Chapter 4
Particle Filter Based Anomaly Detection for Aircraft Actuator Systems

D. Brown, G. Georgoulas, H. Bae, G. Vachtsevanos, R. Chen, Y.H. Ho, G. Tannenbaum and J.B. Schroeder

Abstract This paper describes the background, simulation and experimental evaluation of an anomaly detector for Brushless DC motor winding insulation faults in the context of an aircraft Electro-Mechanical Actuator (EMA) application. Results acquired from an internal Failure Modes and Effects Analysis (FMEA) study identified turn-to-turn winding faults as the primary mechanism, or mode, of failure. Physics-of-failure mechanisms used to develop a model for the identified fault are provided. The model was implemented in Simulink to simulate the dynamics of the motor with a turn-to-turn insulation winding fault. Then, an experimental test procedure was devised and executed to validate the model. Additionally, a diagnostic feature, identified by the fault model and derived using Hilbert transforms, was validated using the Simulink model and experimental data for several fault dimensions. Next, a feature extraction routine preprocesses monitoring parameters and passes the resulting features to a particle filter. The particle filter, based on Bayesian estimation theory, allows for representation and management of uncertainty in a computationally efficient manner. The resulting anomaly detection routine declares a fault only when a specified confidence level is reached at a given false alarm rate. Finally, the real-time performance of the anomaly detector is evaluated using LabVIEW.

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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>rad</td>
<td>Motor (or rotor) position</td>
</tr>
<tr>
<td>( \omega )</td>
<td>rad/s</td>
<td>Motor (or rotor) speed</td>
</tr>
<tr>
<td>( \Psi_{abc} )</td>
<td>Wb</td>
<td>Stator back-emf vector</td>
</tr>
<tr>
<td>( \psi_m )</td>
<td>Wb</td>
<td>Magnitude of magnetic flux linkage</td>
</tr>
<tr>
<td>( \Psi_m )</td>
<td>Wb</td>
<td>Magnetic flux linkage vector</td>
</tr>
<tr>
<td>( \psi_s )</td>
<td>V</td>
<td>Series back-emf</td>
</tr>
<tr>
<td>( \psi_s^f )</td>
<td>V</td>
<td>Series back-emf with fault</td>
</tr>
<tr>
<td>( i_{abc} )</td>
<td>A</td>
<td>Stator winding current vector</td>
</tr>
<tr>
<td>( k )</td>
<td>–</td>
<td>Number of turns between fault</td>
</tr>
<tr>
<td>( L_{abc} )</td>
<td>H</td>
<td>Stator inductance matrix</td>
</tr>
<tr>
<td>( L_{ij} )</td>
<td>H</td>
<td>Self inductance of ith phase winding</td>
</tr>
<tr>
<td>( L_{ij} )</td>
<td>H</td>
<td>Mutual inductance between ( i )th and ( j )th phase windings</td>
</tr>
<tr>
<td>( L_{ij}^{-1} )</td>
<td></td>
<td>Inverse stator inductance of the ( i )th and ( j )th phase winding</td>
</tr>
<tr>
<td>( L_s )</td>
<td>H</td>
<td>Series inductance</td>
</tr>
<tr>
<td>( L_s^f )</td>
<td>H</td>
<td>Series inductance with fault</td>
</tr>
<tr>
<td>( N )</td>
<td>–</td>
<td>Number of turns per winding</td>
</tr>
<tr>
<td>( P )</td>
<td>–</td>
<td>Number of magnetic poles</td>
</tr>
<tr>
<td>( R_{abc} )</td>
<td>( \Omega )</td>
<td>Stator resistance matrix</td>
</tr>
<tr>
<td>( R_f )</td>
<td>( \Omega )</td>
<td>Turn-to-turn winding fault resistance</td>
</tr>
<tr>
<td>( R_{ij} )</td>
<td>( \Omega )</td>
<td>Resistance of ith phase winding</td>
</tr>
<tr>
<td>( R_s )</td>
<td>( \Omega )</td>
<td>Series resistance</td>
</tr>
<tr>
<td>( R_s^f )</td>
<td>( \Omega )</td>
<td>Series resistance with fault</td>
</tr>
<tr>
<td>( t )</td>
<td>s</td>
<td>Continuous time index</td>
</tr>
<tr>
<td>( T_e )</td>
<td>N ( \cdot ) m</td>
<td>Motor torque</td>
</tr>
<tr>
<td>( U_{abc} )</td>
<td>V</td>
<td>Phase-to-neutral voltage vector</td>
</tr>
<tr>
<td>( w_i^f )</td>
<td>–</td>
<td>Winding fault dimension for the ( i )th phase winding</td>
</tr>
</tbody>
</table>

### Vector/Matrix Scalar Representation

- \( \Psi_{abc} = [\psi_a \ \psi_b \ \psi_c]^T \)
- \( \Psi_m = [\psi_{am} \ \psi_{bm} \ \psi_{cm}]^T \)
- \( i_{abc} = [i_a \ i_b \ i_c]^T \)
- \( U_{abc} = [U_a \ U_b \ U_c]^T \)
- \( L_{abc} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \)