EXPERIMENTAL VALIDATION AND DYNAMIC SIMULATION OF ROTOR FAULTS IN INDUCTION MOTORS

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Outlines

• The Problem
• Background
• Research Approach and Results
• Conclusion
• Acknowledgements
The Problem

Motors are the beating heart of industrial mining

About 50% of industrial mining expenses are due to faults

In geographically remote and landlocked locations such as Mongolia, this problem is a significant one.
Background: Online condition monitoring of motors

• Used to better understand the current health and performance of equipment

• Measures vibration to record changes in the operation of the equipment

https://windrock.com/blog/why-condition-monitoring-is-important/
Research Approach: Objectives

The objectives of this research then, are:

- to determine whether characteristic frequencies in spectrum analysis to determine rotor faults is based on dynamic simulation and
- to validate results in the laboratory and test in the field.
Equations of dynamic simulation

\[
[V_s]_{3x1} = [v_a^s, v_b^s, v_c^s]_{3x1}^T \\
[I_s]_{3x1} = [i_a^s, i_b^s, i_c^s]_{3x1}^T \\
[V_r]_{nx1}^T = [v_1^r, v_2^r, \ldots, v_{nx1}^r]^T \\
[I_r]_{nx1} = [i_1^r, i_2^r, \ldots, i_{nx1}^r]^T \\
[A_s]_{3x1} = [A_a^s, A_b^s, A_c^s]_{3x1}^T \\
[A_r]_{nx1} = [A_1^r, A_2^r, \ldots, A_{nx1}^r]_{nx1}^T \\
[M] = \begin{bmatrix} R_s & \frac{dL_{sr}}{dt} & \omega \\ \frac{dL_{rs}}{dt} & R_r & \omega \end{bmatrix}; \quad \omega = \frac{d\theta}{dt}
\]

\[
[N] = \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}
\]

\[
T_e = I_s^T \frac{dL_{sr}}{d\theta} I_r
\]

\[
T_e = J \frac{d^2\theta}{dt^2} + B_m \frac{d\theta}{dt} + T_L
\]
Mutual inductance between a rotor loop and stator phases

\[
\begin{align*}
L & \leq \theta \cdots L(L + 0) \chi 0 \theta + \cdots L(L + 0) = L(L + 0), \\
\cdots & \\
L & \chi L(L + 0) = L(L + 0) + \cdots L(L + 0) = L(L + 0).
\end{align*}
\]

Mutual inductance between faulty rotor loop and stator phases

\[
\begin{align*}
\text{Winding Function} & \\
N(x) & = \frac{w_i}{2 \pi} \left[ 2\pi(\theta - \theta_{i1}) + \delta(\pi - \alpha_i) \right], \\
& \text{where} \quad \theta_{i1} - \frac{\delta}{2} \leq \theta \leq \theta_{i1} + \frac{\delta}{2}, \\
& \text{and} \quad \theta_{i2} - \frac{\delta}{2} \leq \theta \leq \theta_{i2} + \frac{\delta}{2}.
\end{align*}
\]

\[
N_i(\theta) = \begin{cases} 
\frac{w_i}{2 \pi} \left[ 2\pi(\theta - \theta_{i1}) + \delta(\pi - \alpha_i) \right], \\
\begin{cases} 
\begin{cases} 
\frac{\delta}{2} & \text{if } \theta_{i1} - \frac{\delta}{2} \leq \theta \leq \theta_{i1} + \frac{\delta}{2}, \\
\frac{\delta}{2} & \text{if } \theta_{i2} - \frac{\delta}{2} \leq \theta \leq \theta_{i2} + \frac{\delta}{2}, \\
0 & \text{otherwise}
\end{cases} \\
\frac{\delta}{2} & \text{if } \theta_{i1} - \frac{\delta}{2} \leq \theta \leq \theta_{i1} + \frac{\delta}{2}.
\end{cases}
\end{cases}
\]

\[
L_{mm} + 2(L_b + L_e) - (L_{r2r1} + L_b) \cdots - L_{r1rn-1} - (L_{r1rn} + L_b) \\
-(L_{r2r1} + L_b) L_{mm} + 2(L_b + L_e) \cdots - L_{r2rn-1} \cdots - L_{r2rn}
\]

Flowchart of dynamic simulation

\[
[R_S]_{3x3} = \begin{bmatrix}
R_a & 0 & 0 \\
0 & R_b^s & 0 \\
0 & 0 & R_b^s
\end{bmatrix}
\]

Research Approach: Motor Simulation and Dynamics

Resistance of rotor end-rings of healthy motor (get_Rr) (get_matrix_reduce)

Resistance of broken rotor bar (get_Rr_nrb)

Resistance of rotor end (get_Rr)

Stator resistance (get_M)
Inductances of motors
Dynamic simulation design
Results of dynamic simulation

Stator Current

Healthy

Broken Rotor bar

Torques

Steady State

Transient
Spectrum analysis of steady state
Spectrum analysis of steady state of torque

Healthy

fr = 24.2 Гц – RPM;
fs = 50 Гц – Supply;
fr = fr * nbr – frequency from rotor bars

Broken Rotor bar

fsm = 3.2 Гц Гулсайлт
### Spectrum analysis of steady state of torque

#### Healthy

<table>
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<tr>
<th>1</th>
<th>Роторын давтамжийн гармоник, fr</th>
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\[ fn = \alpha frs \mp \beta fs \mp \gamma fr \]
### Spectrum analysis of steady state of torque

#### Broken Rotor bars

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\[ fn = \alpha frs \pm \beta fs \pm \gamma fr \pm \delta fsm \]
Laboratory-Based Validation of Results

Laboratory for validating torque’s spectrum

Laboratory for validating vibration spectrum
Laboratory-Based Test: Vibration Analysis

Healthy

Broken rotor bar

\( f_{sm} = 3.2 \text{Гц} \) Гулсальт
Laboratory-Based Test: Torque Analysis

Healthy

Broken rotor bar

\[ f_{sm} = 0.6 \text{ Hz Slip} \]
Conclusions

• The characteristic frequencies of a broken rotor appear as harmonics of the slip frequency on both sides of the peak magnitude at the rotation per second, and at the frequency of rotor bar, in the torque spectrum and the vibration spectrum, respectively.
Conclusions

• To determine if a broken rotor bar exists, the characteristic frequencies in the vibration analysis are the same as those in the torque analysis. Therefore, either a vibration data acquisition device or a torque data acquisition device can be used.
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THANK YOU