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Presenters

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.

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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IREQ
Jean-Francois Drapeau

Day 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
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<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
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<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>
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<tr>
<td>16:30 – 17:00</td>
<td>Level-Based Reporting</td>
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<td>18:00</td>
<td>Dinner</td>
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Day 2

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<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>
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<tr>
<td>08:15 – 09:30</td>
<td>Diagnostic Accuracies</td>
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<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>
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<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

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 Overview

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.

NEETRAC Mission & Vision
Members 2009-2010

1. 3M
2. ABB
3. Ameren Services
4. American Electric Power
5. Baltimore Gas & Electric
6. British Columbia Hydro
7. Borealis Compounds LLC
8. Con Edison
9. Cooper Power Systems
10. Dominion/Virginia Power
11. Dow Chemical Company
12. Duke Energy
13. Entergy
14. Exelon
15. First Energy
16. Florida Power & Light
17. GRESCO Utility Supply
18. Hubbell
19. NRECA
20. NSTAR
21. PacifiCorp
22. Prysmian Cables & Systems
23. Public Service Electric & Gas
24. S&C Electric Company
25. South Carolina Electric & Gas
26. Southern California Edison
27. Southern Company
28. Southern States
29. Southwire
30. Thomas and Betts/Homac
31. TVA
32. tyco / Raychem
33. Zenergy Power

NEETRAC Membership Growth

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>
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<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>
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<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>
Facilities: High Voltage Lab

Facilities: Low Voltage & Mechanical Lab

Investment vs. ΔV

Observed Failures vs. Failure Estimate vs. Prediction

Historical vs. Prediction
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

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CDFI Background

- 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.

Why do we need diagnostics?
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>MV</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>
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<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.
Participants

American Electric Power
Ameren
Cablewise / Utilix
CenterPoint Energy
Con Edison
Cooper Power Systems
Duke Power Company
Exelon (Commonwealth Edison & PECO)
First Energy
Florida Power & Light
Georgia Tech
GRESCO
HDW Electronics
High Voltage, Inc
HV Diagnostics
HV Technologies
Hydro Quebec
IMCORP
NRECA
PaciCorp (added mid 2005)
Pacific Gas & Electric (added Jan 06)
PEPCO
Oncor (TXU)
Prismian
Public Service Electric & Gas
Tyco / Raychem
Southern California Edison
Southern Company
Southwire

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

CDFI

Analysis
Lab Studies
Field Studies
Dissemination

Lab Studies
(Service Aged Cables)

VLF Withstand
Tan δ
PD

Test Time
Test Voltage Forensics
Time Stability
Voltage Stability
Non-Uniform Degradation
Neutral Corrosion
Calibration
Phase Pattern
Feature Extraction
Classification
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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</thead>
<tbody>
<tr>
<td>Diagnostic</td>
<td>DC Withstand</td>
<td>-</td>
<td>78,105</td>
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<tr>
<td></td>
<td>Monitored Withstand</td>
<td>-</td>
<td>149</td>
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<tr>
<td></td>
<td>PD Offline</td>
<td>2</td>
<td>490</td>
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<td></td>
<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>
<td></td>
<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>
<td>89,000</td>
<td></td>
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</tbody>
</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

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.
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

- Distant Shocks
- Contaminant
- Crack
- Void
- Water tree
- Corroded Neutral
- Electrical tree

Defect → Stress Enhancement → Failure
Defect Types in Extruded Cable Accessories

- Void
- Tracking

Treeing Degrades 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

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

Diagnostics used in Challenging Areas
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 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……..

Histograms – They show the distribution

Boxplot – No Assumptions About Distribution
Boxplot – No Assumptions About Distribution

Upper Quartile 75% of data lie below

Whisker Extends from the box to the Max or Min

Lower Quartile 25% of data lie below

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

Weibull Distribution – Useful for Failure Data

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

Value being measured

Weibull Distribution – Useful for Failure Data

63.3% of samples are likely to have a moisture content below 2.2%
Weibull Distribution

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

Failure Rates

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

Moisture (%)

Percent

Weibull - % G

Shape: 1.228
Scale: 2.214
n
0.01
0.10
1.00
10.00
0
1
2
3
4
5
6
7
8
9
10

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

Installed Capacity (%)

PILC HMAPE APEPE EPR TRXPE UNKNOWN

Peak at 140

Failure Rate [#/100 Miles/Year]
CDFI Regional Meeting – Oct 13-14, 2009 Columbus OH

### Failure Split

- **Unknown**: 1.1%
- **Terminations**: 5.6%
- **Splices**: 37.1%
- **Cable**: 56.2%

### Failures by Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>Unknown</td>
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</tr>
<tr>
<td>Terminations</td>
<td>80%</td>
</tr>
<tr>
<td>Splice</td>
<td>60%</td>
</tr>
<tr>
<td>Cable</td>
<td>40%</td>
</tr>
<tr>
<td>Accessories</td>
<td>20%</td>
</tr>
<tr>
<td>Unknown Source</td>
<td>0%</td>
</tr>
</tbody>
</table>

### System Failure Rate Estimates – By Equipment

- **Cable**: 8.0 failures per 100 miles per year
- **Splice**: 7.0 failures per 100 miles per year
- **Termination**: 6.0 failures per 100 miles per year
- **Unknown Source**: 5.0 failures per 100 miles per year
- **Accessories**: 4.0 failures per 100 miles per year

### Each Utility is Different

- **Utility 1**: 16%
- **Utility 2**: 14%
- **Utility 3**: 4%
- **Utility 4**: 23%
- **Utility 5**: 13%
- **Utility 6**: 7%
- **Utility 7**: 15%
- **Utility 8**: 19%
- **Utility 9**: 24%
- **Utility 10**: 11%
- **Utility 11**: 2%
- **Utility 12**: 1%

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

Analytical Techniques
Spotting Reliability Improvement

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

Accuracies Really Matter

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QUESTIONS
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)

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

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

When to deploy diagnostics

- Commissioning
- Condition Assessment
- Operational Stress
- Time (Years)

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.

Withstand Test Process

- 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.

Voltages and Times for VLF covered in IEEE Std. 400.2

Examples of Withstand Units

VLF Waveforms

- Sinusoidal
- Cosine-Rectangular
**Test Sequences**

- **Simple VLF Withstand to IEEE 400.2 Levels**
- Test time 30 mins

**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 vs. Time graph showing the process of the test.
Tan δ Equipment

Cable System Equivalent

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

Cable System Equivalent

Tan δ Ramp Test Data

- Tip-Up
- Mean

30 Cycles
Time Domain Reflectometry

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

TDR Equipment

**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 Equipment


Distribution of PD along Lengths

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

<table>
<thead>
<tr>
<th>Cable Section</th>
<th>Accessory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No PD</td>
</tr>
<tr>
<td></td>
<td>PD</td>
</tr>
</tbody>
</table>

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 predefined level with post test analysis
Offline PD Test Process

Voltage

Discharge measurement

Time

Offline PD

Offline PD Equipment

PD Pulse

140 mV

180 pC

PD Pulse

Offline PD
**PD Phase Resolved Pattern**

- Offline PD

**Offline PD (60 & 0.1Hz) Outcome Sequences**

- No PD
- 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**

- **Global**
  - DC Leakage
  - TDR
- **Local**
  - PD
  - VLF Withstand
  - DC Withstand

**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 δ – Cannot detect voids or electrical trees
  - PD – Cannot detect water trees (water filled voids)

**Advantage of Multiple Diagnostics**

**QUESTIONS**
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
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• 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

Case Study
Roswell, GA
November 2008 & January 2009

TDR
Tan Delta
Monitored Withstand
Offline PD

Roswell Map

SELECTION
### 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.

### Knowledge Based Selection System

![Diagram of Knowledge Based Selection System](image)

#### 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>DC Leakage</th>
<th>Monitored Withstand</th>
<th>TDR &amp; Historical Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace Small Portion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace Segment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replace Accessories</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Have a shortlist of three techniques:
- Monitored Withstand, Offline PD and VLF (30 mins) offer economic benefit over doing nothing.

### 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
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

Initial Corrective Action Options

- Replace splices only – no detailed records assume 12 splices.
- Complete system replacement.
GENERATION

Overhead and Cabinet Terminations

TDR Results

Tan δ Monitored Withstand
Monitored Withstand - Stability

- 18 Segments Tested
- Pass - Stable Loss
- Pass - Un Stable Loss
- 30 min test
- 60 min test

Sequence of Lengths Tested (miles)

If this had been a Simple Withstand

- No Failures On Test
- 18 Segments Tested

Hierarchy of Tan Delta

Importance

- Tan δ
- Time
- Stability
- Tip Up
  \[1.5U_0 - 0.5U_0\]
- Tan δ
  \[U_0\]

Test Results - Local Perspective

- Action Required
- Further Study
- No Action

Case Study: Roswell
Test Results - Local Perspective

Targeted Offline PD (VLF)

Targeted Offline PD Test – Segment 6

PD Inception – local perspective

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

**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**
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.

Examples

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-Based</td>
<td>Good</td>
<td>?</td>
</tr>
</tbody>
</table>

“Black Box”
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

---

Outcome Segregation

Measure | Monitor
---|---
| ![Chart](chart1.png)

- 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

---

Data Driven

Measure | Monitor | Accuracy Verified
---|---|---
| ![Chart](chart2.png)

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

---

Darwinian

Measure | Monitor | Update Assessment
---|---|---
| ![Chart](chart3.png)

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

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; 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**

Online PD Performance Curve

<table>
<thead>
<tr>
<th>Time to Failure (Years)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0%</td>
</tr>
<tr>
<td>0.5</td>
<td>3%</td>
</tr>
<tr>
<td>1.0</td>
<td>18%</td>
</tr>
<tr>
<td>2.0</td>
<td>89%</td>
</tr>
<tr>
<td>5.0</td>
<td>85%</td>
</tr>
</tbody>
</table>

Provider Data Classes based on failures

<table>
<thead>
<tr>
<th>Level</th>
<th>Time to Failure (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Probabilistic Approach - Tan δ

<table>
<thead>
<tr>
<th>Service Failures [% of Tested]</th>
<th>CDFI Data Classes based on data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>ACTION REQUIRED</td>
</tr>
<tr>
<td>2.0</td>
<td>FURTHER STUDY</td>
</tr>
<tr>
<td>3.0</td>
<td>NO ACTION</td>
</tr>
</tbody>
</table>

Elasped Time between test and failure in service at May 09 (Month)
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  - Accuracies Really Matter
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- Summary

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.

<table>
<thead>
<tr>
<th>Probability</th>
<th>No Failure</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Good”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Bad”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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.

**Accuracies**

Variable time horizons of 2-8 years

<table>
<thead>
<tr>
<th>No Action Accuracy</th>
<th>Action Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>80</td>
<td>99</td>
</tr>
<tr>
<td>60</td>
<td>88</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>20</td>
<td>72</td>
</tr>
<tr>
<td>0</td>
<td>56</td>
</tr>
</tbody>
</table>

**Overall Accuracy**

<table>
<thead>
<tr>
<th>Amount</th>
<th>[No Action Accuracy]</th>
<th>[Action Accuracy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>96</td>
<td>100</td>
</tr>
<tr>
<td>80</td>
<td>99</td>
<td>88</td>
</tr>
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<tr>
<td>40</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>72</td>
<td>20</td>
</tr>
<tr>
<td>0</td>
<td>56</td>
<td>0</td>
</tr>
</tbody>
</table>

**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

Action Required

Avoided Corrective Actions

Avoided service failures

Accuracies Really Matter

Diagnostic Program Loss

No Action Required

Action Required

Future service failures

Unneeded Corrective Actions

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**

- Program Cost Range
  - Consequence
  - Corrective Actions
  - Diagnostic
  - Selection
Example – Few Customers

Example – Many Customers

Evolution of Failures (1)
Evolution of Failure Rates (2)

<table>
<thead>
<tr>
<th>Year</th>
<th>Failure Rate (% of Start)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>1</td>
<td>140</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

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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QUESTIONS
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

By Diagnostic Technique

Category
- No Use
- Occasional
- Standard
- Testing

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.

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 Aging Complete</td>
<td>Testing Complete Aging Underway</td>
</tr>
</tbody>
</table>
Laboratory Setup

VLF Units

Phase A
U₀ & Ambient Temp Aging
Sinusoidal VLF

Withstand Testing Periods
(variable durations)

Failures are the primary metric for evaluation
Phase B
2U₀ & 45 °C Ageing
Cosine-Rectangular VLF
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

Phase B End

CDFI Meeting - Aug 20-21 San Ramon, CA

Failures on Test (1)

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

Voltages and Times for VLF covered in IEEE Std. 400.2

Hold Entry
Ramp Entry

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

IEEE Recommendation
IEEE 400.2 Range

IEEE 400.2 Range

9700 Conductor Miles
>2000 Conductor Miles
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.

Length Adjustments

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

Choose an appropriate base length

Length Adjustments

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

Censored
Expect Failures Increase with Time

Time on Test [Minutes] vs Failures on Test [% of Tested]

Expectation

“Early” Phase Matters

DC Ramp Entry

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

“Early” and “Hold” Failure Mechanisms

VLF Hold Entry

Multiple failure modes

DC or VLF Simple Withstand

Length Adjusted

0.97% Difference
“Early” and “Hold” Phases

![Bar graph showing failures on test as a percentage of sections.

