AN APPLIED APPROACH FOR SPEED ESTIMATION OF INDUCTION MOTORS USING SENSORLESS FLUX OBSERVER SYSTEM WITH SLIDING MODE FIELD ORIENTED CONTROL

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ABSTRACT

In this paper a new observer model in parallel with a sliding mode concept for a field oriented control drive system is proposed to robustly estimate the rotor speed without the use of speed sensor. The proposed system takes into account the problem of stator resistance variation [16] [17]. To make the new observer robust in terms of motor parameter variations and eliminate the impact of stator resistance, the feedback correction on the output of the observer (the motor current, flux and speed) is used. The results of the comparison of the outputs of a sliding mode based drive system and the one without it are performed using Matlab/Simulink. Qualitative and quantitative results in comparison with state of the art research indicate that the proposed approach is robust with minimum estimated errors.

Key words: vector control, Field control, fuzzy, PI, Induction motor, sliding mode, sensorless observer.


1. INTRODUCTION

An induction motor converts electrical energy delivered to the stator into mechanical energy by the electromagnetic interaction between the stator and rotor circuits [1]. It plays an important role in industries due to its robustness and low cost. [2-4]. On high-performance Induction Motor (IM) drives or any variable speed drives the transient behaviour of the
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machine is taken into account, such as the stator current, rotor speed and drive system implementation without a mechanical speed sensor [5-15] [22-23]. The coupling between the stator and the rotor windings of induction motors causes a poor dynamic response of this motor compared with DC motors. This coupling is described using complex differential equations with time-varying rotor position dependant mutual inductances between the stator and rotor. To improve the dynamic performance of the motor vector control is used. This is achieved with the three-phase IM model described using orthogonal d and q axes in a suitable reference frame.

Several papers discussed the simulation results of the Sensorless Flux Observer System with Sliding Mode Field Oriented Control and Speed Estimation of Induction Motors and the adaptive and modified observers. In the discussion the simulation and experimental results of some of these papers will be presented and compared to the obtained results.

This paper deals with a coordinate system that rotates with the rotor flux, thus, decoupling the electromagnetic torque and flux. An estimation of the rotor and stator flux and stator current are achieved using an observer.

The variation of motor parameters is the main challenge in an observer design. The detuning of the stator resistance $R_s$ plays a major role in the inaccurate estimation of the stator current, stator flux, rotor flux and the rotor speed [5, 6], [11], [13] as well as changing the resistance of the rotor and the inductance of the motor during flux [13]. These changes in motor parameter must be taken into account in the control process by using a closed-loop observer. This paper uses a Sliding-Mode Observer (SMO) based field oriented control (FOC) scheme that is robust and effective against parameter variations.

2. INDUCTION MOTOR MODEL

The differential equations of stator current and rotor flux vector components in $\alpha\beta$ coordinate system rotating with an arbitrary angular speed of the squirrel cage type induction motor are [15]:

$$\frac{di_{s\alpha}}{dt} = b_1i_{s\alpha} + b_2\psi_{r\alpha} + \omega_s i_{s\beta} + b_3\omega_r\psi_{r\beta} + b_4v_{s\alpha}$$

$$\frac{di_{s\beta}}{dt} = b_1i_{s\beta} + b_2\psi_{r\beta} - \omega_s i_{s\alpha} - b_3\omega_r\psi_{r\alpha} + b_4v_{s\beta}$$

$$\frac{d\psi_{r\alpha}}{dt} = b_5\psi_{r\alpha} + (\omega_s - \omega_r)\psi_{r\beta} + \frac{R_m L_r}{L_r} i_{s\alpha}$$

$$\frac{d\psi_{r\beta}}{dt} = b_5\psi_{r\beta} - (\omega_s - \omega_r)\psi_{r\alpha} + \frac{R_m L_r}{L_r} i_{s\beta}$$

$$\frac{d\omega_r}{dt} = \frac{L_m}{L_r} (\psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha}) - \frac{1}{J} m_0$$

where, $i_{s\alpha}$, $i_{s\beta}$, $v_{s\alpha}$, $v_{s\beta}$, $\psi_{r\alpha}$ and $\psi_{r\beta}$ are the stator current, voltage vectors and rotor flux in coordinate $\alpha\beta$ system rotating with arbitrary speed $\omega_s$, $\omega_r$ is the angular speed of the coordinate system and rotor shaft. $R_s$, $R_r$, $L_s$, $L_r$, $L_m$, $J$ and $m_0$ are stator and rotor resistances and inductances, mutual inductance, the inertia and the load torque respectively.

