Asset Management of MV Cables using Data Driven Health Indices for Water Treeing

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Background

• (MV) XLPE insulated cables were first installed in the early 1960’s.
• Expected to perform reliably for ≈30 yrs.
• Not aware that moisture, voltage stress, imperfections would combine to grow water trees.
• Many cables failed after few years.
• This impacted operating costs that electric utilities are still dealing with today.
Prior Work to Historical Archive

- >450 different examinations
- >40 Utilities
- Individual Reports -> Database
- >1500 large Vented Trees
- >3200 large Bowtie Trees
- Meta Data
  - Generation
  - Material
  - Neutral Condition
  - Prior Failures
- 21,000 data entries

### Summary of Largest Water Tree Sites Identified (Wafer or Hot Oil)

<table>
<thead>
<tr>
<th>Tree Type</th>
<th>Tree Length (mils)</th>
<th>% Growth through Wall</th>
<th>Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BT</td>
<td>100</td>
<td>38</td>
<td>5 mil Void</td>
</tr>
<tr>
<td>BT</td>
<td>67</td>
<td>26</td>
<td>9 mil Contaminant</td>
</tr>
<tr>
<td>ISAT</td>
<td>88</td>
<td>34</td>
<td>Unknown</td>
</tr>
<tr>
<td>BT</td>
<td>35</td>
<td>13</td>
<td>11 mil Contaminant</td>
</tr>
<tr>
<td>CSAT</td>
<td>80</td>
<td>31</td>
<td>Unknown</td>
</tr>
<tr>
<td>Example 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BT</td>
<td>27</td>
<td>10</td>
<td>Small Particle</td>
</tr>
<tr>
<td>Example 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISAT</td>
<td>254</td>
<td>Full</td>
<td>Unknown</td>
</tr>
<tr>
<td>BT</td>
<td>30</td>
<td>12</td>
<td>Small Particle</td>
</tr>
</tbody>
</table>
Basic Assessments

Cables are extracted from the field

• Failed
• Siblings of Failures
• Concerning
Evolution of Tree Length – Measured Data

- Age data are generally available
- These are grouped to determine the distribution of lengths of trees in “Age Bins” – Mean Lengths
- These estimates use all available tree lengths
Diagnostic Process to Manage the Asset

Rules of Thumb
(Heuristics)

Classification Algorithms
(Machine Learning, Pattern Recognition)

Generate Data
Collate Data
Calculate Features
Health Index Algorithm

- Water Tree
- Develop Meta Data
- Longest
- Median
- Density
- Generation

Calculated Features

SAIFI of selected countries vs % underground

SAIFI vs % underground graph
Measured Tree Diagnostic - Heuristic

Heuristic Engineering Expertise

Trees > 50% of insulation correlate with Failure in Service

<table>
<thead>
<tr>
<th></th>
<th>Trees &lt;50%</th>
<th>Trees &gt;50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survived in Service</td>
<td>80</td>
<td>32</td>
</tr>
<tr>
<td>Failed in Service</td>
<td>76</td>
<td>24</td>
</tr>
</tbody>
</table>

Overall → 49%

Expert Driven Heuristics not effective
Use More Information?

- Longest Vented
- Median Vented
- Number of Vented

- Longest Bowtie
- Median Bowtie
- Number of Bowtie
Health Indices for Asset Management

• Health Indices summarise many inputs (Treeing, Age, History, Generation, etc)
• Most are simple “Rules of Thumb” developed based on expert opinion

\[ HI = \alpha \text{Length} + \beta \text{Density} + \gamma \text{Generation} + \ldots + \ldots \]

• In this work large datasets are available hence the most appropriate way forward is to use a “Machine Learning / Algorithmic” approach
• Determine the Weights (\( \alpha, \beta, \gamma, \ldots, \ldots \))
• For
  • Length – Bowtie & Vented, Longest & Median
  • Density - Bowtie & Vented
  • Meta Data – Generation, Age
## Evolving Cable Design Solutions

<table>
<thead>
<tr>
<th>Generation</th>
<th>Insulation</th>
<th>Semiconductors</th>
<th>Jacket</th>
<th>Barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Paper Tape</td>
<td>Carbon Tape</td>
<td>Jacket</td>
<td>Extruded Lead</td>
</tr>
<tr>
<td>1</td>
<td>Thermoplastic HMPWE</td>
<td>Graphite / Carbon Tape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>XLPE or EPR</td>
<td>Extruded Thermoplastic</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>XLPE or EPR</td>
<td>Graphite / Carbon Tape</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>XLPE or EPR</td>
<td>Extruded Thermoplastic</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Blocking</td>
</tr>
<tr>
<td>6</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Blocking</td>
</tr>
<tr>
<td>7</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Blocking</td>
</tr>
<tr>
<td>8</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Blocking</td>
</tr>
<tr>
<td>9</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Blocking</td>
</tr>
<tr>
<td>10</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Weightings for Water Tree Factors

- LVT
- MVT
- DVT
- LBT
- MBT
- DBT
- GEN
- AGE

BOWTIE

10th International Conference on Insulated Power Cables
Health Index – Algorithm & Machine Learning

<table>
<thead>
<tr>
<th>Predict</th>
<th>Survive</th>
<th>Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survived in Service</td>
<td>74</td>
<td>24</td>
</tr>
<tr>
<td>Failed in Service</td>
<td>35</td>
<td>65</td>
</tr>
</tbody>
</table>

Overall → 70%

Current Optimum
Generating Context

- Individual Health Index (HI)
- HI’s have meaning – large values = more / big trees = poorer performance
- Provide a context for future measurements
- Auto update with new data
- Provides a “relative prioritization”
Case Study

• 8 cable investigations for 1979 vintage cables
• None of these cables have experienced a failure in service
• Interested in relative health and what actions are suggested by experience
Case Study

• 8 cable investigations for 1979 vintage cables
  • 4 - 5 in “No Immediate Action Required”
  • 2 - 3 in “Watch”
  • 1 in “Action Required”

A 50% reduction opportunity in the O&M budget of today
Conclusions

• Collated data is the basis for analyses – datamining is worth the effort
  • Brings insights
  • Enables testing of “Heuristics / Tribal Knowledge”

• Data and Expertise derived Health Indices
  • Outperform simple Heuristics
  • Capture valuable knowledge

• Health Indices provide
  • Context
  • Transparent decision making

• There is a way to make use of the information that come from forensic cable analyses