Length Adjusted

- Failures on Test (% of Tested Sections)
  - Failures due to VLF (0.03%)
  - Failures due to Early (0.20%)

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

Withstand Testing Experience

![Line graph showing survivors as a percentage of total tested.

Dielectric Withstand

- Many early failures
- What happens during “Hold” phase?

Test Performance for Different Utilities

![Graph showing failures on test as a percentage of 1000 ft segments.

1000 ft Length Adj.

- Failures on Test (% of 1000 ft Segments)
  - Utility A1
  - Utility A2
  - Utility DH
  - Utility I

Test Performance for Different Utilities

![Graph showing failures on test as a percentage of 1000 ft segments.

1000 ft Length Adj.

- Failures on Test (% of 1000 ft Segments)
  - Utility A1
  - Utility A2
  - Utility DH
  - Utility I

Survivors (% of Total Tested)

- Many early failures
- What happens during “Hold” phase?

Dielectric Withstand
Survivor Curves – Length Adjusted

Dataset Lengths versus FOT Rate

Collated Experience

Effect of Test Voltage
Are Cascading Failures a Concern?

**All Insulations (IEEE600.2 Perspective)**

- PE: 5.5% < 0.2%
- PILC: 94.3%

**421 Tests**

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 (U_0)</td>
<td>472</td>
<td>1247</td>
</tr>
<tr>
<td>30 Min @ 1.8 (U_0)</td>
<td>637</td>
<td>2247</td>
</tr>
</tbody>
</table>

**Dielectric Withstand**

Test Failures

- **1.8 Uo 30 mins**
  - FOT: 36.3%
  - Pass: 34.7%
- **2.5 Uo 15 mins**
  - FOT: 46.2%
  - Pass: 53.7%

**3-Phase Segments**

**Performance After Test – Pass/No Pass**

- **1.8 Uo, 30 minutes**

- **3.5 Failures/100 miles/year**
- **0.40 Failures/100 miles/year**

**Service Failures [% of Tests]**

<table>
<thead>
<tr>
<th>Time (Days since Test)</th>
<th>Test Failures [% of Tests]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.2%</td>
</tr>
<tr>
<td>120</td>
<td>2.8%</td>
</tr>
<tr>
<td>1000</td>
<td>2.3%</td>
</tr>
</tbody>
</table>
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

QUESTIONS
Length Effects – Segments Failing Withstand

Lengths within a Local Region

VLF Tan δ of Cable Systems

Can segregated based on areas where the curves break
Define areas that are "normal" and "unusual"

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

Cable System – Treatment

Service Performance / Accuracy

CDFI Perspective on Tan δ

- Provides information on the whole cable system
- Most useful features are
  - Time Stability
  - Differential Tan δ (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%

---

No PD

PD
Variability in PD Location

Percentage of PD (%)

0 20 40 60 80 100
Cable Accessory

Diagnostic Results (Overall)

226 Conductor Miles

Online PD

Variability in Diagnostic Results

PD Occurrence (#/1000 ft)

All PD Accessory PD Cable PD

How often is PD found?

PD Occurrence (#/2000 ft)

Cable PD Accessory PD All PD

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

If diagnostic had been followed

Number of Service Failures

Time of Failure since test (Days)

ACCESSORY
CABLE
45 Actions recommended
32 Actions recommended

Service Failures in Actions had been taken

Time of Failure since test (Days)
Estimated Failure Reduction

- The 40 recommended actions would have avoided 14 failures.
- The 52 recommended actions would have avoided 23 failures.

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.

Probabilistic Approach – Online PD

- The probability of failure is plotted against the days between test and failure.
- The red line represents the PD class and shows a lower failure rate compared to the black line for PD without online PD.

