Cable Diagnostic Focused Initiative Regional Meeting

NEETRAC

Hosted by
American Electric Power
Columbus, OH
October 13-14, 2009
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• This material is based upon work supported by the Department of Energy under Award No DE-FC02-04CH1237
Dr. Nigel Hampton is the Program Manager for Reliability work at NEETRAC. He has worked in the Power Cable arena for more than 20 years.

Vice-chair of the ICC subcommittee on diagnostic testing (Sub F)

Convenor of CIGRE WGB1.28 on On-site Partial Discharge Assessment of HV and EHV cable systems.
Presenters

Mr. Rick Hartlein is the Director of NEETRAC and Principal Investigator for this project. He has over 30 years of experience performing research projects on Power Cable Systems. He actively participates in the development of industry standards and specifications for underground cable systems and has served as Chair of ICC.
Presenters

Dr. Joshua Perkel is a Research Engineer in the Assessment group at NEETRAC. He has worked in the Power Cable arena for more than 5 years. Josh holds a PhD in electrical engineering from the Georgia Institute of Technology.
CDFI Contributors

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Ron Harley
J.C. Hernandez
Salman Mohagheghi

IREQ
Jean-Francois Drapeau
## Day 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
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</thead>
<tbody>
<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00 – 13:10</td>
<td>Welcome</td>
</tr>
<tr>
<td>13:10 – 13:30</td>
<td>NEETRAC Overview</td>
</tr>
<tr>
<td>13:30 – 14:00</td>
<td>CDFI Background/Overview</td>
</tr>
<tr>
<td>14:00 – 14:30</td>
<td>Cable System Failure Process</td>
</tr>
<tr>
<td>14:30 – 14:45</td>
<td>SAGE Concept</td>
</tr>
<tr>
<td>14:45 – 15:00</td>
<td>Break</td>
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<tr>
<td>15:00 – 16:00</td>
<td>Diagnostic Testing Technologies</td>
</tr>
<tr>
<td>16:00 – 16:30</td>
<td>Case Study: Roswell</td>
</tr>
<tr>
<td>16:30 – 17:00</td>
<td>Level-Based Reporting</td>
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<tr>
<td>18:00</td>
<td>Dinner</td>
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## Day 2

<table>
<thead>
<tr>
<th>Time</th>
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<tbody>
<tr>
<td>07:30 – 08:00</td>
<td>Continental Breakfast</td>
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<tr>
<td>08:00 – 08:15</td>
<td>Review Day 1</td>
</tr>
<tr>
<td>08:15 – 09:30</td>
<td>Diagnostic Accuracies</td>
</tr>
<tr>
<td>09:30 – 10:00</td>
<td>Accuracies Really Matter</td>
</tr>
<tr>
<td>10:00 – 10:15</td>
<td>Break</td>
</tr>
<tr>
<td>10:15 – 11:20</td>
<td>The Things That Are Much Clearer Now - Research</td>
</tr>
<tr>
<td>11:25 – 11:45</td>
<td>Selecting a Diagnostic Testing Technology</td>
</tr>
<tr>
<td>11:45 – 12:00</td>
<td>Summary</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
</tr>
</tbody>
</table>
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Analytical Techniques & Failure Rates
• Diagnostic Testing Technologies
• Case Study: Roswell
• Level Based Reporting Systems
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
NEETRAC Overview
Background

• Created in 1996 when Georgia Power donated the facilities of its Research Center to Georgia Tech.

• 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*. 
NEETRAC Mission & Vision

**Mission**
To provide a venue where NEETRAC Staff, NEETRAC Members and the Georgia Tech Academic community can collaborate to solve problems in the T&D Arena.

**Vision**
We will build on our expertise to become the leading national Center for collaborative applied and strategic research and development for electric transmission and distribution.
<table>
<thead>
<tr>
<th>Members 2009-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 3M</td>
</tr>
<tr>
<td>2. ABB</td>
</tr>
<tr>
<td>3. Ameren Services</td>
</tr>
<tr>
<td>4. American Electric Power</td>
</tr>
<tr>
<td>5. Baltimore Gas &amp; Electric</td>
</tr>
<tr>
<td>6. British Columbia Hydro</td>
</tr>
<tr>
<td>7. Borealis Compounds LLC</td>
</tr>
<tr>
<td>8. Con Edison</td>
</tr>
<tr>
<td>9. Cooper Power Systems</td>
</tr>
<tr>
<td>10. Dominion/Virginia Power</td>
</tr>
<tr>
<td>11. Dow Chemical Company</td>
</tr>
<tr>
<td>12. Duke Energy</td>
</tr>
<tr>
<td>13. Entergy</td>
</tr>
<tr>
<td>14. Exelon</td>
</tr>
<tr>
<td>15. First Energy</td>
</tr>
<tr>
<td>16. Florida Power &amp; Light</td>
</tr>
<tr>
<td>17. GRESCO Utility Supply</td>
</tr>
<tr>
<td>18. Hubbell</td>
</tr>
<tr>
<td>19. NRECA</td>
</tr>
<tr>
<td>20. NSTAR</td>
</tr>
<tr>
<td>21. PacifiCorp</td>
</tr>
<tr>
<td>22. Prysmian Cables &amp; Systems</td>
</tr>
<tr>
<td>23. Public Service Electric &amp; Gas</td>
</tr>
<tr>
<td>24. S&amp;C Electric Company</td>
</tr>
<tr>
<td>25. South Carolina Electric &amp; Gas</td>
</tr>
<tr>
<td>26. Southern California Edison</td>
</tr>
<tr>
<td>27. Southern Company</td>
</tr>
<tr>
<td>28. Southern States</td>
</tr>
<tr>
<td>29. Southwire</td>
</tr>
<tr>
<td>30. Thomas and Betts/Homac</td>
</tr>
<tr>
<td>31. TVA</td>
</tr>
<tr>
<td>32. tyco / Raychem</td>
</tr>
<tr>
<td>33. Zenergy Power</td>
</tr>
</tbody>
</table>

CDFI Regional Meeting – Oct 13-14, 2009 Columbus OH
NEETRAC Membership Growth

Year

Members

- 1996
- 1998
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010

2009

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NEETRAC Overview
Members

- Utility Members
  - Serve over 70,000,000 customers

- Manufacturing Members
  - Primary suppliers of T&D equipment to electric utilities in the United States
## Focus Areas Developed

<table>
<thead>
<tr>
<th>PRIMARY FOCUS AREA</th>
<th>FOCUS SEGMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware/Equipment Testing</td>
<td>Application Research</td>
</tr>
<tr>
<td></td>
<td>Product Evaluation</td>
</tr>
<tr>
<td></td>
<td>Engineering Analysis &amp; Support</td>
</tr>
<tr>
<td></td>
<td>Equipment Spec. &amp; Test Protocol Development</td>
</tr>
<tr>
<td>New Technology/Research</td>
<td>New Product Development</td>
</tr>
<tr>
<td></td>
<td>Research</td>
</tr>
<tr>
<td></td>
<td>System Enhancements</td>
</tr>
<tr>
<td>Reliability</td>
<td>Asset Management</td>
</tr>
<tr>
<td></td>
<td>Condition Assessment</td>
</tr>
<tr>
<td></td>
<td>Forensics</td>
</tr>
<tr>
<td>System Analysis</td>
<td>Operation, Installation, Design</td>
</tr>
<tr>
<td></td>
<td>Power Quality/Grounding</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
</tr>
<tr>
<td></td>
<td>Training/Education</td>
</tr>
</tbody>
</table>

**FOCUS SEGMENT**

- PRIMARY FOCUS AREA
  - NEETRAC Overview

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CDFI Regional Meeting – Oct 13-14, 2009 Columbus OH
Facilities: High Voltage Lab
Facilities: Low Voltage & Mechanical Lab
CDFI Regional Meeting – October 13-14, 2009 Columbus OH

NEETRAC Overview

Investment

$\Delta V$

$P_{\text{loss}}$
<table>
<thead>
<tr>
<th>Year</th>
<th>Observed Failures</th>
<th>Failure Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>35</td>
</tr>
</tbody>
</table>

![Graph showing observed failures and failure estimate over years](image-url)
Staff

• 25 Research Staff
  – Ph.D degrees (EE & Physics)
  – M.S. degrees (EE, IE, & ME)
  – Bachelors degrees (EE & ME)

• 5 Administrative and IT Support

• 1 Coop Student
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Analytical Techniques & Failure Rates
• Diagnostic Testing Technologies
• Case Study: Roswell
• Level Based Reporting Systems
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
CDFI Background
Why do we need diagnostics?

• Underground cable system infrastructure is aging (and failing). Much of the system is older than its design life.

• Not enough money / manufacturing capacity to simply replace cable systems because they are old.

• Need diagnostic tools that can help us decide which cables/accessories to replace & which can be left in service.

• Always remember that we are talking about the cable SYSTEM, not just cable.
### Where has CDFI focused?

