SPEED SENSORLESS INDIRECT FIELD ORIENTED CONTROL OF INDUCTION MOTOR USING AN EXTENDED KALMAN FILTER

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Abstract: This paper presents the performance of the extended Kalman filter (EKF) for speed sensorless indirect field oriented control (IFOC) of a squirrel cage induction motor (IM) supplied by a pulse width modulated (PWM) voltage-source inverter. The rotor speed of the induction motor is estimated, according to this method, using the direct measurements of the stator voltages and currents without the speed sensor. The regulator of speed used is an IP type. Simulation results are illustrated and demonstrate the good performance and robustness of the extended Kalman filter observer to estimate the high and low speeds.

Key-words: EKF, IFOC, IM, PWM voltage-source inverter, Observer, Speed Sensorless.

1. Introduction
Because of the highly non-linear dynamic structure of the induction motor drives, a vector control method has been widely used for high performance applications and has become the standard in various industries. Furthermore, the strategy of the indirect field oriented control is the most technique used in induction motor control. This technique was introduced by Blaschke and Leonard and employs a direct estimation, by using sensors, of slip frequency obtained from the induction parameters, and adding to the shaft speed to determine the angular frequency.

Since three decades, great efforts have been made to increase the mechanical robustness and reliability of the induction motor, and to reduce costs and hardware complexity. Thus it is necessary to eliminate the speed sensor. Most methods are basically on the extended Kalman filter for the design of sensorless control schemes of the IM. This stochastic observer estimates simultaneously the states and the parameters of a dynamic process of the induction motor drive by measuring the stator voltages and currents. In this paper, we present the design of a high performance sensorless IM indirect field oriented control. The non-linear observer (EKF) is developed to estimate the rotor speed. Simulation results are illustrated to highlight the robustness and the performance of the proposed control scheme in high and low speeds and against load torque variations.

2. Dynamic model of induction motor
A dynamic model of the induction motor in stationary reference frame fixed to the stator can be expressed, by choosing stator currents and rotor fluxes as state variables and stator voltages as input variables, in the form of the state equation as shown below:

\[ x = Ax + Bu \]
\[ y = Cx \]

Where:
\[ x = \begin{bmatrix} i_{\alpha s} & i_{\beta s} & \phi_{\alpha r} & \phi_{\beta r} \end{bmatrix}^T \]
\[ u = \begin{bmatrix} u_{\alpha s} & u_{\beta s} \end{bmatrix}^T \]
\[ y = \begin{bmatrix} i_{\alpha s} & i_{\beta s} \end{bmatrix}^T \]

\[ A = \begin{bmatrix}
\frac{1}{\sigma T_1} + \frac{1-\sigma}{\sigma T_1} & 0 & \frac{1-\sigma}{\sigma L_{nT_1}} & \frac{1-\sigma}{\sigma L_{mT_1}} \\
0 & \frac{1}{\sigma T_1} + \frac{1-\sigma}{\sigma T_1} & \frac{1-\sigma}{\sigma L_{nT_1}} & \frac{1-\sigma}{\sigma L_{mT_1}} \\
\frac{L_{nT}}{T_1} & 0 & 1 & -\omega \\
0 & \frac{L_{nT}}{T_1} & \omega & 1 \\
\end{bmatrix} \]
3. Principle of the indirect field oriented control

The main objective of the vector control of IM is to independently control the torque and the flux. The d-axis is aligned with the rotor flux space vector $\mathbf{L}_d$. In this case, the electromagnetic torque can be expressed as:

$$ Te = p \frac{L_m}{L_s} \phi_i i_{sd}^* $$

(3)

The rotor flux and the torque are controlled by $i_{sd}^*$ and $i_{sq}^*$ respectively. The reference value of the rotor flux $\phi_i$, when it is divided by the magnetizing inductance, the direct-axis stator current reference $i_{sd}^*$ is obtained:

$$ i_{sd}^* = \frac{\phi_i^*}{L_s} $$

(4)

The quadrature-axis stator current $i_{sq}^*$ is proportional to the reference torque $T_e^*$:

$$ i_{sq}^* = \frac{1}{p} \frac{L_\alpha}{L_m} T_e^* $$

(5)

The angular slip frequency of the rotor flux $\omega_s$ is calculated from the reference values $i_{sd}^*$ and $i_{sq}^*$:

$$ \omega_s = \frac{i_{sq}^*}{T_e^*} i_{sd}^* $$

(6)

The angular speed of the rotor flux $\omega_s$ is equal to the sum of the angular rotor speed and the angular slip frequency of the rotor flux:

$$ \omega_s = \omega_a + p\Omega $$

(7)

Where $p$ is the pole-pair.

