Overview of the Cable Diagnostic Focused Initiative Project

NEETRAC
National Electric Energy Testing Research and Applications Center

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Outline

• NEETRAC Overview.
• Why do we need diagnostics?
• Basics of Power Cable Systems.
• Basics of Power Cable Diagnostics.
• Cable Diagnostic Focused Initiative (CDFI) Project.
• Evolution of VLF-Tan δ criteria (PE Based).
• Dissemination.
• Reflections.
• Q&A.

NEETRAC Overview

• 15 years ago NEETRAC was set up as a **self supporting center** within the School of Electrical and Computer Engineering of the Georgia Tech.

• NEETRAC is a membership based center, conducting research programs for the *Electric Energy Transmission and Distribution Industry*.

• Utility Members: Serve over 70,000,000 customers.

• Manufacturing Members: Primary suppliers of T&D equipment to electric utilities in the Canada, Mexico & United States.
Members 2011-2012

1. 3M
2. ABB
3. Ameren
4. American Electric Power
5. BC Hydro
6. Borealis Compounds LLC
7. Consolidated Edison Co. of New York
8. Cooper Power Systems
9. Dominion Virginia Power
10. Dow Chemical Company
11. Duke Energy Company
12. Entergy
13. Exelon / Commonwealth Edison & PECO
14. First Energy
15. Florida Power & Light
16. GRESCO
17. Hubbell Power Systems
18. Landis + Gyr
19. MacLean Power Systems
20. NRECA
21. NSTAR
22. PPL Electric Utilities
23. Pacific Gas & Electric
24. Pacificorp
25. Progress Energy
26. Prysmian
27. Public Service Electric & Gas
28. S&C Electric
29. Smart Wire Grid
30. South Carolina Electric and Gas
31. Southern California Edison
32. Southern Company
33. Southern States
34. Southwire
35. Thomas & Betts
36. TVA
37. TE Connectivity
38. Varentec
39. Viakable
40. Zenery
Why do we need diagnostics?

- Underground cable system infrastructure is complex and aging.
- Failures are increasing.
- If not addressed then old infrastructure will not support future operation of the grid.
- Not enough money / manufacturing capacity to simply replace because they are old.
- Need diagnostic tools to prioritize Active Asset Management.
- Always remember we talk about the cable SYSTEM, not just cable.

5.2 times
Power Cable Systems

The Power Cable System

Terminations
Splices

Installation Methods

Direct buried
Direct buried conduit

Voltage classification:

LV  < 6 kV
MV  6 - 36 kV
HV  36 - 161 kV
EHV > 161 kV

Courtesy of NEETRAC

Prior Technologies
Today's Technologies

Insulation MV
Laminated
Extruded

PILC
Thermoplastic
THW/PE

XLPE

TRXLPE

EPR
In the ideal case, power cable diagnostic techniques must be
Safe

Effective
Useful

Valuable
Diagnostic Testing of Cable Systems

- A field test made during the operating life of a cable system that is intended to determine and locate aging or degradation that may cause cable and accessory failure.
- Tests may be:
  - On-line or off-line.
  - Bulk property or a localized.
  - Low or medium probability of failure in test.
- Periodic testing to develop trends probably gives better assessment than a one-time measurement.

For Effective Diagnostic Testing:

- Need to **know** aging/degradation and failure mechanisms, and rate of aging of different cable systems.
- Need to **measure** properties or characteristics of cable systems, bulk and local, that give an indication of how much aging has occurred.
- Need to **interpret** data to estimate remaining life.

*The more details that are available, the more accurate the interpretation*
Cable Diagnostic Focused Initiative Project

At the Start (< 2005)

- For many utilities, the usefulness of diagnostic testing was unclear.
- The focus was on the technique, not the approach.
- The overall benefits were not well defined.
- There was almost no independently collated and analyzed data.
- There were no independent tools for evaluating diagnostic effectiveness.
Diagnostic Tests Available

Bulk Property Measurements:
- Tan $\delta$ at single frequency (e.g., 60 Hz, 0.1 Hz, etc).
- Tan $\delta$ over frequency range (dielectric spectroscopy).
- Recovery voltage.
- Polarization/depolarization currents.
- Neutral resistance.

Local Property Measurements:
- Visual inspection.
- Withstand.
- Partial discharge.
- Time domain reflectometry.