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
Location of PD

- 60.6% of PD sites detected in accessories
- Termination: 26.3%
- Cable: 39.4%
- Splice: 34.3%

222 Conductor Miles

60.6% of PD sites detected in accessories

PD Sites per Length

- Median = 0.96 PD Sites/1000 ft
- Approx. 1 PD Site/1000 ft

Performance Curves – Cable PD

Service Performance – Different Programs

- Time Since Test [Days]
- Service Failures [% of Segments]

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

Start of programs

Group:
- Control
- Full
- Pilot

Present

Approx. 1 PD Site/1000 ft
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>Control</td>
<td>3.25</td>
<td>--</td>
</tr>
<tr>
<td>Generated Post Test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full</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>Pilot</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>

PD Charge Magnitude Distributions

PD Inception Voltage

Multi Feature Classification
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
CDFI
Combined Diagnostics

Survey of Use of Diagnostics

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

Multiple Diagnostics

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

Tan δ Ramp

- Voltage:
  - 1.0
  - 1.5
  - 2.0

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 gradual

Tan δ Ramp & Monitored Withstand

After Repair…

Failure Segment HL_23_22

Elbow Failure Hampton Leas
Monitored Withstand - Tan $\delta$

Withstand Test Outcomes:
- UNSTABLE
- High Loss
- High TU
- Poor Stability

Monitored VLF Withstand to IEEE400.2 Levels

Cincinnati Test Protocol

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: 2700 ft
- Median Length: 3100 ft

**Simple Withstand Results**

- On a 1000 ft basis
  - 98.5% survive
  - 1.5% fail

**Mean Tan δ During Withstand**

- Graph showing TD (E-3) vs. time with different results indicated.
- Results:
  - No Pass: Tan Delta
  - No Pass: Monitored Withstand
  - Pass: Tan Delta & Withstand
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

Questions
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

KBS Example

- Input from the User
  - Type of Cable – Non-Jacketed
- Select the Appropriate Case
  - Age – Risk
- Suggested Methods
  - Based on Ease of Use (%)
  - Based on Time (%)
  - Based on Cost (%)
- Fuzzy System Rule Base for Case in
  - Age - Risk Level

- Extruded Cable Condition
  - 50 Years or more obsolete (980 – 1170)
  - 30 to 40 years old (725 – 1075)
  - 20 to 30 years old (600 – 725)
  - 10 to 20 years old (500 – 600)
  - Less than 10 years old (400 – 500)

- Suggested Method
  - Replace Large Area
  - Replace Segment
  - Replace Small Portion (4 – 6)
  - Replace Accessory Ohm
  - Local Reinforcement
  - Unknown
**Short Listing of Diagnostic Approaches**

- **Recommended by Most Experts**
  - Discharge
  - Monitored Withstand
  - Simple Withstand
  - Dielectric
  - Historical Data
  - Simple Withstand

- **Recommended by Fewest Experts**
  - Monitored Withstand
  - Simple Withstand

**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>
<td>42</td>
<td>Low</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Paper</td>
<td>25</td>
<td>High</td>
<td>40 - 50</td>
</tr>
</tbody>
</table>

**Questions**
Outline

- NEETRAC Overview
- CDFI Background/Overview
- Cable System Failure Process
- SAGE Concept
- Analytical Techniques & Failure Rates
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- Accuracies Really Matter
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- 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

Information Content

High

Low

Simple

Some Skill

Difficult

Diagnostic Information

Ease of Utility Implementation

Summary

Information Content

High

Low

Simple

Some Skill

Difficult

Diagnostic Information

Ease of Utility Implementation

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Difficult

Diagnostic Information

Ease of Utility Implementation

Summary
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.

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 I 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>Task</th>
<th>Participants</th>
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</thead>
<tbody>
<tr>
<td>Ameren</td>
<td>Hipotronics</td>
</tr>
<tr>
<td>Centerpoint</td>
<td>HV Diagnostics</td>
</tr>
<tr>
<td>Consolidated Edison</td>
<td>Hydro Quebec</td>
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<tr>
<td>Cooper Power Systems</td>
<td>NRECA</td>
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<tr>
<td>Duke</td>
<td>Pacific Gas &amp; Electric</td>
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<tr>
<td>EPRI</td>
<td>Southern Company</td>
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<tr>
<td>GRESCO</td>
<td>Southwire</td>
</tr>
<tr>
<td>High Voltage, Inc</td>
<td>Tyco/Raychem</td>
</tr>
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</table>

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>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Level</td>
<td>MV</td>
<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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<tr>
<td>Cable</td>
<td>Service Aged</td>
<td>Service Aged &amp; Laboratory Aging of Service Aged</td>
</tr>
<tr>
<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>Data</td>
<td>Utility Distribution System</td>
<td>Distribution, Industrial &amp; Transmission</td>
</tr>
<tr>
<td>Lab Studies</td>
<td>Field Aged Cable</td>
<td>Cable &amp; Accessories</td>
</tr>
</tbody>
</table>

**QUESTIONS**