Fig. 1 shows a block diagram of the indirect field oriented control system (IFOC) for a sensorless induction motor.

4. Extended Kalman filter algorithm for rotor speed estimation

An extended Kalman filter is a stochastic observer used for state and parameters estimation of a non-linear dynamic system in real time disturbed by random noise.

The filter estimation is obtained from the predicted values of the states and this is corrected recursively by using a correction term, which is the product of the Kalman gain and the deviation of the estimated measurement output vector and the actual output vector. The Kalman gain is chosen to result in the best possible estimated states [5].

4.1 Selection of the time-domain motor model

The dimension of the state vector is increased by adding an angular speed of rotor, in this case, the angular speed of the rotor is considered as a state variable and the state vector becomes:

$$ x = \begin{bmatrix} i_{sd} & i_{sq} & \phi_{r\alpha} & \phi_{r\beta} & \omega \end{bmatrix}^T $$

(8)

The time-domain motor model is given as:

$$ \dot{x} = f(x, u) $$

(9)

$$ y = h(x) $$

(10)
Where:

\[
f(x, u) = \begin{bmatrix}
\frac{1}{\sigma_T^2} + 1 - \sigma_A & \frac{1}{\sigma_T^2} - \omega & \frac{1}{\omega_T^2} - \phi & \frac{1}{\tau_T} - \omega \\
0 & \frac{1}{\sigma_T^2} + 1 - \sigma_A & \frac{1}{\omega_T^2} - \phi & \frac{1}{\tau_T} - \omega \\
-\frac{1}{\sigma_T^2} \phi & 0 & \frac{1}{\omega_T^2} + \phi & \frac{1}{\tau_T} + \omega \\
-\frac{1}{\sigma_T^2} \phi & 0 & \frac{1}{\omega_T^2} + \phi & \frac{1}{\tau_T} + \omega \\
\end{bmatrix}
\]

\[
h(x) = \begin{bmatrix}
s_\alpha \\
s_\beta \\
st \\
\end{bmatrix}
\]

4.2 Discretization of the induction motor

The time-discrete state space model of the induction motor can be obtained from eqns (1, 2) as follow:

\[
x_{i+1} = f(x_i, u_i) = A_i x_i + B_i u_i \\
y_i = h(x_i) = C_i x_i
\]

Where:

\[
A_i = I + A T_i \\
B_i = B T_i \\
C_i = C
\]

The state vector is disturbed by system noise vector \(v\), and the measurement vector is disturbed by the measurement noise vector \(w\):

\[
x_{i+1} = f(x_i, u_i) + w_i \\
y_i = h(x_i) + v_i
\]

4.3 Determination of the noise and state covariance matrices \(Q, R\) and \(P\)

A critical part of the design of the EKF is to use correct initial values for the various covariance matrices, \(Q, R,\) and \(P\). These have important effects on the filter stability and convergence time. To obtain the best estimate value of the speed, it is important to use accurate initial values for the covariance matrices of the system noise, measurement noise and the state noise \(Q, R\) and \(P\) respectively [5]. These matrices are assumed as diagonal covariance matrices.

4.4 Implementation of the discretized EKF algorithm

The extended Kalman filter algorithm is a recursive state estimator and is based on two main stages, a prediction stage and a filtering stage:

**Prediction:** During this stage, the next predicted values of the states \(\hat{x}(k+1)\) and the predicted state covariance matrix \(P\) are obtained.

**Filtering:** During this stage, the filtered states \(x\) are obtained from the predicted estimates by adding a correction term \(K(y - \hat{y})\) to the predicted value \(\hat{x}\).