$$b_1 = -\frac{R_s L_r^2 + R_r L_m^2}{L_r a} , b_2 = \frac{R_s L_m}{L_r a}, b_3 = \frac{L_m}{a}, b_4 = \frac{L_r}{a}, b_5 = -\frac{R_r}{L_r} , a = (1 - \frac{L_m^2}{L_r L_s}) L_r L_s$$

3. SLIDING MODE FIELD ORIENTED CONTROL (SM FOC)

The use of a SMO for induction motor drive provided promising results [6-14]. In this work, the complete system, a SM FOC, is shown in Fig 1. The controller consists of the Proportional Integral (PI) and the fuzzy logic controller (FLC). The PI controller is widely used in industries due to its simplicity, effectiveness and low price [18]. Whereas PI controller
became unsuccessful when the controlled system become highly nonlinear and uncertain [19]. The (FLC) proposed by Lotfi A.Zadeh in 1965. Fuzzy logic controllers are based on fuzzy inference systems, which consists of three parts: Fuzzification interface, Decision-making unit and Defuzzification interface [20]. Generally, there is no systematic procedure used to choose the rules of the (FLC). Mainly, it depends on the practical experience and the system performance [21-22] and it has been widely used for nonlinear systems [23]. The measured three phase stator currents of the IM are transformed from abc frame into the stationary αβ frame and then transformed into the rotating dq frame using the following equations [24]:

$$\begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix} = \begin{bmatrix}
\cos(\omega t) & \sin(\omega t) & 0 \\
-\sin(\omega t) & \cos(\omega t) & 0
\end{bmatrix} \begin{bmatrix}
i_{sA} \\
i_{sB}
\end{bmatrix}$$

$$\begin{bmatrix}
i_{sA} \\
i_{sB}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & \frac{1}{2} & -\frac{1}{2} \\
\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}$$

These current values are compared with a desired flux producing current $i_{sd}^*$ and torque producing current $i_{sq}^*$ and to provide the reference signal for the space vector PWM inverter its controlled with a linear current PI controller.

The controllers are tuned using trial and error methods. The new observer system then estimates the rotor and stator flux. These are used to estimate the stator current, which is compared with the actual current. The error is used in sliding mode observer as a correcting factor.

A flux position calculator is used to calculate the angular position of the rotor flux in order to provide field orientation, by alignment the stator current $i_{sd}$ with the rotor flux. The outer flux control and speed control loops provide the values of $i_{sd}^*$ and $i_{sq}^*$. These values are then transformed into stationary the αβ frame by using the rotor flux angle in order to match the motor model.

![Figure 1 Block diagram of the SM FOC of the IM drive](image)

**Figure 1** Block diagram of the SM FOC of the IM drive

### 4. ROTOR AND STATOR FLUX OBSERVER

Fig.2 shows the stator and rotor flux observer used in this paper. This observer system does not contain a speed sensor; the trend of developing it was the elimination of angular speeds. This was made by combinations using the machine model and observer systems presented in [5]. This elimination process is one of the main advantages in the motor drive application. It is based on the following set of equations:
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\[
\frac{L_s}{R_s} \frac{d\hat{\psi}_s}{dt} = -\hat{\psi}_s + \frac{L_m}{L_r} \hat{\psi}_r + \frac{L_s}{R_s} \hat{\psi}_s
\]  
(6)

\[
\frac{L_m}{L_sL_r - L_m^2} \frac{d\hat{\psi}_r}{dt} = -\frac{d\hat{i}_s}{dt} - \frac{L_r}{L_sL_r - L_m^2} R_s \hat{\psi}_s - b_2 \hat{\psi}_s
\]  
(7)

The outputs of the observer from (6) and (7) are the estimated values of the stator \(\hat{\psi}_s\) and the rotor flux linkage \(\hat{\psi}_r\). Then the stator current \(\hat{i}_s\) is calculated by using the estimated stator and rotor fluxes. Equation (8) is used in this paper to calculate the stator current vector [6].