<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>
</tr>
</tbody>
</table>
## Where has CDFI focused?

<table>
<thead>
<tr>
<th>Element</th>
<th>CDFI Focus, Phase I</th>
<th>Not Included in CDFI, Phase I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Level</td>
<td>MV</td>
<td>HV</td>
</tr>
<tr>
<td>Test Type</td>
<td>Condition Assessment</td>
<td>Commissioning</td>
</tr>
<tr>
<td>Cable</td>
<td>Service Aged</td>
<td>Laboratory Aged</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Currently in use in US</td>
<td>Not used in US</td>
</tr>
<tr>
<td>Data</td>
<td>Utility Distribution System</td>
<td>Industrial &amp; Transmission</td>
</tr>
<tr>
<td>Lab Studies</td>
<td>Field Aged Cable</td>
<td>Accessories</td>
</tr>
</tbody>
</table>
Overview

• In the CDFI, NEETRAC worked with 17 utilities, 5 manufacturers and 5 diagnostic providers to achieve the objective of clarifying the concerns and defining the benefits of diagnostic testing.

• Phase 1 has almost exclusively focused on aged medium voltage systems.

• This is the largest coherent study of cable system diagnostics anywhere.
CDFI Background/Overview

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Participants

<table>
<thead>
<tr>
<th>American Electric Power</th>
<th>HV Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ameren</td>
<td>Hydro Quebec</td>
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<tr>
<td>Cablewise / Utilx</td>
<td>IMCOPR</td>
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<td>CenterPoint Energy</td>
<td>NRECA</td>
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<tr>
<td>Con Edison</td>
<td>PacifiCorp (added mid 2005)</td>
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<td>Cooper Power Systems</td>
<td>Pacific Gas &amp; Electric (added Jan 06)</td>
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<td>Duke Power Company</td>
<td>PEPCO</td>
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<tr>
<td>Exelon (Commonwealth Edison &amp; PECO)</td>
<td>Oncor (TXU)</td>
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<tr>
<td>First Energy</td>
<td>Prysmian</td>
</tr>
<tr>
<td>Florida Power &amp; Light</td>
<td>Public Service Electric &amp; Gas</td>
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<td>Georgia Tech</td>
<td>Tyco / Raychem</td>
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<td>Southern California Edison</td>
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<td>HDW Electronics</td>
<td>Southern Company</td>
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<tr>
<td>High Voltage, Inc</td>
<td>Southwire</td>
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<tr>
<td>HV Diagnostics</td>
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</table>
CDFI - Primary Activities

1) Technology Review
2) Analysis of Existing (Historical) Data
3) Collection and Analysis of Field (New) Data
4) Verification of VLF Test Levels
5) Defect Characterization
6) Develop Knowledge Based System
7) Quantify Economic Benefits
8) Reports, Update Meetings and Tech Transfer Seminars

Analyses are data / results driven
CDFI Activities

Lab Studies
(Service Aged Cables)

VLF Withstand
- Test Time
- Test Voltage
- Forensics

Tan δ
- Time Stability
- Voltage Stability
- Non-Uniform Degradation
- Neutral Corrosion

PD
- Calibration
- Phase Pattern
- Feature Extraction
- Classification
CDFI Activities

Field Studies

Georgia Power
XLPE
Jkt & UnJkt
21 Conductor Miles

Offline PD (0.1Hz)
Offline PD (60Hz)
Tan δ
Monitored Withstand

Evans
Macon
Roswell

Duke
XLPE & Paper
Jkt & UnJkt
29 Conductor Miles

Offline PD (0.1Hz)
Tan δ
Monitored Withstand

Charlotte * 2
Cincinnati
Clemson
Morresville
CDFI Activities

Analysis
89,000 Conductor Miles

Value / Benefit
Accuracies
Utility Data
IEEE Std Work
Knowledge Based Systems

Economic Model SAGE
DC Withstand
Offline PD
Online PD
Tan δ
VLF Withstand

400 Omnibus
400.2 VLF

Survey Expert System Application
CDFI Activities

Utility Data

Con Ed
- DC Withstand
- Online PD
- VLF Withstand

Com Ed
- Offline PD (60Hz)
- Online PD
- Tan Delta
- VLF Withstand

PPL
- Offline PD (0.1Hz)
- Tan Delta

Alabama Power
- Online PD

Keyspan
- Offline PD (0.1Hz)
- Tan Delta
CDFI Activities

Utility Data

- FPL
  - Offline PD (60Hz)
  - VLF Withstand
- PEPCO
  - Offline PD (60Hz)
  - Offline PD (0.1Hz)
  - Online PD
  - VLF Withstand
- PG&E
  - Offline PD (60Hz)
  - Online PD
  - Tan δ
- ONCOR
  - Offline PD (60Hz)
  - Online PD
- Ameren
  - Offline PD (60Hz)
# Dataset Sizes

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Technique</th>
<th>Laboratory [Conductor miles]</th>
<th>Field [Conductor miles]</th>
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<tr>
<td>Diagnostic</td>
<td>DC Withstand</td>
<td>-</td>
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<td>Monitored Withstand</td>
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<td>PD Offline</td>
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<td>PD Online</td>
<td>-</td>
<td>262</td>
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<tr>
<td></td>
<td>Tan δ</td>
<td>1.5</td>
<td>550</td>
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<tr>
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<td>VLF Withstand</td>
<td>1.5</td>
<td>9,810</td>
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<tr>
<td></td>
<td>IRC</td>
<td>0.3</td>
<td>-</td>
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<tr>
<td>Service Performance</td>
<td>ALL</td>
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<td>89,000</td>
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</table>
Data Perspective

• Results presented must be viewed in light:
  – CDFI focus
  – Available data

The data you will see here are

  – Real
  – Generated by or provided to utilities
  – Not as complete as we would like
Benefits from Diagnostic Programs
Decreasing failures associated with diagnostics and actions

CDFI Background/Overview
At the Start

- For many utilities, the usefulness of diagnostic testing was unclear.
- The focus was on the technique, not the approach.
- The economic benefits were not well defined.
- There was almost no independently collated and analyzed data.
- There were no independent tools for evaluating diagnostic effectiveness.
Where we are today (1)

1. Diagnostics work – they tell you many useful things, but not everything.
2. Diagnostics do not work in all situations.
3. Diagnostics have great difficulty definitively determining the longevity of individual devices.
4. Utilities HAVE to act on ALL replacement & repair recommendations to get improved reliability.
5. The performance of a diagnostic program depends on
   • Where you use the diagnostic
   • When you use the diagnostic
   • What diagnostic you use
   • What you do afterwards
Where we are today (2)

6. Quantitative analysis is complex BUT is needed to clearly see benefits.

7. Diagnostic data require skilled interpretation to establish how to act.

8. No one diagnostic is likely to provide the detailed data required for accurate diagnoses.

9. Large quantities of field data are needed to establish the accuracy/limitations of different diagnostic technologies.

10. Important to have correct expectations – diagnostics are useful but not perfect!
Overview

• In the CDFI, NEETRAC worked with 17 utilities, 5 manufacturers and 5 diagnostic providers to achieve the objective of **clarifying the concerns and defining the benefits of diagnostic testing.**

• We have come a long way wrt the project objective.
  – Analysis driven by data / results
  – Developed a good understanding that diagnostic testing can be useful, but the technologies are not perfect.
  – Developed ways to define diagnostic technology accuracy and found ways to handle inaccuracies.
  – Developed diagnostic *technology selection* and *economic analysis* tools.
  – Understand that there is yet more to learn.
QUESTIONS
Outline

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- Selecting a Diagnostic Testing Technology
- Summary
How things fail and what fails have a big impact on the selection of diagnostics

Cable System Failure Process
Cable System Defects

• Several causes exist for defects to occur in cable systems.
  – Manufacturing, installation, aging, etc.

• The characteristics of a defect affect the influence it has on the system’s performance.

• Defects represent non-uniform regions in the insulation material – these lead to stress enhancement.
Extruded Cable Defects

- Oxidized Insulation
- Hot Conductor
- Water trees
- Crack
- Void
- Contaminant
- Electrical tree
- Corroded Neutral
Defect Types in Extruded Cable Accessories

Cable System Failure Process
Treeing Degrade Insulation Materials

• Treeing weakens the cable system – does not necessarily mean that failure is imminent
• Two basic types – they are fundamentally different beasts
  – Water Tree
    • Bowtie
    • Vented
  – Electrical

Electrical
Vented
Bow tie
Concern

Treeing is a complicated phenomenon.
Conversion of Water to Electrical Trees

- Acts as a stress enhancement or protrusion (non-conducting)
- Water tree increases local electric field stress
- Water tree also creates local mechanical stresses
- If electrical and mechanical stresses high enough ⇒ electrical tree initiates
- Electrical tree completes the failure path – rapid growth compared to water trees

Electrical tree growing from water tree
Diagnostics used in Challenging Areas

Cable System Failure Process
Diagnostics in the Field

Cable System Failure Process
Summary

• Cable system aging is a complex phenomenon.

• Multiple factors cause systems to age.

• Increases in dielectric loss and partial discharge are key phenomenon.

• The aging process is nonlinear.

• Diagnostics must take these factors into consideration.
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SAGE Approach to Diagnostic Programs
Diagnostic Program

Failures [#]

Selection
Action
Generation
Evaluation

Increasing Failures
Decreasing Failures

SAGE Concept
Diagnostic Program Phases - SAGE

**Selection**
Data compilation and analysis needed to identify circuits that are at-risk for failure (at-risk population).

**Action**
Determine what actions can be taken on circuits based on the results of diagnostic testing.

**Generation**
Conduct diagnostic testing of the at-risk population.

**Evaluation**
Monitor at-risk population after testing to observe/improve performance of diagnostic program.
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Analytical Techniques
&
Failure Rates
Statistical Approach to Data Analysis

- Engineers are generally not fond of statistics
- We sometimes make decisions from test data using approaches that are overly simplified
- NEETRAC uses analytically rigorous techniques to enhance our approach to data analysis
- A quick tutorial……..
Cable Moisture Content (Raw Data)

[Bar chart showing moisture content percentages for different cables labeled D to S.]
Histograms – They show the distribution

Mean 2.057
StDev 1.866
N  14

Moisture (%)

Frequency

0 1 2 3 4 5 6
-1 0 1 2 3 4 5 6

Normal

Analytical Techniques
Boxplot – No Assumptions About Distribution

Median
50% of data lie above and below

Mean
Boxplot – No Assumptions About Distribution

- **Upper Quartile**: 75% of data lie below.
- **Lower Quartile**: 25% of data lie below.
- **Whisker**: Extends from the box to the Max or Min.
Boxplot – No Assumptions About Distribution

Outlier
A datum that cannot be considered to be part of the majority of the data

Moisture (%)
Weibull Distribution – Useful for Failure Data

Weibull - 95% CI

Probability, expressed as a %, of a sample having a lower value

Value being measured

---

Shape 1.228
Scale 2.214
N 14

Moisture (%) vs. Percent

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Weibull Distribution

63.3% of samples are likely to have a moisture content below 2.2%
Even though we only have data for 14 samples we can make predictions outside of the range 2% of samples are likely to have moisture contents below 0.09%.
Statistical Approach to Data Analysis

• Introduces rigor to the data analysis process
• Allows you to see true differences between data sets
• Allows you to combine data sets to gain further insight
• Reduces ambiguities
• Allows for extrapolation
• Recognizes that there are different types of data
• Allows for increased accuracy of the analysis when the data is sparse and imperfect
Composition of US MV system

![Bar chart showing the composition of US MV system](chart.png)
Failure Rates

Failure Rate [#/100 Miles/Year]

- Peak at 140
- Max: 140
- Mean: 12
- Upper Quartile: 8
- Median: 3.5
- Lower Quartile: 1.6

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Failure Split

- Splices: 37.1%
- Cable: 56.2%
- Terminations: 5.6%
- Unknown: 1.1%
Failures by Equipment

- Disbursement of Failures (%)
  - Cable - all (%)
  - Splice - all (%)
  - Terminations - all (%)
  - Unknown - all (%)

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Each Utility is Different

![Bar chart showing the percentage of Cable, Unknown Source, and Accessories for different utilities.]

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System Failure Rate Estimates – By Equipment

Failure Rate - Monte Carlo Estimate (#/100miles/yr)
Spotting Reliability Improvement

Need control population to ensure the source of benefit is the diagnostics programme

Diagnostic Programme

Accuracies Really Matter
Spotting Reliability Improvement

Need control population to ensure the source of benefit is the diagnostics programme

Control
Diagnostic Programme

Log Cumulative Failures

Log Time [Days since Start]
QUESTIONS
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Analytical Techniques & Failure Rates
• Diagnostic Testing Technologies
• Case Study: Roswell
• Level Based Reporting Systems
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
Diagnostic Testing Technologies
Introduction

• A wide range of diagnostic techniques are commercially available.

• Tests are performed either offline (circuit de-energized)) or online (energized) and by service providers or utility crews.

• Different voltage sources may be used to perform the same measurement.
  – DC
  – 60 Hz. AC
  – Very Low Frequency (VLF) AC
  – Damped AC (DAC)
Utility Use of Diagnostics
Diagnostic Survey

• A survey of CDFI participants in 2006 was conducted to determine how diagnostics were employed.

• Survey was updated at the end of 2008.

• Survey results focused CDFI work on technologies currently used in the USA.
Survey of Use of Diagnostics

- 27.8%: No Testing
- 41.7%: Testing - one technique
- 30.6%: Testing - > one technique
Survey of Use of Diagnostics

More than one technique used
No testing
One technique used

No Testing
96.0%

4.0%
Testing

25.0%

Diagnostic Testing Technologies

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When to deploy diagnostics

Cable System Performance

Operational Stress

Time (Years)

Commissioning

Condition Assessment

Diagnostic Testing Technologies
Technologies

- Simple Dielectric Withstand
- Dielectric Loss (Tan δ & Dielectric Spectroscopy)
- Time Domain Reflectometry (TDR)
- Online Partial Discharge (PD)
- Offline Partial Discharge (PD)
- Isothermal Relaxation Current (IRC)
- Recovery Voltage (RV)
- Combined Diagnostics
Clarifying Cable Diagnostics

• Diagnosis is defined as the art or act of identifying a disease from its signs and symptoms\(^1\).

• A diagnosis would tell you what is wrong with your cable system (broken neutral, insulation voids, overheating connector etc.).

• Cable diagnostics today tell you whether your cable system is “sick” or not.

• Utilities typically ask diagnostics to tell them which parts of the cable system are “sick.”

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?
Context – is important

Data Generation from Diagnostic Measurement

Local Context
Comparisons within one area

Global Context
Comparison with many tests
Databases
Standards
Simple Dielectric Withstand
Simple Dielectric Withstand

Test Description
• Application of voltage above normal operating voltage for a prescribed duration.
• Attempts to drive weakest location(s) within cable segment to failure while segment is not in service.

Field Application
• Offline test that may use:
  – DC
  – 60 Hz. AC
  – VLF AC
  – Damped AC
• Testing may be performed by a service provider or utility crew.
Voltages and Times for VLF covered in IEEE Std. 400.2

The goal is to have circuit out of service, test it such that “imminent” service failures are made to occur on the test and not in service

Simple Dielectric Withstand
Examples of Withstand Units
VLF Waveforms

Sinusoidal

Cosine-Rectangular
Test Sequences

Simple VLF Withstand to IEEE400.2 Levels

Test time 30 mins

Cumulative Length Tested in One Year (Miles)

Withstand Test Outcomes

Simple Dielectric Withstand
Dielectric Loss (Tan δ)
Dielectric Loss (Tan δ)

**Test Description**
- Measures total cable system loss (cable, elbows, splices & terminations).
- May be performed at one or more frequencies (dielectric spectroscopy).
- May be performed at multiple voltage levels.
- Monitoring may be conducted for long durations.

**Field Application**
- Offline test that may use:
  - 60 Hz. AC
  - VLF AC
  - Damped AC
- Testing may be performed by a service provider or utility crew.
- Step voltage up to pre determined level with post test analysis
Dielectric Loss Test Process

Voltage

Time

Loss measurement

Tan δ
Tan δ Equipment
Cable System Equivalent

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

Tan δ
Tan δ Ramp Test Data

![Graph showing Tan δ ramp test data with time and voltage plotted against delta value. The graph includes markers for voltage at 0.5, 1.0, 1.5, and 1.7 p.u. with corresponding mean and tip up points. The graph highlights 30 cycles of data.](chart.png)
Time Domain Reflectometry
Time Domain Reflectometry (TDR)

Test Description
• Measures changes in the cable impedance as a function of circuit length by observing the pattern of wave reflections.
• Used to identify locations of accessories, faults, etc.

Field Application
• Offline test that uses a low voltage, high frequency pulse generator.
• Testing may be performed by a service provider or utility crew.
TDR Principles

Near End  TDR Equipment  L  Joint  Far End

Near End  Far End  L
TDR Equipment

Lengths Tested

Panel variable: Technique

Based on diagnostic data supplied to CDFI

Measurements made with TDR

Median 814 ft

Median 485 ft

Median 3500 ft
Online Partial Discharge
Online Partial Discharge

Test Description
• Measurement and interpretation of discharge and signals on cable segments and/or accessories.
• Signals captured over minutes / hours.
• Monitoring may be conducted for long durations.

Field Application
• Online test that does not require external voltage supply (no customer outage required)
• Testing performed by a service provider.
• Assessment criteria are unique to each embodiment of the technology
• Measurements require sensor placement at multiple locations along cable circuit
Online PD Test Process

Voltage

Continuous measurement

$U_0$

Time

Online PD
Online PD Equipment

Distribution of PD along Lengths

- 5000 ft. portion of sample feeder
- Mixture of different PD levels for different sections and accessories.
Offline Partial Discharge
Offline Partial Discharge

Test Description

- Measurement and interpretation of partial discharge signals above normal operating voltages.
- Signal reflections (combined with TDR information) allows location to be identified within cable segment.

