Cable Diagnostic Focused Initiative
Regional Meeting

NEETRAC

Hosted by
Pacific Gas and Electric
San Ramon, CA
August 19-20, 2009

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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. Nigel has a PhD in Physics from the University of Bath UK. He is currently the vice-chair of the Insulated Conductor Committee’s subcommittee on diagnostic testing (Subcommittee F).

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

NEETRAC
Jorge Altamirano
Tim Andrews
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Nigel Hampton (Co-PI)

Georgia Tech - ECE
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Ron Harley
J.C. Hernandez
Salman Mohagheghi

IREQ
Jean-Francois Drapeau
Rick Hartlein (PI)
Thomas Parker
Joshua Perkel

CDFI - Aug. 19-20 San Ramon, CA
Day 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
</tr>
</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>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>Case Study: Roswell</td>
</tr>
<tr>
<td>16:00 – 16:30</td>
<td>Diagnostic Accuracies</td>
</tr>
<tr>
<td>16:30 – 17:00</td>
<td>Diagnostic Testing Technologies (Part I)</td>
</tr>
<tr>
<td>18:00</td>
<td>Dinner</td>
</tr>
</tbody>
</table>

Day 2

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
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</thead>
<tbody>
<tr>
<td>07:30 – 08:00</td>
<td>Continental Breakfast</td>
</tr>
<tr>
<td>08:00 – 08:15</td>
<td>Review Day 1</td>
</tr>
<tr>
<td>08:15 – 09:30</td>
<td>Diagnostic Testing Technologies (Part II)</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 We Know Now That We Did Not Know Before</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>

Dinner – Pasta Primavera

- Limited menu due to potential numbers ($21 fixed price)
  - Butternut Squash Ravioli
  - Chicken Piccata
  - Linguine with Red or White Clam Sauce
- Full bar available
- Short walk from conference center
  - 3124-C Crow Canyon Pl.
Outline

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- Diagnostic Testing Technologies
- Accuracies Really Matter
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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.
### Members 2009-2010

<table>
<thead>
<tr>
<th>Utility Members</th>
<th>Manufacturing Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide &gt; 50% of power sold in the US</td>
<td>Primary suppliers of T&amp;D equipment to electric utilities in the United States</td>
</tr>
<tr>
<td>Serve over 64,000,000 customers</td>
<td></td>
</tr>
</tbody>
</table>

### NEETRAC Membership Growth

<table>
<thead>
<tr>
<th>Year</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td>20</td>
</tr>
<tr>
<td>2000</td>
<td>40</td>
</tr>
</tbody>
</table>

### 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, Product Evaluation, Engineering Analysis &amp; Support, Equipment Spec. &amp; Test Protocol Development</td>
</tr>
<tr>
<td>New Technology/Research</td>
<td>New Product Development, Research, System Enhancements</td>
</tr>
<tr>
<td>Reliability</td>
<td>Asset Management, Condition Assessment, Forensics</td>
</tr>
<tr>
<td>System Analysis</td>
<td>Operation, Installation, Design, Power Quality/Grounding, Safety, Training/Education</td>
</tr>
</tbody>
</table>
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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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.
Composition of US MV system

![Composition of US MV system graph]

Failure Split

![Failure Split pie chart]

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 / Utilx
- 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
- PacifiCorp (added mid 2005)
- Pacific Gas & Electric (added Jan 06)
- PEPCO
- Oncor (TXU)
- Prsmain
- Public Service Electric & Gas
- Tyco / Raychem
- Southern California Edison
- Southern Company
- Southwire
- HV Technologies
- Hydro Quebec
- IMCORP
- NRECA
- PacifiCorp (added mid 2005)
- Pacific Gas & Electric (added Jan 06)
- PEPCO
- Oncor (TXU)
- Prsmain
- 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