\[
\hat{i}_s = \frac{(L_r \Phi_s - L_m \hat{\psi}_r)}{(1 - \frac{L_m^2}{L_r L_s}) L_s L_r}
\]  
(8)

Where \(1 - \frac{L_m^2}{L_r L_s}\) is \(\delta\) the total leakage factor

5. SLIDING MODE ROTOR AND STATOR FLUX OBSERVER

To establish the sliding mode observer, stator currents on \(\alpha\beta\) mode are considered. Including the sign of the error between the estimated values and the actual measured stator currents to a feedback of the stator and rotor flux observers. The model now will establish the sliding mode observers. These observers are represented as error compensators to the parameter mismatch between the motor and the observer as shown in Fig. 2.

Obviously, the calibration of resistance \(R_s\) will greatly influence the estimated values of both flux and current, whereas the controller has no rotor or motor speed. Therefore, the overall equations using the sliding observer positions become as follows:

\[
\frac{L_s}{R_s} \frac{d\hat{\psi}_s}{dt} = -\hat{\psi}_s + \frac{L_m}{L_r} \hat{\psi}_r + \frac{L_s}{R_s} \hat{\psi}_s
\]  
(9)

\[
\frac{L_m}{L_sL_r - L_m^2} \frac{d\hat{\psi}_r}{dt} = -\frac{d\hat{i}_s}{dt} - \frac{L_r}{L_sL_r - L_m^2} R_s \hat{\psi}_s + b_2 \hat{\psi}_s - D_s
\]  
(10)

Where

\[
D_s = k_s \text{sign}(\hat{i}_s - \hat{i}_s)
\]  
(11)

is the sliding function such that

\[
\text{sign}(\hat{i}_s - \hat{i}_s) = \begin{cases} 
1, & \text{if } \hat{i}_s > \hat{i}_s \\
0, & \text{if } \hat{i}_s = \hat{i}_s \\
-1, & \text{if } \hat{i}_s < \hat{i}_s 
\end{cases}
\]  
(12)

The corrected rotor flux is calculated using the difference between the stator current and its estimate as a correcting signal in the rotor flux calculation, which is sensitive to the variation of the stator resistance as shown in (7). Then the stator flux is estimated using this corrected rotor flux. The sliding mode gain \(k_s\) is adjusted so that the error is diverged to zero as fast as possible, i.e. the error between the estimated and the actual stator current approaches zero so that the sliding surface is achieved [11, 14]. Using trial and error method the value of \(k_s\) is tuned in simulation, so that the error is decreased and the transient behavior is improved.
Figure 2 Sliding mode rotor flux observer

The following equations is used to estimate the rotor speed:

\[ \hat{\omega}_r = \hat{\omega}_e - \hat{\omega}_{\text{slip}} \]  

(13)

Where \( \hat{\omega}_e \) is the electrical speed and \( \hat{\omega}_{\text{slip}} \) is the slip speed. And:

\[ \hat{\omega}_{\text{slip}} = \frac{L_m i_{\text{sq}}}{\tau_r |\hat{\psi}_r|} \]  

(14)

\[ \hat{\omega}_r = \frac{\rho_{r\beta} \hat{\psi}_{r\alpha} - \rho_{r\alpha} \hat{\psi}_{r\beta}}{|\hat{\psi}_r|^2} \]  

(15)

Where \( \tau_r \) is the rotor time constant and equals \( L_r/R_r \).

The flux observer provides the rotor flux components and their time derivatives \( \rho_{r\beta} \), \( \rho_{r\alpha} \) respectively and it is shown in fig. 2. So there is no need to compute the time derivative of the rotor fluxes.