Field Application

- Offline test that may use:
  - 60 Hz. AC service provider
  - VLF AC utility crew
  - Damped AC utility crew
- Step voltage up to pre determined level with post test analysis
Offline PD Test Process

Voltage

Time

Discharge measurement

Offline PD
Offline PD Equipment
PD Pulse

- Amplitude [V]
  - 1.5E-1
  - 1.0E-1
  - 5.0E-2
  - 0.0E+0
  - -6.8E-2

- Time [ns]
  - 0
  - 250
  - 500
  - 750
  - 1120

- 140 mV
- 180 pC

Offline PD
PD Pulse
PD Phase Resolved Pattern

- Amplitude [V]
  - 2.50E-1
  - 1.25E-1
  - 0
  - -1.25E-1
  - -2.50E-1

- Phase [Deg]
  - 0
  - 180
  - 360
  - -2.50E-1
  - -1.25E-1
  - -0

- Amplitude [pC]
  - 323
  - 162
  - 0
  - -162
  - -323

Offline PD
PD Phase Resolved Pattern

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Offline PD (60 & 0.1Hz) Outcome Sequences

No PD

PD

Offline PD
Isothermal Relaxation Current
Recovery Voltage
Isothermal Relaxation Current

Test Description
• Measures the time constant of trapped charges within the insulation material as they are discharged.
• Discharge current is observed for 15-30 minutes.

Field Application
• Offline test that uses DC to charge the cable segment up to 1kV.
• Testing is performed by a service provider.
Recovery Voltage

Test Description

• Similar to IRC only voltage is monitored instead of current

Field Application

• Offline test that requires initial charging by DC source up to 2kV.
• Testing is performed by a service provider.
What does this mean for IRC & RV?

- Use limited to evaluation studies in the laboratory
- Possibly too sensitive for field use
Combined Diagnostics

Multiple degradation mechanisms mean that two diagnostics are often better than one
What Diagnostics are Combined

- DC Leakage
- Tan δ
- DC Withstand
- PD
- VLF Withstand

Global

Local

Combined Diagnostics
Drawbacks of a Single Approach

- Each diagnostic looks for symptoms of one failure mechanism
  - Voids and water trees cannot generally be detected by a single technique

- Overlooks short term time evolution of diagnostic measurements

- Technique specific:
  - Withstand – No idea by how much segment passed
  - $\tan \delta$ – Cannot detect voids or electrical trees
  - PD – Cannot detect water trees (water filled voids)
Advantage of Multiple Diagnostics

Diagnostic 2

Good

BAD

GOOD

Diagnostic 1

Combined Diagnostics
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Case Study
Roswell, GA
November 2008 & January 2009

TDR
Tan Delta
Monitored Withstand
Offline PD
Roswell Map
Case Study: Roswell
Roswell Background Info.

- 1980 vintage XLPE feeder cable, 1000 kcmil, 260 mils wall, jacketed.
- Failures have occurred over the years – no data on source
- Recently experienced very high failure rates of splices on this section: 80 failures / 100 miles / yr.
- Overall there have been 10 -15 failures of these splices in last two years on a variety of GPC feeders.
- Splice replacement may be acceptable if there is a technical basis.
# Summary for Diagnostic Selection

<table>
<thead>
<tr>
<th>Action Scenario</th>
<th>DC Withstand</th>
<th>VLF 15 Mins</th>
<th>VLF 30 Mins</th>
<th>VLF 60 Mins</th>
<th>HV DC Leakage</th>
<th>Monitored Withstand</th>
<th>Tan Delta Monitored</th>
<th>PD Online</th>
<th>PD Offline</th>
<th>TDR &amp; Historical Records ONLY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace Small Portion</td>
<td>Red</td>
<td>Green</td>
<td>Yellow</td>
<td>Red</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>Replace Segment</td>
<td>Red</td>
<td>Green</td>
<td>Yellow</td>
<td>Red</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>Replace Accessories</td>
<td>Red</td>
<td>Green</td>
<td>Yellow</td>
<td>Red</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Green</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

Have a shortlist of three techniques

Case Study: Roswell

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Economic Details – prior to testing

- Complete System Replacement $1,000,000 approx
- Complete Splice Replacement $60,000
- Test time (determined by switching) 3 - 4 Days
- Selection Costs $5,000
- Splice Replacement 7 Days
- Retest after remediation 1 Day

Monitored Withstand, Offline PD and VLF (30 mins) offer economic benefit over doing nothing.

Case Study: Roswell
Estimating Risks/Outcomes

• All diagnostics pose some level of risk

• A qualitative estimate of risk is useful at the planning stage.

• Past experience can be used as a statistical guide for predicting basic outcomes of testing (risk of failure on test and in service after test)

• Predictions are not intended to be “right” but set expectations and give a baseline to recognize “unusual” diagnostics results.

• CDFI has large quantities of field data which enable these predictions.

Case Study: Roswell
Scenario Assessment before Testing

**Offline PD – Typical Observations**
- 0.5% fails on test, no customer interrupted
- 1 PD site / 1,000ft
- 40% of discharges in cable

**Qualitative Prediction (12 months)**
- 0-1 fails on test
- 51 discharge sites
- 15 splices
- 1-2 failure within 12 months after test
- Historical Outcomes: 1-3 Failures

**Monitored Withstand – Typical Observations**
- < 4% (1000ft sections) fails on test, no customer interrupted
- 70% of loss tests indicate no further action

**Qualitative Prediction (12 months)**
- 1-2 fails on test
- 3 assessed for further consideration
- 0-1 failure within 12 months after test
- Historical Outcomes: 1-3 Failures
ACTION

Case Study: Roswell
Initial Corrective Action Options

• Replace splices only – no detailed records assume 12 splices.

• Complete system replacement.
Case Study: Roswell
Overhead and Cabinet Terminations

Case Study: Roswell
Tan δ Monitored Withstand

Case Study: Roswell
Monitored Withstand - Stability

Case Study: Roswell

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If this had been a Simple Withstand

No Failures On Test

18 Segments Tested

Case Study: Roswell
Hierarchy of Tan Delta

- **Importance**
- **Tan δ**
  - **Time Stability**
  - **Tip Up**
    - $[1.5U_0 - 0.5U_0]$  
  - **Tan δ**  
    - $[U_0]$  

Case Study: Roswell
Test Results - Local Perspective

Case Study: Roswell

Segment 7 Phase 3
Segment 7 Phase 2
Segment 7 Phase 1
Segment 6 Phase 3
Segment 6 Phase 2
Segment 6 Phase 1
Segment 5 Phase 3
Segment 5 Phase 2
Segment 5 Phase 1
Segment 3 Phase 3
Segment 3 Phase 2
Segment 3 Phase 1
Segment 2 Phase 3
Segment 2 Phase 2
Segment 2 Phase 1
Segment 1 Phase 3
Segment 1 Phase 2
Segment 1 Phase 1

Action_Required
Further_Study
No_Action
Test Results - Local Perspective

Case Study: Roswell

Sequence of Measurement

Tip Up (1e-3)

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

No Action

Further Study

Action Required

Classified as Action Required due to instability

Caution: Action Required due to instability
Targeted Offline PD (VLF)

Case Study: Roswell
Targeted Offline PD Test – Segment 6

Open symbols represent the anomalous TDR reflections.

Case Study: Roswell
PD Inception – local perspective

Case Study: Roswell
EVALUATION

Case Study: Roswell
Evaluation after Testing

Offline PD
- 15,000ft actually tested
- Estimate
  - 15 discharge sites
    - 6 cable,
    - 9 accessories
  - 6 splices
  - <1 failure in 12 months from test
- Actual
  - 7 discharge sites
    - 0 cable,
    - 7 accessories
  - 25 splices
  - 0 failure in 8 months since test

Monitored Withstand
- 51,000ft actually tested
- Estimate
  - 2 fails on test
  - 3 assessed for further consideration by loss
  - 0.5 failure in 12 months from test
- Actual
  - 0 fails on test
  - 6 assessed for further consideration by stability, tip up & loss
  - 1 failure (cable) in 9 months since test

Case Study: Roswell
After Testing…

- Actions have been performed by GPC.
  - Suspect splice investigated, actually broken neutral.
  - Damaged termination replaced.
  - Test excavations & Ground Penetrating Radar tests conducted, concluded that it was not practical to replace splices as planned

- System re-enforcements planned.

- All tested circuits have been left in service and are being monitored by GPC.
QUESTIONS
Outline

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• Case Study: Roswell
• **Level Based Reporting Systems**
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
Level-Based Reporting Systems

What do they mean?