The state estimates are obtained in the following steps:

* Initialization of the state vector and covariance matrices.
* Prediction of the state vector

\[
\hat{x}_{i+1} = f(x_i, u_i)
\]
• Prediction covariance computation

\[ P_{k+1} = F_k P_k F_k + Q \]  
(16)

Where \( F_k = \frac{\partial \hat{f}(x_k, u_k)}{x_k} \)  
(17)

\[ F_i = \begin{bmatrix}
1 - T \left( \frac{1 - \sigma_1}{\sigma T} \right) & 0 & T \frac{1 - \sigma_1}{\sigma L \omega} & 0 & T \frac{1 - \sigma_1}{\sigma L \omega} \\
0 & 1 - T \left( \frac{1 - \sigma_1}{\sigma T} \right) & 0 & T \frac{1 - \sigma_1}{\sigma L \omega} & 0 \\
T \frac{1 - \sigma_1}{L \omega} & 0 & 1 - T \left( \frac{1 - \sigma_1}{\sigma T} \right) & 0 & T \frac{1 - \sigma_1}{\sigma L \omega} \\
0 & T \frac{1 - \sigma_1}{L \omega} & T \omega & 1 - T \left( \frac{1 - \sigma_1}{\sigma T} \right) & T \frac{1 - \sigma_1}{\sigma L \omega} \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \]

• Kalman gain computation

\[ K_{x_{est}} = P_{x_{est}} H_i^T [H_i P_{x_{est}} H_i + R_i]^{-1} \]  
(18)

Where \( H_i = \frac{\partial h(x_k)}{x_k} \)  
(19)

\[ H_i = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0
\end{bmatrix} \]

• State vector estimation

\[ \hat{x}_{k+1|i} = \hat{x}_{k|i} + K_{x_{est}} (y_{k+1} - H_i \hat{x}_{k|i}) \]  
(20)

• Covariance matrix of estimation error

\[ P_{x_{est|i}} = P_{x_{est|i}} - K_{x_{est|i}} H_i P_{x_{est|i}} \]  
(21)

Where \( ^\wedge \) denotes the estimation value.

5. Simulation results

The simulations are done for the speed estimation of induction motor by indirect field oriented control method with extended Kalman using the MATLAB/Simulink software. Classical Proportional-Integral controllers are used for speed and stator current loops. The IM parameters used in simulation are given in table 1. The performances of the observer are analyzed according to the simulation of the following transients:

a. Inversion of the speed

To test the robustness of the sensorless control, we applied a changing of the speed reference from 100 rad/s and -100 rad/s. Fig.2 presents the actual, estimated speed, and estimation error. Fig.3 presents the real rotor flux, estimated rotor flux and the estimation error.

![Fig. 2. Actual and estimated speed.](image_url)

![Fig. 3. Actual and estimated flux.](image_url)

b. Operation at low speed

To test the good working of the EKF, the simulation was established in low speed. Fig.4 illustrates the process of speed estimation with a speed reference between 5 rad/s and -5 rad/s.

![Fig. 4. Actual and estimated speed.](image_url)
c. Variation of the load torque
To test the performance at high speed a load torque equal to 20 N.m is applied between 1s and 2.5s.

6. Conclusion
In this paper, an extended Kalman filter approach for indirect field oriented control of the induction motor drive has been proposed and tested. In this proposed scheme, the estimate of rotor speed is obtained from the directly measurable stator currents and voltages. Simulation results show good performance and robustness of the sensorless vector control at high and low speeds. In addition, the simulation results show the robustness of the proposed algorithm against measurement noises and load torque variations. Finally, an IP regulator has been used in the speed control of an IFOC.

Appendix

\[
\begin{align*}
P & = 3 \text{ KW} & U_r & = 220 \text{ V} & f & = 50 \text{ Hz} \\
p & = 2 & R_s & = 2.2 \text{ } \Omega & R_r & = 2.68 \text{ } \Omega \\
L_s & = 229 \text{ } \text{H} & L_r & = 229 \text{ } \text{H} & L_m & = 217 \text{ } \text{H} \\
J & = 0.047 \text{ Kg.m}^2 & f_v & = 0.004 \text{ Kg.m}^2/\text{s} & W_r & = 1440 \text{ rpm} \\
\end{align*}
\]

Table 1. Induction motor parameters

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<thead>
<tr>
<th>Time[s]</th>
<th>Rotor flux[Wb]</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
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Fig. 5. Actual and estimated speed.

Fig. 6. Actual and estimated speed.

Fig. 7. Actual and estimated flux.
References


