Project Introduction, Current Status and Future Plan

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Problem Statement

Rich gas → gas, NGL, condensate

Dewatering → Compression
Problem Statement

HV Synchronous (42 MW)
Problem Statement

- Critical Component
  - Motor (Ageing of stator winding insulation)

- Requirements
  - Summer (3 units)
  - Winter (6 units)

- Current Status
  - 5 commissioned in 1996
  - 1 new (2006)
Machinery Prognostics

• Traditional reliability approaches
  – Event data based
  – Replacement/failure times of historical units

• Prognostic approaches
  – Condition data based

• Integrated
  – Both on event and condition data
    • Depends on the availability

Reference: Aiwina (2009)
Prognosis

\[ RUL(t) = \inf \{ h: X(t + h) \in S_L | X(t) \not\in S_L \} \]

\[ X(t) = \text{Random Variable (Condition) at time } t \]
\[ S_L = \text{Set of failed states} \]

Reference: Xiongzi (2011)
Machinery Prognostics

Reference: Based on Vachtsevanos (2006) and Si (2011)

Under laboratory condition
Not always practical for CM
Some tests are destructive
Condition Indicator

- Diagnostic Vs. Prognostic

- **Diagnosis** - identify failure mode (cause of malfunction)
- **Prognosis** - generate rational estimation of RUL with available data (medical history)

*Flu? Let me calculate the probability of you surviving 10 more years!!*

Reference: Lee (2014)
Condition Indicator

• Available Test Procedures (Insulation Quality)
  – Insulation Resistance
  – Polarization Index
  – Hi-Pot Test
  – Partial Discharge
  – ….. Etc.

• Partial Discharge (PD)
  – Dielectric breakdown of electric insulation under high voltage
  – Creates small sparks in holes and bombard them

Online PD Monitoring

- **OLPD measures**
  - Number of PD pulses
  - PD Magnitude (Qm)
  - Phase position

- **PD Magnitude**
  - Highest PD pulses with minimum repetition rate of 10 pulses/sec
  - Higher value indicates more deteriorated winding (Stone, 2006)

**Diagram:**

- Bipolar Machine PD
- Pulse Magnitude vs. Phase Angle
- Qm vs. Years
- Typical trend in PD magnitude of stator windings (Stone (2012))
Preliminary Approach

• Choice of statistical model
  – Gamma process
• Reasons-
  – Strictly monotonic increasing degradation
  – Useful for optimal inspection and maintenance decisions making
• Limitations
  – Linear expected degradation

Gamma Process

- PDF of Gamma distribution:

\[ f_{A(t),b}(x) = \frac{1}{\Gamma(A(t))} b^{A(t)} x^{A(t)-1} e^{-bx} \]

- \( A(t) = \) Shape function
- \( b = \) Scalar parameter

- Mean:

\[ E(X_t) = \frac{A(t)}{b} \]

- Variance:

\[ Var(X_t) = \frac{A(t)}{b^2} \]
Non-Homogeneous Gamma Process

- Non-homogeneous Gamma Process modeling
  - How deterioration increases over time? (Assuming temporal variability)
  - Shape function, $A(t) = c \cdot t^u$ (Empirical studies)

Simulation Process

- **Available Methods**
  - Gamma increment sampling
    - Simulate independent increments w.r.t. tiny amount of time
    
    \[
    Ga(\delta|A(t_i) - A(t_{i-1}), b) = \frac{b^{A(t_i) - A(t_{i-1})}}{\Gamma(A(t) - A(t_{i-1}))} \delta^{[A(t) - A(t_{i-1})]-1} e^{-b\delta}
    \]
    
    A.K.A – Gamma Sequential Sampling (GSS)
  
  - Gamma bridge sampling
    - Draw samples from CDF of deterioration

Simulated NHGP Paths

Gamma process paths

One path out of 100 samples
Changes in Shape

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations
Changes in Scaler Parameter