What do they provide to users?
Level-Based Reporting Systems

- Level-based (i.e. “1, 2, 3”, “Defer, Repair, Replace”, “Act, Don’t Act” etc.) reporting systems are increasingly common.

- Useful for condensing complex information into easier to understand categories.

- Categories typically represent the output from a “black box” analysis approach.

**Diagram:**

- Measurement
- System Data
- Experience

**“Black Box”**

- Level

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Examples

Measurement

Low  High

Level-Based

Good  ?  Bad

Level Based Reporting Systems
How to Establish Levels

Data Driven
Measurement data “naturally” segregate themselves into distinct classes

Outcome Segregation
Use service performance after measurement to segregate measurement data

Darwinian
Utilize all available knowledge and new data to update levels as needed
Data Driven

- Data distributions define levels – multiple modes characterize different mechanisms
- Levels determined before monitoring phase
- Accuracies can be determined after monitoring

Level Based Reporting Systems
Outcome Segregation

- No prior knowledge of how measurements correlate with failures
- Levels determined after sufficiently long monitoring period
- Accuracies cannot be determined until levels have been set

Implement

Adjust Levels to Correlate To Failures
Darwinian

- Prior knowledge used to generate initial assessments
- Levels updated based on service performance or other factors
- Accuracies cannot be determined until levels have stabilized

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Level Based Reporting Systems
Caveats of Level-Based Systems

- Levels clearly indicate a hierarchy
  - “5” worse than “4”  “Replace” worse than “Defer”

- No sense of the magnitude of the difference
  - How much worse is “Act” than “Further Study” in terms of service performance?

- Comparisons / interpretation of different level-based reporting systems is difficult.

- Consistency of black box over time – does the result mean the same thing next year? Cannot reassess later when you’ve learned more.
  - Stability = 0.5E-3, Tip Up = 20E-3  vs Further Study Required

Need to associate meaning with the levels
Online PD Performance Curve

Level Based Reporting Systems

Provider Data Classes based on failures

<table>
<thead>
<tr>
<th>Level</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td>3%</td>
<td>18%</td>
<td>89%</td>
</tr>
</tbody>
</table>

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### Alternate Interpretation

<table>
<thead>
<tr>
<th>Original Level</th>
<th>Alternate Class (based on probability of failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;&lt; 3</td>
</tr>
<tr>
<td>2</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>89</td>
</tr>
</tbody>
</table>

Class **18** has 6 times poorer endurance than Class **3**

Class **89** is 5 times poorer than Class **18**
Probabilistic Approach - Tan δ

CDFI Data
Classes based on data

Service Failures [% of Tested]

Professed Time between test and failure at May 09 (Month)

Action
- ACTION REQUIRED
- FURTHER STUDY
- NO ACTION

Level Based Reporting Systems
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Diagnostic Accuracies

What are diagnostic accuracies?
Why do they matter?
Performance of Diagnostics

- Performance evaluation primarily focuses on diagnostic accuracy.

- Diagnostic accuracies quantify the diagnostic’s ability to correctly assess a circuit’s condition.

- Accuracy must be assessed based on “pilot” type field test programs in which no actions are performed.

- Circuits must be tracked for a sufficient period of time.
Diagnostic Measurements and Failures

Symptoms are difficult to relate to future failures unless they are in the extremes.

Probability

“Good”

No Failure

“Bad”

Failure

Diagnostic Measurement

Diagnostic Accuracies
Where does the “accuracy” come from?

Accuracies can be computed based on different approaches.

Service Performance After Testing

Comparison of Different Diagnostics

In CDFI, the focus has been on comparing diagnostic data to service performance data.
Objective of Diagnostic Tests

The target population contains both “Good” and “Bad” components
- “Good” – Will not fail within diagnostic time horizon
- “Bad” – Will fail within diagnostic time horizon

<table>
<thead>
<tr>
<th>“Bad” Components</th>
<th>Target Population</th>
<th>“Good” Components</th>
</tr>
</thead>
</table>

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Diagnostic Accuracies
Diagnostic Operation

Applying the diagnostic will separate the population into:
- No Action Required group
- Action Required group
Perspective

• Diagnostic technologies are designed to find anomalies in the field.

• Detecting the presence of an anomaly is not sufficient.

• The goal must be to detect an anomaly which leads to reduced reliability (failure in service) or compromised performance (severed neutrals – stray voltage).

• In the CDFI, when a diagnostic indicates that a circuit is “bad” we interpret that to mean the circuit will fail in the near future.
Variable time horizons of 2-8 years

No Action Accuracy

Action Accuracy

Diagnostic Accuracies
Review

- Two types of diagnostic accuracy
  - Overall Accuracy – Used to compare diagnostics
  - Condition-Specific Accuracy – Used to assess economics of diagnostic programs

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Lower Quartile [%]</th>
<th>Upper Quartile [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Action</td>
<td>96</td>
<td>100</td>
</tr>
<tr>
<td>Action</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>Overall</td>
<td>65</td>
<td>95</td>
</tr>
</tbody>
</table>
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Why Do Accuracies Matter?
Diagnostic Program Benefit

No Action Required

Avoided Corrective Actions

Action Required

Avoided service failures

Accuracies Really Matter
Diagnostic Program Loss

No Action Required

Future service failures

Action Required

Unneeded Corrective Actions

Accuracies Really Matter
Total Diagnostic Program Cost

Cost [$]

Selection

Diagnostic

Corrective Actions

Consequence

Total Diagnostic Program Cost

Accuracies Really Matter

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Accuracies Really Matter
Considerations

- Diagnostic program economic calculations are based on ability to **predict** future failures.

- Total diagnostic program cost is more sensitive to certain elements than others.
  - Failure Rate
  - Diagnostic Accuracy
  - Failure Consequence
Uncertainty in Diagnostic Program Costs

Cost [$]

Program Cost Range

Accuracies Really Matter

Consequence

Corrective Actions

Diagnostic

Selection
Uncertainty in Diagnostic Program Costs

Cost [$]

Program Cost Range

BENEFIT

LOSS

Alternate Program 1

Accuracies Really Matter
Example – Few Customers

Accuracies Really Matter
Example – Many Customers

Accuracies Really Matter
Evolution of Failures (1)

- Pre-Diagnostic Program
- Program Start Up

Log Time (Days)
Log Cumulative Failures
- Type
  - FAILURE
  - TEST

Failures Increasing
Evolution of Testing (1)
Evolution of Failure Rates (1)

![Graph showing failure rates over years]

- **Test Program Ramp Up**
- **Failure Rate**
- **Year 0 Gradient**
- **Inc Rate**
<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Tests (% of Year 3 Test Level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
</tr>
</tbody>
</table>

Evolution of Testing (2)

Test Program Ramp Up

Year 3 Level
Evolution of Failures (2)

- Pre-Diagnostic Program
- Program Start Up
- Full Program

Log Time (Days)

Log Cumulative Failures

Type
- FAILURE
- TEST
Evolution of Failure Rates (2)

- Test Program Ramp Up
- Full Program

Year 0 Gradient

Failures still rising just not as fast
Summary

• Diagnostic programs include four cost elements (Selection, Diagnostic, Corrective Action, and Consequence)

• Benefit can be obtained from:
  – Fewer corrective actions
  – Improved reliability (fewer service failures)

• Modeling economics requires probabilistic approaches since many cost parameters are not known
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The Things That Are Much Clearer Now – CDFI Research
CDFI Work in Lab and Field

• Dielectric Withstand
  – Simple
  – VLF Laboratory Study
• Dielectric Loss
• Partial Discharge
  – Online
  – Offline 60 Hz.
• Combined Diagnostics
  – Monitored Withstand
CDFI
Dielectric Withstand
Dielectric Withstand

- Withstand techniques are most widely used diagnostic in the USA.
- Most utilities use VLF (either sine or cosine-rectangular) in their withstand programs.
- Test duration and voltage are critical to performance.
  - Need to look at both performance on test and service performance
- Explored the concept of “Monitored” Withstand tests.
VLF Lab Program
Overview

• Test program combining aging at $U_0$ with multiple applications of high voltage VLF.

• Uses field aged cable samples - one area within one utility.

• Evaluate the effects of
  – Voltage and time on the performance on test and
  – Subsequent reliability during service voltages.

