Non-invasive State Estimation for Slip-Ring Induction Motor using Discrete-time and Continuous-time Extended Kalman Filters

SSSR Sarathbabu Duvvuri

Abstract: In this manuscript, a modified extended slip-ring induction motor model using reference frame theory is presented. State estimation is carried using derivative-free and derivative non-linear Kalman filters. The results show the advantage of the proposed state estimation in realistic applications from the rotor side.

Keywords: Autocorrelation coefficient (ACC), Nonlinear Kalman filter (EKF), reference frame theory, slip-ring induction motor (SRIM).

I. INTRODUCTION

This is an extension work presented in [6]. The paper is organized as follows: after the introduction in Section I, a modified extended SRIM model is presented in detail in Section II followed by state estimation using discrete-time nonlinear Kalman filter and continuous-time nonlinear Kalman filter for the proposed SRIM model in Section III. Main simulation results, analysis and observations are presented in Section IV. Finally, Section V presents the concluding remarks.

II. MODIFIED SLIP-RING INDUCTION MOTOR MODEL

The 8th order SRIM model based on abc machine variables presented in is computationally intensive. By using reference frame theory, abc machine model presented in [1], [2] is transformed in to synchronously rotating reference frame, the SRIM model based on \[ v_{ útil, n} \], is formulated as:

\[ i_2 = \frac{1}{L_s} \left( v_2 + i_2 \frac{R_s}{L_s} \right) + \frac{1}{L_m} \left( v_2 - \omega_m \omega_s \right) \]

\[ i_1 = \frac{1}{L_s} \left( v_1 + \omega_m \omega_s i_2 + \frac{R_s}{L_s} \right) + \frac{1}{L_m} \left( \omega_m \omega_s i_2 - \omega_m \omega_s \right) \]

\[ v_0 = \frac{1}{L_s} \left( v_0 + \omega_m \omega_s \right) + \frac{1}{L_m} \left( \omega_m \omega_s - \omega_m \omega_s \right) \]

\[ \omega_m = \frac{1}{J} \left( T_m - B_s \omega_s \right) \]

\[ \omega_s = 0 \]

III. STATE-ESTIMATION OF SLIP-RING INDUCTION MOTOR MODEL

Different conventional EKF algorithms are developed for the state estimation of extended state space model of SRIM model [3]-[11].

IV. MAIN SIMULATION RESULTS AND DISCUSSIONS

Simulations of SRIM and state estimation with nonlinear Kalman filters have been carried out using MATLAB program.

TABLE-I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>( P_{\text{rated}} )</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Line voltage</td>
<td>( V_l )</td>
<td>415 V</td>
</tr>
<tr>
<td>Line current</td>
<td>( I_l )</td>
<td>7.5 A</td>
</tr>
<tr>
<td>Rated speed</td>
<td>( N_{\text{rated}} )</td>
<td>1410 rpm</td>
</tr>
<tr>
<td>Load torque</td>
<td>( T_l )</td>
<td>25 Nm</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>( f_s )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of pole-pairs</td>
<td>( n_p )</td>
<td>2</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>( r_s )</td>
<td>2.283 Ω</td>
</tr>
<tr>
<td>Rotor resistance (stator referred)</td>
<td>( r_r )</td>
<td>2.133 Ω</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>( L_{ds} )</td>
<td>11.1 mH</td>
</tr>
<tr>
<td>Rotor leakage inductance (stator referred)</td>
<td>( L_{dr} )</td>
<td>11.1 mH</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>( L_{ms} = L_{ms} )</td>
<td>310 mH</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>( L_s )</td>
<td>476.1 mH</td>
</tr>
<tr>
<td>Rotor inductance (stator referred)</td>
<td>( L_r )</td>
<td>476.1 mH</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>( L_m )</td>
<td>465 mH</td>
</tr>
<tr>
<td>Rotor inertia</td>
<td>( J )</td>
<td>0.06 kg.m²</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>( B_l )</td>
<td>0.001 N.m/(rad/sec)</td>
</tr>
</tbody>
</table>

- Case I: SRIM with DTEKF

A. SRIM fed from unbalanced supply and variable speed

Fig. 1 and Fig. 2 represents unbalanced input supply fed to SRIM in abc and qd0 reference frames.

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* Correspondence Author

SSSR Sarathbabu Duvvuri, Department of Electrical and Electronics Engineering, Shri Vishnu Engineering College for Women Bhimavaram (Autonomous), Jawaharlal Nehru Technological University Kakinada, AP, INDIA. Email: ee11p1007@iith.ac.in
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Fig. 1. Line voltages.

Fig. 2. Line voltages in stationary reference frame.

Fig. 3. Rotor currents.

Fig. 4. Rotor currents in qd-axis.

Fig. 5. Rotor fluxes in qd-axis.

Fig. 6. Rotor speed in rpm.