CDFI Phase I vs. CDFI Phase II

<table>
<thead>
<tr>
<th>Element</th>
<th>CDFI Focus, Phase I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Level</td>
<td>MV</td>
</tr>
<tr>
<td>Test Type</td>
<td>Condition Assessment</td>
</tr>
<tr>
<td>Cable</td>
<td>Service Aged</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Currently in use in US</td>
</tr>
<tr>
<td>Data</td>
<td>Utility Distribution System</td>
</tr>
<tr>
<td>Lab Studies</td>
<td>Field Aged Cable</td>
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</table>

Phase II Participants

Participants

<table>
<thead>
<tr>
<th>Utilities</th>
<th>Manufacturers</th>
<th>Diagnostic Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Electric Power</td>
<td>FirstEnergy</td>
<td>Borealis</td>
</tr>
<tr>
<td>Ameren</td>
<td>FPL</td>
<td>Cooper Power Systems</td>
</tr>
<tr>
<td>BC Hydro</td>
<td>Hydro Quebec</td>
<td>Dow</td>
</tr>
<tr>
<td>CenterPoint Energy</td>
<td>NRECA</td>
<td>Prysmian</td>
</tr>
<tr>
<td>Consolidated Edison</td>
<td>Pacific Gas &amp; Electric</td>
<td>Southwire</td>
</tr>
<tr>
<td>Dominion</td>
<td>PacifiCorp</td>
<td>TE Connectivity</td>
</tr>
<tr>
<td>Duke Energy</td>
<td>SCE&amp;G</td>
<td>HV Technologies</td>
</tr>
<tr>
<td>EPRI</td>
<td>Southern California</td>
<td>Techlmp SPA</td>
</tr>
<tr>
<td>Exelon</td>
<td>Southern Company</td>
<td></td>
</tr>
</tbody>
</table>
Working in the following areas

- Withstand Tests.
- AC Commissioning Tests.
- PD Tests (Online & Offline).
- Very Low Frequency (VLF).
- Damped AC.
- Time Domain Spectroscopy.
- Artificial Intelligence.

Rather than describe ALL THE WORK we have chosen to follow the evolution of VLF Tan δ tests as this provides a good “Roadmap” for the work.

Evolution of VLF-Tan δ Criteria (PE-Based)
Tan $\delta$

- Cable insulation is represented by an equivalent circuit.
- Circuit consists of a resistor and a capacitor.

Cable system (cable, splices, and terminations) is reduced to simple circuit.

$Tan \delta = DF = \frac{I_R}{I_C} = \frac{1}{\omega RC} = \frac{\sigma}{\omega \varepsilon'}$

VLF Tan $\delta$ Diagnostic Features

- Feature: Tan $\delta$ Level
- Feature: Voltage Dependence
- Feature: Time Dependence

VLF Tan δ Diagnostic Features (2)

Condition Assessment

Feature: Tan δ Level

Feature: Time Dependence

Feature: Voltage Dependence

VLF Tan δ Diagnostic Features (3)

- How to use the features?
- Have all the features the same relevance?
- How to handle different insulation types?
- How to establish criteria?
Tan δ Equipment


Diagnostic Spectrum

- Extreme conditions are easy to decide what to do about.
- What to do about the ones in the middle?
- How to define the boundaries?

Increasing Tan δ Diagnostic Feature
Evolution of VLF-Tan δ Criteria (PE-Based)

<table>
<thead>
<tr>
<th>Year</th>
<th>Assessment Hierarchy</th>
<th>Criteria</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2001</td>
<td>Tan δ</td>
<td>None</td>
<td>-</td>
</tr>
<tr>
<td>2001 - 2004</td>
<td>Tan δ (U₀ or 2U₀)</td>
<td>PE criteria only</td>
<td>IEEE Std. 400 - 2001 release</td>
</tr>
<tr>
<td></td>
<td>Tip Up</td>
<td></td>
<td>No technical basis described</td>
</tr>
<tr>
<td></td>
<td>(2U₀ &amp; U₀)</td>
<td></td>
<td>No based on data described</td>
</tr>
</tbody>
</table>

Approximately 50% of all tested cable segments have to be replaced.
Evolution of VLF-Tan δ Criteria (PE-Based)

<table>
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<th>Year</th>
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</thead>
<tbody>
<tr>
<td>2004</td>
<td></td>
<td>Start CDFI Phase I</td>
<td></td>
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<tr>
<td>2007</td>
<td>Tan δ Stability</td>
<td>Qualitative</td>
<td>Criteria based on physical understanding &amp; statistical analysis of</td>
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<tr>
<td></td>
<td>(Std Dev @ Uc)</td>
<td></td>
<td>collated data from North American</td>
</tr>
<tr>
<td></td>
<td>Tip Up</td>
<td></td>
<td>cable systems</td>
</tr>
<tr>
<td>2008-</td>
<td>PE criteria for</td>
<td></td>
<td>Disseminated in first Tan δ Brochure</td>
</tr>
<tr>
<td>2010</td>
<td>individual features</td>
<td></td>
<td>Included in update of IEEE Std. 400.2</td>
</tr>
<tr>
<td></td>
<td>based on data</td>
<td></td>
<td></td>
</tr>
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</table>

