
</tr>
<tr>
<td>1000</td>
<td>3.5</td>
<td>0.105</td>
<td>0.5</td>
</tr>
<tr>
<td>1500</td>
<td>2</td>
<td>0.104</td>
<td>0.55</td>
</tr>
<tr>
<td>With FLCC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>1.1</td>
<td>0.27</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>1.4</td>
<td>0.48</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>2.3</td>
<td>0.95</td>
</tr>
<tr>
<td>1000</td>
<td>12</td>
<td>2.7</td>
<td>1.4</td>
</tr>
<tr>
<td>1500</td>
<td>8</td>
<td>2.8</td>
<td>2</td>
</tr>
</tbody>
</table>

### VI. CONCLUSION

In this paper, hybrid observer of CSMO and FSMO scheme has been described. It uses only phase currents and voltages that can be easily measured by motor terminals to estimate rotor position and speed and without extra hardware, which makes it cost effective. Also, on line gains correction and automatic observer selection for all speeds are very effective on the speed estimation errors, position estimation errors at steady state. In addition, for torque ripple minimization, optimum estimation of position and speed, fuzzy logic control has been applied. Fuzzy logic current compensator generates new phase current profile and effectively reduces torque ripple for all speeds. Simulation results show that the proposed SRM drive decrease estimation errors and torque ripple, effectively. The method has good performance in wide speed range.

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