**Primary Metric**
Survival during aging and testing

**Secondary Metrics**
  – Before and after each VLF application, PD at $U_0$
  – Between Phase A & B IRC, PD (AC $2.2U_0$, DAC), Tan $\delta$
# VLF Phases

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>Service Aged XLPE</td>
<td>Phase A Survivors</td>
</tr>
<tr>
<td>Aging Voltage</td>
<td>$U_0$</td>
<td>$2U_0$</td>
</tr>
<tr>
<td>Aging Temperature</td>
<td>Ambient</td>
<td>45 °C</td>
</tr>
<tr>
<td>VLF Voltage Type</td>
<td>Sine 0.1Hz</td>
<td>Cosine-Rectangular 0.1Hz</td>
</tr>
<tr>
<td>Status</td>
<td>Testing Complete</td>
<td>Testing Complete</td>
</tr>
<tr>
<td></td>
<td>Aging Complete</td>
<td>Aging Underway</td>
</tr>
</tbody>
</table>
Laboratory Setup

Dielectric Withstand
VLF Units

Sinusoidal

Cosine-Rectangular

Dielectric Withstand
Phase A

$U_0$ & Ambient Temp Aging

Sinusoidal VLF

Dielectric Withstand
Failures are the primary metric for evaluation

Withstand Testing Periods (variable durations)
1: No Withstand

2: VLF
2.2U0
15 Min

3: VLF
3.6U0
120 Min

4: VLF
2.5U0
60 Min

5: VLF
2.2U0
120 Min

6: 60 Hz.
3.6U0
0.25 Min

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1: No Withstand

2: VLF
2.2U0
15 Min

3: VLF
3.6U0
120 Min

4: VLF
2.5U0
60 Min

5: VLF
2.2U0
120 Min

6: 60 Hz.
3.6U0
0.25 Min

No Failures

No Failures

3 VLF Failures
No Aging Failures

2 VLF Failures
No Aging Failures

No Failures

2 60 Hz. Failures
No Aging Failures

Dielectric Withstand
Phase B
2U₀ & 45 °C Ageing
Cosine-Rectangular VLF

Dielectric Withstand
1: No Withstand

2: VLF
2.2U0
15 Min

3: VLF
3.6U0
120 Min

4: VLF
2.5U0
60 Min

5: VLF
2.2U0
120 Min

6: 60 Hz.
3.6U0
0.25 Min

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<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>T1</td>
<td>No Failures</td>
<td>No Failures</td>
<td>10 VLF Failures</td>
<td>No Aging Failures</td>
<td>No Failures</td>
<td>No EV Failures</td>
</tr>
<tr>
<td>T2</td>
<td>No Failures</td>
<td>No Failures</td>
<td>2 VLF Failures</td>
<td>No Aging Failures</td>
<td>No Failures</td>
<td>2 Aging Failures</td>
</tr>
<tr>
<td>T3</td>
<td>No Failures</td>
<td>No Failures</td>
<td>No Failures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>No Failures</td>
<td>No Failures</td>
<td>No Failures</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Failures on Test (1)

Dielectric Withstand
Voltage Effect on Times to Failure

Both curves show that higher voltage leads to increased failure rate on test.
VLF Test Program Summary

• Analysis of Phase A is complete.

• Phase B (2U₀ aging, 45°C Cosine Rectangular) underway.

• Phases A & B show that no VLF exposed samples have failed under 60 Hz aging @ U₀ & 2U₀.

• Phase B tests shows two samples without VLF exposure failed during 60 Hz aging @ 2U₀.

• VLF failures on test:
  – Less than 15 mins: 12 % (2 failures)
  – 15 – 60 mins: 71 % (12 failures)
Withstand Field Experience
Withstand Test Process

Voltagen

EARLY

HOLD

Voltagess and Times
for VLF covered in
IEEE Std. 400.2

Ramp Entry

Hold Entry

\( t = 0 \)

\( t_{\text{Test}} \)

Time

Dielectric Withstand
Withstand Testing Experience

Time on Test [Minutes]
Survivors [% of Total Lengths Tested]

IEEE Recommendation
IEEE 400.2 Range

Dielectric Withstand
Withstand Testing Experience

9700 Conductor Miles
>2000 Conductor Miles

Time on Test [Minutes]

Survivors [% of Total Tested]

IEEE 400.2
VLF USA Utilities

Dielectric Withstand
Why the differences in Survivor Curves?

Survivor curves differ between utilities because of:

- Test Voltage
- Tested Length
- Composition

“Early” Failures on Test
Length Distribution (Overall)

Wide variability in circuit lengths

Median Length = 3500 ft
Length Adjustments

• Comparison of withstand failure on test rates must include length adjustments.

1,900 ft.

Choose an appropriate base length
Length Adjustments

• Comparison of withstand failure on test rates must include length adjustments.

1,900 ft.

500 ft. 500 ft. 500 ft. 400 ft.

Failure

Censored
Expect Failures Increase with Time

Dielectric Withstand
“Early” Phase Matters

DC Ramp Entry

60% of failures on test occurred during “Early” phase

Time on Test [Minutes]

Failures on Test [% of Tested]

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“Early” and “Hold” Failure Mechanisms

VLF Hold Entry

Time on Test [Min] vs Failures on Test [% of Total Tested]

Multiple failure modes

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DC or VLF Simple Withstand

Length Adjusted

Failures on Test [% of Tested Sections]

0.0 0.1 0.2 0.3 0.4 0.5

DC  VLF

0.17 % Difference

Dielectric Withstand
“Early” and “Hold” Phases

Difference between VLF and DC is primarily result of “Early” phase

Dielectric Withstand
Withstand Testing Experience

Many early failures

What happens during “Hold” phase?
Test Performance for Different Utilities

1000 ft Length Adj.

- Utility A1
- Utility A2
- Utility D
- Utility H
- Utility I

Failures on Test [% of 1000 ft. Segments] vs. Time on Test [Minutes]

Dielectric Withstand
Test Performance for Different Utilities

1000 ft Length Adj.

- **Utility**:
  - A1
  - A2
  - D
  - H
  - I

- **Failures on Test [% of 1000 ft. Segments]**:
  - A1: 3.5%
  - A2: 3.2%
  - D: 0.2%
  - H: 35.5%
  - I: 4.3%

- **Time on Test [Minutes]**:
  - 0.01
  - 0.1
  - 1.0
  - 10.0
  - 100.0
  - 1000.0

Dielectric Withstand
Survivor Curves – Length Adjusted

![Graph showing survivor curves for different utility systems](image_url)

Survivor Rate on VLF Tests (% of 1000 ft Sections)

- Utility System categories: A1, A2, DHIJVARIOUS

![Inset graph showing detailed survivor curves](image_url)

Survivor Rate on VLF Tests (%)

- Utility System categories: A1, A2, DHIJVARIOUS

Dielectric Withstand
Dataset Lengths versus FOT Rate

Outlier data points

Dielectric Withstand
Collated Experience

Subset of 2800 miles of the 9800 miles in total for VLF where we have length data

Dielectric Withstand
Effect of Test Voltage

Dielectric Withstand
Are Cascading Failures a Concern?

All Insulations
(IEEE 400.2 Perspective)

- 5.5% <0.2%
- 94.3%

Number of VLF Failures following IEEE 400.2

- PE
  - 5.7% 0.1%
  - 95.2 - 95.8%

- PILC
  - 94.1%

421 Tests

Dielectric Withstand
Service Experience

2650 Conductor Miles

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Time to Failure 5% [Days]</th>
<th>Time to Failure 10% [Days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Min @ 2.5 U₀</td>
<td>472</td>
<td>1247</td>
</tr>
<tr>
<td>30 Min @ 1.8 U₀</td>
<td>637</td>
<td>2247</td>
</tr>
</tbody>
</table>

Dielectric Withstand
Test Failures

3-Phase Segments

1.8 Uo 30 mins
- Pass: 71.0%
- FOT: 29.0%

2.5 Uo 15 mins
- Pass: 53.7%
- FOT: 46.3%

Dielectric Withstand
Performance After Test – Pass/No Pass

1.8 Uo, 30 minutes

Service Failures [% of Tests]

Time [Days since Test]

Test Result
- Pass
- FOT

3.5 Failures/100 miles/year
0.40 Failures/100 miles/year
28.3%
3.2%
2 Years

Dielectric Withstand

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Service Performance - 15 min. vs 30 min.

2.5 Uo, 15 min

1.8 Uo, 30 minutes

Dielectric Withstand
CDFI Perspective on Withstand

- The technique is widely used by utilities
- Tested circuits most often display improved reliability
- Circuits normally Pass the tests
  - 97% of 1000 ft lengths Pass the test
- Multiple / cascading failures rarely occur in the field
- 30 min. tests at IEEE 400.2 voltage levels give better service performance than higher voltage 15 min. tests
CDFI Perspective on Withstand

• Modifications to IEEE400.2 recommendations need to be considered very carefully

• Test voltages & times are related and cannot be determined independently

• Many test failures occur early in the test, useful information is revealed by tracking of the time to failure

• Higher voltage test protocols cause more failures on test but they do not necessarily lead to better service performance
QUESTIONS
CDFI
Dielectric Loss
Prevailing View – Tan Delta

Importance

Tan δ

Tip Up

[2U₀ – 1U₀]
CDFI Suggestion – Tan Delta

Importance

\[ \text{Time Stability} \]

\[ \text{Tip Up} \quad [1.5\text{U}_0 - 0.5\text{U}_0] \]

\[ \text{Tip Up} \quad [\text{U}_0] \]

\[ \text{Tan} \ \delta \]

\[ \text{Tan} \ \delta \]
Tan δ Ramp Test Data

Voltage [p.u.]