- Analysis
- Lab Studies
- Field Studies
- Dissemination

CDFI Knowledge Based Systems

- Value / Benefit
- Accuracies
- Utility Data
- IEEE Std Work
- VLF Withstand
- Tan δ
- PD
- Georgia Power
- Duke
- Meetings
- Publications
- Industry
- CDFI
CDFI Activities

Utility Data

- FPL
  - Offline PD (60Hz)
  - Offline PD (60Hz)
  - VLF Withstand
- PEPCO
  - Offline PD (60Hz)
  - VLF Withstand
- PG&E
  - Offline PD (60Hz)
  - Online PD
  - VLF Withstand
- ONCOR
  - Offline PD (60Hz)
  - Online PD
- Ameren
  - Offline PD (60Hz)
  - VLF Withstand

Dataset Sizes

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Technique</th>
<th>Laboratory [Conductor miles]</th>
<th>Field [Conductor miles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic</td>
<td>DC Withstand</td>
<td>-</td>
<td>78,105</td>
</tr>
<tr>
<td></td>
<td>Monitored Withstand</td>
<td>-</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>PD Offline</td>
<td>2</td>
<td>490</td>
</tr>
<tr>
<td></td>
<td>PD Online</td>
<td>-</td>
<td>262</td>
</tr>
<tr>
<td></td>
<td>Tan δ</td>
<td>1.5</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>VLF Withstand</td>
<td>1.5</td>
<td>9,810</td>
</tr>
<tr>
<td></td>
<td>IRC</td>
<td>0.3</td>
<td>-</td>
</tr>
</tbody>
</table>

Service Performance

- ALL
  - 89,000

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.
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How things fail and what fails have a big impact on the selection of diagnostics

Cable System Failure Process

Failure Rates

Peak at 140

Failure Rate [#/100 Miles/Year]

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

Failures by Equipment

Disbursement of Failures (%)

Cable System Failure Process
### Failure Rate Estimates – By Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Rate ( failures/km yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Rate</td>
<td>8.0</td>
</tr>
<tr>
<td>Splice Rate</td>
<td>7.0</td>
</tr>
<tr>
<td>Term Rate</td>
<td>6.0</td>
</tr>
<tr>
<td>Unk Rate</td>
<td>5.0</td>
</tr>
<tr>
<td>Cable Rate</td>
<td>4.0</td>
</tr>
<tr>
<td>Term Rate</td>
<td>3.0</td>
</tr>
<tr>
<td>Unk Rate</td>
<td>2.5</td>
</tr>
<tr>
<td>Cable Rate</td>
<td>2.0</td>
</tr>
<tr>
<td>Term Rate</td>
<td>1.5</td>
</tr>
<tr>
<td>Unk Rate</td>
<td>1.0</td>
</tr>
<tr>
<td>Cable Rate</td>
<td>0.5</td>
</tr>
<tr>
<td>Term Rate</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Major Cable Components

- **Extruded**
  - Conductor
  - Conductor Shield
  - Insulation
  - Insulation Shield
  - Metallic Shield/Neutral
  - Jacket (Recommended)

- **PILC**
  - Conductor
  - Conductor Shield
  - Insulation
  - Insulation Shield
  - Metallic Shield/Neutral
  - Jacket

- [http://www.otds.co.uk/cables.php](http://www.otds.co.uk/cables.php)

### Defect Types in Extruded Cables

1. Cavity at shield(s)
2. Cavities due to shrinkage
3. Insulation shield defect
4. Contaminant (poor adhesion)
5. Protrusions at shield(s)
6. Splinter/Fiber
7. Contaminants in insulation or shields

### Conversion of Water to Electrical Trees

- Acts as a stress enhancement or protrusion (non-conducting)
- Water tree increases local electric field
- 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

Electrical tree growing from water tree
Defect Types in Extruded Cable Accessories

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.

QUESTIONS
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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.