VLF Tan δ Diagnostic Features

Condition Assessment

Feature: Tan δ Level

Feature: Voltage Dependence

Feature: Time Dependence
Mean Tan δ Distributions by Insulation

Service Failures After Test
Sample Tan δ Criteria (PE-Based)

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>VLF-TD Stability (standard deviation) at $U_0$ [10-3]</th>
<th>Differential TD TD 1.5 $U_0$ – TD 0.5 $U_0$ [10-3]</th>
<th>Mean VLF-TD at $U_0$ [10-3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Action Required</td>
<td>&lt;0.05 &amp; &lt;5 &amp; &lt;4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Further Study</td>
<td>0.05 to 5 Or 80 Or 4 to 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Action Required</td>
<td>&gt;0.5 &gt;80 &gt;50</td>
<td></td>
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Decreasing importance of feature

Evolution of VLF-Tan δ Criteria (PE-Based)

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<tbody>
<tr>
<td>2010</td>
<td></td>
<td>Start CDFI Phase II</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Tan δ Stability (Std Dev @ $U_0$) Tip Up (1.5$U_0$ &amp; 0.5$U_0$) Mean Tan δ (@$U_0$) Tip Up of Tip Up (TUTU)</td>
<td>PE criteria for individual features based on data Principal Component Analysis (PCA) of combined diagnostic features</td>
<td>Criteria based on physical understanding &amp; statistical analysis of collated data from North American cable systems Disseminated in Tan δ Excel Tools from mid 2011 onwards Disseminated in Tan δ Brochure from 2012 onwards Included in future updates of IEEE Std. 400.2</td>
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### Example 1 from SNOPUD

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>VLF-TD Stability (standard deviation) at $U_0$ [10-3]</th>
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<tr>
<td>No Action Required</td>
<td>$&lt;0.05$ &amp;</td>
<td>$&lt;5$</td>
<td>$&lt;4$</td>
</tr>
<tr>
<td>Further Study</td>
<td>0.05 to 0.5</td>
<td>5 to 80</td>
<td>4 to 50</td>
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<tr>
<td>Action Required</td>
<td>$&gt;0.5$</td>
<td>$&gt;80$</td>
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Stability 0
Tip Up 614
Tan Delta 2.3

What is the classification?

### Example 2 from SNOPUD

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>VLF-TD Stability (standard deviation) at $U_0$ [10-3]</th>
<th>Differential TD $1.5 U_0 - TD 0.5 U_0$ [10-3]</th>
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Stability 3.8
Tip Up 259
Tan Delta 17

What is the classification?
Example 3 from SNOPUD

Stability 0.1  
Tip Up 1.9  
Tan Delta 2.2

What is the classification?

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>VLF-TD Stability (standard deviation) at U₀ [10⁻³]</th>
<th>Differential TD TD 1.5 U₀ – TD 0.5 U₀ [10⁻³]</th>
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<td>&amp;</td>
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Multivariate / Artificial Intelligence Methods

- Interpretation is challenging with three features:
  - TD Stability.
  - Differential TD.
  - Mean TD.

- More convenient if features could be numerically combined to give a single “Health Index”

- Principal Component Analysis provides a convenient route.
Example 1 from SNOPUD

Stability 0
Tip Up 614
Tan Delta 2.3

What is the classification?

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### Dissemination
Technical Papers

- ICC Meetings.
- IEEE Conferences.
- Jicable 2011.
  - CDFI related papers presented:
    - Knowledge Based System (KBS).
    - Establishing Tan δ Criteria.
    - Monitored Withstand.
    - Diagnostic Testing of Submarine Cables (with IREQ).
- IEEE Transactions.
- IEEE Insulation Magazine.

http://www.neetrac.gatech.edu/publications.html
Reflections

• Approach to data analysis established in CDFI.

• Collaboration is absolutely essential.

• Many questions answered, there still remain gaps in how to best:
  – Define the Benefits.
  – Identify anomalies that lead to failure.

• Answers will come with continued analysis of field test data as well as controlled laboratory tests.

• The potential value of continued analysis is high.