- 0.5
- 1.0
- 1.5
- 1.7

Mean
Tip Up

Tan-δ [1e-3]

Time [min]
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Tan δ at U₀

Tan Delta @ U₀ (1e⁻³)

ID
- FDR 2-1
- FDR 2-2
- FDR 2-3
- FDR 2-4
- FDR 2-6a
- FDR 2-6b
- FDR 2-7a
- FDR 2-7b

Tan δ
Tan δ and Tip Up Map

- Adjacent phases are different

---

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Tan δ Correlation at Different Voltages

EPR Cables

Same order of performance at < half the voltage
Tan δ Correlation with VLF Withstand

> 99.9% Significant differences in Pass & Not Pass

Filled

Unfilled

Tan Delta (1e-3)

not pass

pass

not pass

pass

Result
Length Effects – Segments Failing Withstand

Filled - EPR

Unfilled - XLPE
Lengths within a Local Region

Tan δ

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50% of the measured data lie below a Tan Delta (at Uo) of 2e-3.

Can be segregated based on areas where the curves break.
Define areas that are “normal” and “unusual”.
VLF Tan δ of Cable Systems

- Total length >250 conductor miles
VLF Tip Up Data of Cable Systems
Cable System – Treatment

Unfilled Polyethylene

Tip Up (1e-3)

Tan δ

No Action

Further Study

Action Required

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Service Performance / Accuracy

Elasped Time between test and failure in service at May 09 (Month)

Likelihood of Failure (%)

ACTION REQUIRED
FURTHER STUDY
NO ACTION

25 Failures, 590 Survivors

20
10
0

FOT
1
10

14
11
10

1.9
2.3
4

36
32
14
11
10

3.6
1.9
4

2.3
2.3
4

14
11
10

10
5

4

2

3

5

10
20
30
40

ACTION REQUIRED
FURTHER STUDY
NO ACTION

25 Failures, 590 Survivors

20
10
0

FOT
1
10

14
11
10

1.9
2.3
4

36
32
14
11
10

3.6
1.9
4

2.3
2.3
4

14
11
10

10
5

4
CDFI Perspective on Tan \( \delta \)

- Provides information on the whole cable system
- Most useful features are
  - Time Stability
  - Differential Tan \( \delta \) (Tip Up)
- Higher loss correlates with increased probability of failure
- Comparisons provide very useful information
  - Length effects
  - Adjacent sections / phases
- Existing levels in IEEE Std. 400 are too conservative. Newer (higher) levels to be in IEEE Std. 400.2 revision
QUESTIONS
CDFI
Online Partial Discharge
Distribution of PD along Lengths

- 5000 ft. portion of sample feeder
- Mixture of different PD levels for different sections and accessories.
Where is PD found?

- Accessory: 54.0%
- Cable: 46.0%
Variability in PD Location

Percentage of PD (%)

Cable

Accessory

Online PD

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Diagnostic Results (Overall)

226 Conductor Miles

Accessory
- 3 (14.8%)
- 4 (2.9%)
- 5 (2.5%)
- 2 (66.6%)

Cable
- 3 (14.4%)
- 4 (1.8%)
- 5 (2.3%)
- 2 (68.0%)

Online PD
Variability in Diagnostic Results

The image contains two box plots comparing the variability of diagnostic results for "Accessory" and "Cable" across five levels (Level 1 to Level 5). The y-axis represents the percent, ranging from 0 to 90 percent. The box plots show the distribution of results at each level, with outliers marked by individual data points.

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How often is PD found?

4.3 signals / 1000 ft
1 PD signal every 4000 ft
Online PD Case Study
Utility Pilot Program
Program Information

- 114 feeder cable miles tested using online PD
- Hybrid system (EPR, XLPE, & PILC)
- Failures tracked for > 3 years after testing
Follow up of Failures

- ACCESSORY: 45 Actions recommended
- CABLE: 52 Actions recommended
If diagnostic had been followed

Service Failures in Actions had been taken

Time of Failure since test (Days)

ACCESSORY

CABLE

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Online PD
Estimated Failure Reduction

- ACCESSORY
  - The 45 recommended Actions would have avoided 14 failures

- CABLE
  - The 52 recommended Actions would have avoided 23 failures
Probabilistic Approach – Online PD

Days Between Test & Failure

Percent

PD Class
- No PD
- PD

0.1
1
1.5
3
6
9
18

1 year
2 years

Electrical Failure on Test <0.1%
CDFI Perspective on Online PD

- Systems with PD at operating voltage have shorter service performance than those without PD at operating voltage.
- Sensor placement on energized cables is more challenging than offline diagnostic techniques.
- Signal analysis is labor intensive.
- Performance data is available for level interpretation.
- Trending (repeat measurements) is likely valuable though difficult for a level-based reporting system.
- Baseline (when new) studies likely to be valuable.
- Can localize to an accessory (when accessory may be accessed with sensor) or to a cable segment.
CDFI
Offline Partial Discharge
CDFI Work

- Analysis of historical PD field test data
- Classification
- Characterization of field samples by PD measurement in laboratory.
- Feature Extraction for Classification
PD Charge Magnitude Distributions

![Histogram of PD Charge Magnitudes]

**Apparent Charge Magnitude [pC]**

<table>
<thead>
<tr>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

**Percent Distribution**

**XLPE Offline PD**

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PD Inception Voltage

![Graph showing PD inception voltage distribution for XLPE offline PD]

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PD Magnitude

Max Limit for 1970’s production

Individual Measurement from the field

Max allowed for current production

PD Measurement Voltage (Uo)

PD Level (pC)
Location of PD

60.6% of PD sites detected in accessories

222 Conductor Miles

- Cable: 39.4%
- Splice: 34.3%
- Termination: 26.3%
PD Sites per Length

Median = 0.96 PD Sites/1000 ft
Approx. 1 PD Site/1000 ft
Performance Curves – Cable PD

![Graph showing service failures over time since test](image)

- **Test Result**
  - NO PASS (red dots)
  - PASS (black squares)

- **Y-axis:** Service Failures [% of Segments]
- **X-axis:** Time Since Test [Days]

- Offline PD
Service Performance – Different Programs

![Graph showing performance metrics for different groups](image)

- **Group**
  - CONTROL
  - FULL
  - PILOT

- **Log Cumulative Failures** vs **Log Time [Days since Start]**

- **Start of programs**

- **Present**

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## Estimated Contribution of Each Group

Crow-AMSAA plots enable numbers of avoided failures to be estimated.

<table>
<thead>
<tr>
<th>Group</th>
<th>Avoided Failures/Length [#/Mile]</th>
<th>Additional Avoided Failures (vs Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control</strong></td>
<td>3.25</td>
<td>--</td>
</tr>
<tr>
<td>Generated Post Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Full</strong></td>
<td>6.55</td>
<td>2.0 x Control</td>
</tr>
<tr>
<td>Diagnostic &amp; Action</td>
<td></td>
<td>3.30</td>
</tr>
<tr>
<td><strong>Pilot</strong></td>
<td>4.33</td>
<td>1.3 x Control</td>
</tr>
<tr>
<td>Diagnostic</td>
<td></td>
<td>1.08</td>
</tr>
</tbody>
</table>

Crow-AMSAA plots enable numbers of avoided failures to be estimated.
PD Charge Magnitude Distributions

Charge Magnitude [pC]

Percent

Variable
- Cable_Failed_PC
- Cable_NOFailed_PC

Charge Magnitude [pC]

Offline PD
Multi Feature Classification

Criterion 1

Criterion 2

Bad

Good

GOOD

BAD

Good

?
Classification - PD Magnitude & PDIV

pC and PDIV are not sufficient to get high classification accuracy
PD Lab Data - Cluster Variable Analysis

Partial Discharge Diagnostic Features

Similarity Level [%]

1. Pos. Phase Range [deg]
2. Pos. Mean Phase [deg]
3. Neg. Qmax [pC*KV]
4. Neg. Mean Energy [pC*KV]
5. Pos. Mean Energy [pC*KV]
6. Neg. Mean Phase [deg]
7. Pos. Max Energy [pC*KV]

50 % Similarity Level

Offline PD
CDFI Perspective on Offline PD

• Systems with PD in cable have shorter service performance than cable without PD (information not available on accessories).
• Signal analysis is labor intensive
• Performance data have not been made available for level interpretation
• Trending (repeat measurements) is likely valuable though difficult for a level-based reporting system
• Baseline (when new) studies likely to be valuable
• Defects must discharge in order to be detected
• Can localize to an accessory and to a short cable length within a segment
QUESTIONS
CDFI
Combined Diagnostics
Survey of Use of Diagnostics

- No Testing: 41.7%
- Testing - one technique: 30.6%
- Testing - > one technique: 27.8%

Combined Diagnostics
Multiple Diagnostics

Combined Diagnostics

- Category
  - Tan Delta / PD: 25.0%
  - VLF / Tan Delta: 75.0%
Tan δ Ramp

Combined Diagnostics
Monitored Withstand - Stable

Stability of Tan-delta monitored through the 15 minute withstand
Monitored Withstand – Unstable

Extended cycle trends of dielectric loss is very unusual.