Fig. 7. (a) error for states ($i_q$, $i_d$, $i_\theta$, $\lambda_q$, $\lambda_d$) (b) ACCs at $t = 0.6$ to $1$ second (normal operation) (c) ACCs at $t = 1$ second (variable speed operation).
Fig. 8. (a) error for states \( (\dot{\theta}, \dot{\omega}, \dot{\gamma}) \) (b) ACCs at \( t = 0.6 \) to 1 second (normal speed) (c) ACCs at \( t = 1 \) second (variable speed).

B. SRIM fed with sudden change in system parameter

In this simulation studies, initially SRIM machine and model are assumed to have same values after certain time \( t = 0.1 \) second, model parameters are changed suddenly. For instance, 5% increase in stator resistance, 5% decrease in rotor resistance, 3% decrease in stator leakage inductance, 3% increase in rotor leakage inductance, and 2% increase in magnetizing inductance. Even though, there is sudden change in parameters, DTEKF state estimator provides better state estimates without showing any deviations from Gaussian noise. The results are also validated using ACCs are presented in Figs 9-10.

Fig. 9. (a) error for states \( (\omega, \tau) \) (b) ACCs at \( t = 0.6 \) to 1 second (normal operations) (c) ACCs at \( t = 1 \) second (parameter variation).

C. SRIM fed with initial state vector mismatch

The DTEKF initial conditions are: state vector \((-0.8816, 0.1514, 0.0008, -0.0314, 1.0687, 0, 154.2355, 4.8955)\) of the motor and the actual motor initial conditions are: state vector \((-8.5189, -1.4321, 0, -0.1618, 0.9626, 0, 147.6410, 0)\).

Fig. 11. (a) error for states \( (\omega, \tau) \) (b) ACCs at \( t = 0.6 \) to 1 second (normal operation) (c) ACCs at \( t = 1 \) second (load variation).

D. SRIM fed from unbalanced supply and variable speed

Fig. 12. (a) error for states \( (T_m) \) (b) ACCs at \( t = 0.6 \) to 1 second (normal operation) (c) ACCs at \( t = 1 \) second (load variation).

- Case II: SRIM with CTEKF

Simulation results for of SRIM for speed and
electro-magnetic torque are clearly presented in Fig. 13, and Fig. 14 respectively.

![Rotor speed in rpm](image1)

**Fig. 13.** Rotor speed in rpm.

![Electromagnetic torque](image2)

**Fig. 14.** Electromagnetic torque.

![Error for states](image3)

**Fig. 15.** (a) error for states ($\dot{\omega}_r$, $\dot{\theta}_r$, $\dot{\omega}_s$, $\dot{\theta}_s$) (b) ACCsat t = 0.6 to 1 second (normal operation) (c) ACCs at t = 1 second (speed variation).

![Error for states](image4)

**Fig. 16.** (a) error for states ($\dot{\omega}_r$, $\dot{\theta}_r$, $\dot{\omega}_s$, $\dot{\theta}_s$) (b) ACCsat t = 0.6 to 1 second (normal operation) (c) ACCs at t = 1 second (speed variation).

![Error for states](image5)

**Fig. 17.** (a) error for states ($\omega$, $T$) (b) ACCsat t = 0.6 to 1 second (normal operation) (c) ACCs at t = 1 second (speed variation).

E. **SRIM fed with sudden change in system parameter**

In this simulation studies, initially SRIM machine and model are assumed to have same values after certain time $t = 0.1$ second, model parameters are changed suddenly. For instance, 5% increase in stator resistance, 5% decrease in rotor resistance, 3% decrease in stator leakage inductance, 3% increase in rotor leakage inductance, and 2% increase in magnetizing inductance. Even though, there is sudden change in parameters, DTEKF state estimator provides better state estimates without showing any deviations from Gaussian noise. The results are also validated using ACCs are presented in Figs. 18.

![Error for states](image6)

**Fig. 18.** (a) error for states ($\omega$, $T$) (b) ACCsat t = 0.6 to 1 second (normal operation) (c) ACCs at t = 1 second (parameter variation).

F. **SRIM fed with initial state mismatch**

In this case study, simulation studies are conducted with an initial state value difference between the machine and model. In all the simulation studies, state noise and measurement noise is introduced. The DTEKF initial conditions are: state vector (-25.8956, -18.2227, 0.0010, -0.5846, 1.2438, 0.0000, 124.5803, 64.1554) of the motor and the actual motor initial conditions are: state vector (3.6514, 0.7937, 0.0000, 0.0975, -1.8312, 0.0000, 144.7279, 0). The results are also validated using autocorrelation coefficients are presented in Fig. 21. Similar analysis is carried for all the case studies, however, results are not provided due to conciseness.

![Rotor speed in rpm](image7)

**Fig. 19.** Rotor speed in rpm.

![Electromagnetic torque](image8)

**Fig. 20.** Electromagnetic torque.
V. CONCLUSION

A comparative analysis for state estimation using DTEKF and CTEKF fed Slip-Ring Induction Motor is presented in this manuscript. Non-invasive state estimation is critical advantage of proposed strategy.

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REFERENCES