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations

Gamma process paths for 100 samples and 101 observations
Parameter Estimation

- Maximum Likelihood Estimation

\[
\psi(x) = \frac{d}{dx} \ln \Gamma(x) = \frac{\Gamma'(x)}{\Gamma(x)}
\]

\[
\hat{C} \text{ must be computed iteratively (Newton-Raphson Method)}
\]

\[
\hat{b} = \frac{m \hat{c} t^u_n}{\sum_{j=1}^{m} x_{n,j}}
\]

\[
\sum_{i=1}^{n} [t^u_i - t^u_{i-1}] \psi(\hat{c}[t^u_i - t^u_{i-1}]) = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{[t^u_i - t^u_{i-1}]}{m} \ln(\delta_{i,j}) = \hat{t}^u_n \ln \left( \frac{m \hat{c} t^u_n}{\sum_{j=1}^{m} x_{n,j}} \right)
\]
Test Result (Example)

Shape function, $A(t) = c \cdot t^u$
Scaler parameter = $b$

Number of components, $M = 100$
Total time, $T = 10$ unit
Time increment = 0.1

Parameter value of generated data, $b = c = u = 2$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Confidence Level</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>2.0919</td>
<td>95%</td>
<td>2.0146</td>
<td>2.1722</td>
</tr>
<tr>
<td>$b$</td>
<td>2.0441</td>
<td></td>
<td>1.9584</td>
<td>2.1336</td>
</tr>
</tbody>
</table>
Estimation Accuracy - Sample size

Accuracy of c estimates
Dataset: c=3, u=2, b=2

Accuracy of b estimates
Dataset: c=3, u=2, b=2
Estimation Accuracy - Initial Observation

Accuracy of c estimates
Dataset: c= 3, u=2, b=2

Accuracy of b estimates
Dataset: c= 3, u=2, b=2

Number of deleted initial observations at the beginning (Total=101)
Opportunistic Observation

Accuracy of estimates removing 5 observations (original estimate = 2.0108)

Dataset: c = 2, u = 2, b = 2

Accuracy of estimates removing 50 observations (original estimate = 2.0108)

Dataset: c = 2, u = 2, b = 2

Accuracy of estimates removing 95 observations (original estimate = 2.0108)

Dataset: c = 2, u = 2, b = 2
RUL (Illustration)
First Hitting Time, $T_L$

$$T_L = \inf(t > 0: X(t) \geq L)$$

CDF of FHT,

$$F(t) = \Pr(T_L < t) = \Pr(X(t) \geq L)$$

$$= \int_{x=L}^{\infty} f_{X(t)}(x) \, dx = \frac{\Gamma(A(t), Lb)}{\Gamma(A(t))}$$

At time $t$ when $X(t)=x(t)$, RUL < $h$

$$P(RUL \leq h) = 1 - P(RUL > h)$$

$$= 1 - P[X(t+h) < L | X(t) = x(t)]$$

$$= 1 - \frac{P[X(t+h) - x(t) < L - x(t)]}{P(X(t) < L)}$$
RUL Results

CDF of RUL distribution with different thresholds
Current inspection time = 2, current degradation level = 1.5384, u=2, c=2

CDF of RUL distribution with different value of scalar parameter
Current inspection time = 2, u=2, c=2

CDF of RUL distribution with different exponential parameter
Current inspection time = 2, c=2, b=2

CDF of RUL distribution with different value of c
Current inspection time = 2, u=2, b=2
An Insight

Increase of PD activity is better indicator than absolute PD magnitude [Zhu (2001)]
Further Workplan

• Compare RUL estimations
  – Inspection intervals
  – Interpretations

• Discuss improvement
  – Adaptive model (update parameter)
  – Stochastic threshold

• Discuss System level RUL
  – Implementations
  – Challenges

• Data collection
  – Requirements
  – Conditions
  – PD? Misinterpretation?
References