TD @ IEEE400.2 level (2.2Uo) [E-3]

Box within data 50% of unusual dielectric loss is very unusual.

Mean

Median

50% of data within box

Combined Diagnostics
Tan $\delta$ Ramp & Monitored Withstand

Voltage [p.u.]
- 0.5
- 1.0
- 1.5
- 1.7

Elbow Failure Hampton Leas
Segment HL_23_22

Combined Diagnostics
After Repair…

Voltage [p.u.]
- 0.5
- 1.0
- 1.5
- 1.7

Elbow Failure Hampton Leas
Segment HL_23_22

After Failure

Combined Diagnostics
Monitored Withstand - Tan δ

- Time of failure in mins
- Simple VLF Withstand to IEEE400.2 Levels
- Monitored VLF Withstand to IEEE400.2 Levels

Cumulative Length Tested in One Year (Miles)

- UNSTABLE
- Poor Stability
- High TU
- High Loss

IEEE400.2 Levels

Combined Diagnostics
Combined Diagnostics
Case Study - Cincinnati
Focus in this section is on the Hold Phase
Ways Not to Pass a Monitored Withstand

Failure – Insulation puncture

OR

High Dielectric Loss

OR

High Instability – Measured by standard deviation in consecutive measurements at one voltage level
Lengths Tested

PILC System

Mean Length - 2700ft
Median Length - 3100ft
Monitored Withstand Results

- No Pass - Tan Delta: 7.9%
- No Pass - Monitored Withstand: 10.9%
- Pass: 81.2%

Details:
- Time: Ramp Tan δ, Monitored Withstand Tan δ
- Voltage: 81.2%
Simple Withstand Results

On a 1000ft basis
98.5% survive
1.5% fail

93.9%
6.1%

Failures in Simple Withstand Mode
Survivors in Simple Withstand Mode
Mean Tan δ During Withstand

- No Pass - Tan Delta
- No Pass - Monitored Withstand
- Pass - Tan Delta & Withstand

Result

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Tan δ and Stability

![Graph showing tan δ and stability results with markers indicating Pass, No Pass for Tan Delta, and Withstand.](image)
QUESTIONS
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Analytical Techniques & Failure Rates
• Diagnostic Testing Technologies
• Case Study: Roswell
• Level Based Reporting Systems
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
Selecting a Diagnostic Technology
Knowledge-Based System
KBS

- Selecting the right diagnostic is not easy.
- No one diagnostic covers everything.
- How you measure is influenced by what you do with the results.
- The KBS captures the experience and knowledge of people who have been operating in the field.
Knowledge-Based Systems

• Knowledge-Based Systems are computer systems that are programmed to imitate human problem-solving.

• Uses a combination of artificial intelligence and reference to a database of knowledge on a particular subject.

• KBS are generally classified into:
  – Expert Systems
  – Case Based Reasoning
  – Fuzzy Logic Based Systems
  – Neural Networks
Extruded Cable Diagnostics

Selecting a Diagnostic Technology
KBS Example

Selecting a Diagnostic Technology

Selecting the Type of Insulation:
- PE Based (HMAPE, XLPE, V/TR)
- EPR
- Paper
- Hybrid

Selecting the Age of the Cable:
- 50 Years or more old (pre 1960)
- 40 to 50 years old (1960 - 1970)
- 30 to 40 years old (1970 - 1980)
- 20 to 30 years old (1980 - 1990)
- 10 to 20 years old (1990 - 2000)
- less than 10 years old (After 2000)

Is the Cable Jacketed?
- No
- Yes

Select your standard approach to remediation:
- Replace Large Area
- Replace Segment
- Replace Small Portion (~6 ft)
- Replace Accessories ONLY
- Liquid Rejuvenation
- Unknown

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Short Listing of Diagnostic Approaches

Selecting a Diagnostic Technology
Impact of Remedial Action

- Hybrid Cable System
- Most service failures occur in Accessories
- Usual remediation is by replacement of cable sections

<table>
<thead>
<tr>
<th>System Component</th>
<th>Portion [%]</th>
<th>Service Failure Rate</th>
<th>Age [yrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>33</td>
<td>Medium</td>
<td>20 - 30</td>
</tr>
<tr>
<td>EPR</td>
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<td>40 - 50</td>
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Selecting a Diagnostic Technology
Hybrid Cable System

Selecting a Diagnostic Technology
QUESTIONS
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Analytical Techniques & Failure Rates
• Diagnostic Testing Technologies
• Case Study: Roswell
• Level Based Reporting Systems
• Diagnostic Accuracies
• Accuracies Really Matter
• The Things That Are Much Clearer Now – CDFI Research
• Selecting a Diagnostic Testing Technology
• Summary
Summary
Diagnostic Information

Adaptive Test Protocols
Tests adjusted in real time according to analysis/decisions made during each test.

Preset Test Protocols
Analysis of data performed after tests are completed.

Ease of Utility Implementation

High

Low

Information Content

Simple
Some Skill
Difficult

Summary
Diagnostic Information

Ease of Utility Implementation

Information Content

High

Low

Simple

Some Skill

Difficult

Easy

Some Skill

Difficult

VLF

DAC

TD Ramp

PD Ramp / Online

DC

Summary

CDFI Regional Meeting – Oct 13-14, 2009 Columbus OH
Diagnostic Information

Ease of Utility Implementation

Information Content

High

Low

Simple

Some Skill

Difficult

TD & PD Ramp
TD & PD Monitored Withstand

TD Ramp w/TD Monitored Withstand

PD Ramp w/PD Monitored Withstand

TD/PD Monitored Withstand

TD Ramp

PD Ramp / Online

VLF

DAC

DC

Summary

CDFI Regional Meeting – Oct 13-14, 2009 Columbus OH
What we have learned about diagnostics (1)

1. A developing database of field failure diagnostic data shows that the diagnostic techniques we have studied can provide useful information about cable system condition.

2. While diagnostic results are often imprecise, diagnostic programs are generally beneficial.

3. The benefits can generally be quantified, but it takes time and effort.

4. Many different data analysis techniques, including some non conventional approaches, are needed to assess diagnostic effectiveness.

5. Utilities HAVE to act on ALL replacement/repair recommendations to get improved reliability.
What we have learned about diagnostics (2)

6. PD & Tan δ measurements and DC* & VLF withstand tests can detect problems in cable systems and can be used to improve system reliability.

7. It is difficult to predict whether or not the problems/defects detected by PD or Tan δ will lead to failure.

8. PD diagnostics are good at establishing groups of cable system segments that are not likely to fail.

9. Tan δ measurements provide more useful features for assessing the condition of cable systems than previously thought.

10. Tan δ & PD measurements require interpretation to establish how to act.

*not recommended in most cases

Summary
What we have learned about diagnostics (3)

11. Interpretation of PD measurements is more complex than interpretation of Tan δ measurements.

12. IRC & RV are particularly difficult to deploy in the field.
Reflections

• Approach to data analysis established in CDFI

• 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 (diagnostic tests followed by circuit performance monitoring) as well as controlled laboratory tests.

• The potential value of continued analysis is high.
CDFI Phase 1 Extension

Schedule: October 1, 2009 - September 30, 2010

Tasks
- VLF Withstand
- Defects
- Field Surveys
- Regional Meetings
CDFI Phase II

Schedule: January 2010? (3 Year Duration)

Tasks
- High Voltage Testing
- Commissioning Tests
- Field Demonstrator
- Field Testing
  - Revisits/Trending
  - Challenging Utility Regions
- Diagnostic Reference Handbook
- Knowledge-Based System
CDFI Phase II Participants (to date)

<table>
<thead>
<tr>
<th>Ameren</th>
<th>Hipotronics</th>
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<tbody>
<tr>
<td>Centerpoint</td>
<td>HV Diagnostics</td>
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<td>Consolidated Edison</td>
<td>Hydro Quebec</td>
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<td>High Voltage, Inc</td>
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DOE Proposal Submitted
## Where does the CDFI go from here?

<table>
<thead>
<tr>
<th>Element</th>
<th>CDFI Focus, Phase I</th>
<th>Proposed CDFI Focus, Phase II</th>
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<tbody>
<tr>
<td>Voltage Level</td>
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<td>MV &amp; some HV</td>
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<tr>
<td>Test Type</td>
<td>Condition Assessment</td>
<td>Condition Assessment &amp; Commissioning / Recommissioning</td>
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<td>Service Aged</td>
<td>Service Aged &amp; Laboratory Aging of Service Aged</td>
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<td>Diagnostics</td>
<td>Currently in use in US</td>
<td>Currently in use in US &amp; those that might reasonably be used</td>
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<tr>
<td>Lab Studies</td>
<td>Field Aged Cable</td>
<td>Cable &amp; Accessories</td>
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**Summary**
QUESTIONS