6. SIMULATION RESULTS

In this work, the impact of the stator resistance was considered to monitor its effect on the drive system. The variation of \( R_s \) was simulated using matlab simulink toolbox for a 5 KW induction motor that can be used for a small wind energy generator or electric vehicle. The data was obtained using the 5 kW induction motor. The data was used in the simulation. The data reflected two different models: the first model represents the proposed SMO while the second represents the normal case. Figs. 3 to 6 consequently show the outputs of the SM FOC drive circuit using the correct values of the stator resistance. This means that stator resistance is kept intact in both the motor model and the observer model. To study the effect of varying the stator resistance on the outcomes, its value is changed by 50%. This value is then used in equation (7) without using the SMO. The results are now shown in Figs. 7 to 9. The figures clearly depict the impact of \( R_s \) on the estimation of the stator current, rotor flux and estimated rotor speed. As a result, the actual speed of the motor is behaving roughly and highly distorted.
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Figure 3 Actual and command $\psi_r$ when the load is changing

Figure 4 Output speed and fluxes: a) Actual and command speed, b) Actual and estimated rotor flux $\psi_r\alpha$, c) Actual and estimated rotor flux $\psi_r\beta$. 
Figure 5 Actual and estimated stator currents.

Figure 6 Error between the Actual and estimated rotor speed.

Figure 7 Command and actual rotor flux when the stator resistance value changed by 50%, without sliding mode observer.
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Figure 8 Rotor flux error when the stator resistance value changed by 50%, without sliding mode observer.

Figure 9 Actual and estimated rotor speed when the stator resistance value changed by 50% , without sliding mode observer.

Next we use the same control command but with a sliding mode observer and 50% $R_s$ variation. The results are shown in Figs. 10 to 13.

Figure 10 $\psi_r$ command and actual when the load is changing with sliding mode observer
Figure 11 Error signal of estimated and actual stator current.

Figure 12 Error signal of estimated and actual rotor flux.

Figure 13 Error signal of estimated and actual rotor speed.
7. DISCUSSION

In [8] the observer is applied to 1 hp (0.7457 kW). The paper proposed an adaptive sliding-mode flux observer for sensorless speed control of induction motors. To make flux and speed estimation robust to parameter variation two sliding mode current observers are used in the method. The simulation results of the actual and estimated rotor to a step speed command of -/+900 rpm, rotor speed error, actual and estimated rotor flux and rotor flux error are shown and from these results it can be noted that the flux and the estimated speed converge to real values very quickly. So the proposed algorithm is convergent, stable, accurate and insensitive to parameter change.

In [25], an integral sliding mode flux observer is presented to estimate the fluxes in the stationary reference frame. The purpose of the integral sliding mode flux observer is to improve the accuracy of control performance and the sliding mode function is based on the errors between the measured and estimated stator currents. The simulation and experimental results of rotor speed, d-axis and the rms values of tracking errors of the rotor speed and flux are shown in the paper and from the results we can notice that in a wide range of speed the observer can give good results.

From the results, we can notice that as the reference speed decreases the error of the rotor speed and flux are decreased in both simulation and experimental results. When the reference speed decreases from 1800 rpm to 500 rpm in the simulation results the steady state error of the rotor speed is reduced from 11.2423 to 3.6515 and the steady state error of the flux is reduced from 0.0018 to 0.0011. Conducting further analysis to the experimental results the steady state error of the rotor speed is reduced from 34.6655 to 22.6904 and the steady state error of the flux is reduced from 0.0027 to 0.0018.

In [26], an improved Sliding Mode observer for rotor fluxes and speed estimation from measured stator terminal voltages and currents is provided. The proposed observer applied to 1 KW induction motor. The simulation results at various ranges of speed [100 rpm, less than 50 rpm and less than 0 rpm] under no load condition is shown and from the results its obvious that the estimated and real speed follows the reference speed perfectly and precisely and the transient time is very low.

In addition, the simulation results of load test at high speed operation is shown and the disturbance is applied by a 4 N.M load torque from 1.5s to 3.5s and the results show that we have a quick convergence in estimation of the rotor speed and very low error. Also the results of dq-axis fluxes, torque and currents are shown. The quantitative analysis are not provided and only visual performance is presented.

In [27], the paper proposes an improved method of speed estimation that combines fuzzy proportional integral control and sliding mode control by adopting genetic algorithm to optimize the parameters of the three sliding mode controllers. The proposed observer was applied to 5.5 KW induction motor. A comparison between the traditional vector controlled system and the proposed system is included in the paper. The simulation results of speed changes from 80 rad/sec to 50 rad/sec are shown for both observer and the improved observer. These results showed reduction of the problems of speed fluctuation and the noise.

Further, the simulation results when 40 N.M load torque was applied showed that the improved observer was able to contain speed fluctuation and the noise.

When load is applied suddenly, the difference between the actual speed and the estimated speed before the improvement and after the improvement are 0.2 rad/s and 0.035 rad/s respectively.
The simulation results at low speed also shown. When the speed is changed from 5 rpm to 3 rpm and 40 N.M is applied; the difference between the actual speed and the given speed is 0.77 rad/sec before improvement and 0.25 after improvement.

The comparison between the sliding mode controller and fuzzy PI controller is also included, the load disturbance is applied from 0.3 to 0.8 sec it can be noted that the fuzzy PI combined with the sliding mode makes the system more robust and more accurate in estimating speed.

Also, the simulation results of electromagnetic torque, three phase stator current before and after improvement are also shown.

In [28], the speed estimation of vector controlled speed sensorless Induction motor using Model Reference Adaptive System and Sliding mode observer is presented. The simulation results at various reference speed (314 rpm, 283 rpm, and 251 rpm ) for rotor speed, speed estimation error and three phase stator currents of induction motor are shown and the simulation results of speed estimation showed that the observer is tracking the reference speed during step change and constant loads and its performance is good at lower speed. However, from the results shown it can be seen that there is fluctuation in the speed even in a steady state.

In [29], an effective sensorless direct torque control scheme for induction motor drive is proposed. The proposed algorithm consists of the association of the feedback linearization-based controller to a combined Model Reference Adaptive System -Sliding mode observer. The proposed observer applied to 1.1 kW IM. A comparison was made between the proposed observer and two other observers. The first observer is a full-order adaptive observer as presented in [30] and the second one is the basic sliding mode observer with open loop speed estimator. The simulation results for all three observers for 1000 rpm are shown and from the results, it can be noted that for the observer the estimated speed followed the real speed. The first observer shows better dynamic error convergence in the transient state. However, the behavior of the second observer in the steady state showed better static error convergence. They claimed that their proposed observer could eliminate the error in both transient and steady states and the estimation is more accurate. Also, for low speed estimation and under a variable speed reference profile the proposed observer provide the best speed estimation, the most reduced estimation error in dynamic state and a very quick convergence in the steady state.

Furthermore, [30] discussed the results of stator flux waveforms, all observers show a good waveforms and an accurate estimation for flux magnitude. For the first observer the static error is around 0.5% and the dynamic error is around 0.092%, for the secondone the static error is around 0.1% and the dynamic error is around 0.25% while for the proposed observer the static error is around 0.006% and the dynamic error is around 0.083%. In all previous papers, their results are mainly qualitative and do not provide justifiable quantitative values to support their claims. The use of adaptive and gentic type of algorithms without proper justification may be directive and don’t lead to robust solutions and different states.

In this work, the observer is applied to a 5 kW induction motor such motor can be used widely in industry for variable speed applications such as electric vehicles, elevators, robots home appliance and it can be used as a driver of the doubly fed induction generator [31-33].

The simulation results for two systems are shown. The first one was based on SM FOC and the second one wasn’t senseless. As it is depicted in the results, it is obviously noted that for the correct value of the stator resistor, the estimated flux, estimated stator currents and the estimated speed converge to the actual values very quickly, with a very low static and dynamic error (less than 0.001). Then both systems have been tested under parameter variation by changing the stator resistance value by 50% for the system without the SMO.
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this case, it was clear that the estimated flux is not converging to the actual value, the rotor flux error is high and the actual speed of the motor is highly distorted. On the other hand, the SM FOC observer is found to be robust to the variations of motor parameters, the estimated flux converge to the actual value, the error between the estimated and actual current is very low (less than 0.05). Furthermore the estimated speed can converge to the actual speed with a very low error (less than 0.01).

8. CONCLUSION

In the paper, to estimate the rotor speed a new sensorless flux observer system has been proposed. The proposed system utilizes the concept of a sliding mode observer, the system performance was tested under various load and parameter variations. The results show that the system is robust to the variation of motor parameters and it also eliminates the effect of Rs on the estimated speed.

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