SAGE at Work

- Selection
- Action
- Generation
- Evaluation

DecreasingFailures
Increasing Failures

Failures [#]
Time

SAGE Concept
Failures [#]

- Decreasing Failures
- Increasing Failures
- Continued Failure Increase

When to deploy diagnostics

- Commissioning
- Operational Stress
- Condition Assessment

Context – is important

Data Generation from Diagnostic Measurement

- Local Context
  Comparisons within one area

Global Context
  Comparison with many tests
  Databases
  Standards

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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 showing selection process]

Summary for Diagnostic Selection

<table>
<thead>
<tr>
<th>Diagnostic Technique</th>
<th>Action Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDR &amp; Historical Data</td>
<td>Replace Small Portion, Replace Segment, Replace Accessories</td>
</tr>
<tr>
<td>DC Withstand</td>
<td>Replace accessories only</td>
</tr>
<tr>
<td>HV DC Leakage</td>
<td>Replace segment</td>
</tr>
<tr>
<td>VLF 60 Mins</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>VLF 30 Mins</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>VLF Offline</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>PD Offline</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>PD Online</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>Tan Delta Monitor</td>
<td>Replace small portion</td>
</tr>
<tr>
<td>HV DC Leakage</td>
<td>Replace small portion</td>
</tr>
</tbody>
</table>

Have a shortlist of three techniques.
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.

Scenario Assessment before Testing

**Offline PD**
- If 51,000ft is tested
- 0.5% fails on test, no customer interrupted
- 1 site / 1,000ft (median)
- 40% discharges in cable
- Estimate
  - 0 fails on test
  - 51 discharge sites
    - 20 cable,
    - 31 accessories
  - 15 splices
  - <2 failure in 12 months from test
- Estimate
- 51 discharge sites
  - 20 cable,
  - 31 accessories
- 15 splices
- <2 failure in 12 months from test

**Monitored Withstand**
- If 51,000ft is tested
- <4% fails on test, no customer interrupted
- <2 fails on test
- 3 assessed for further consideration by loss
- 0.5 failure in 12 months from test

Initial Corrective Action Options

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

**Overhead and Cabinet Terminations**

Case Study: Roswell

If this had been a Simple Withstand

Tan δ Monitored Withstand

If this had been a Simple Withstand

- No Failures On Test
- 18 Segments Tested
- Length Tested (miles) 0 2 4 6 8 10

Case Study: Roswell
Monitored Withstand - Stability

Test Results - Local Perspective

Test Results – Global Perspective

Targeted Offline PD (VLF)
Targeted Offline PD Test – Segment 6

Distance from Cubicle 2 (ft)

Phase

TDR
B - 2
C - 3
PD (Approx Positions)

PD
A - 1

Open symbols represent the anomalous TDR reflections.

PD Inception – local perspective

Position of PD (ft)

VLF Test Voltage (kV)

PD in 1 of 7 splices

PD in 5 of 9 splices

Panel variable: Phase

PD in 5 of 9 splices

Probability of Splice Inception (%)

Monitored Withstand

51,000ft actually tested

2 fails on test

3 assessed for further consideration by loss

0 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 8 months since test

Case Study: Roswell

EVALUATION

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.

Case Study: Roswell

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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.

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

But if the diagnostic is imperfect...

No Action Required  Action Required

Complimentary Diagnoses

<table>
<thead>
<tr>
<th>Category</th>
<th>Action</th>
<th>No Test</th>
<th>Ratio (Action/No Action)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Test</td>
<td>33.8%</td>
<td>52.1%</td>
<td></td>
</tr>
<tr>
<td>Offline VLF TD</td>
<td>14.1%</td>
<td>69.0%</td>
<td></td>
</tr>
<tr>
<td>Online PD</td>
<td>69.0%</td>
<td>33.8%</td>
<td></td>
</tr>
<tr>
<td>VLF TD</td>
<td>19.7%</td>
<td>3.2%</td>
<td></td>
</tr>
</tbody>
</table>

Perspective

- Diagnostics make measurements in the field and find Anomalies.
- Detecting the presence of an Anomaly is, in our view, not sufficient.
- The goal, in our view, is to detect an Anomaly which leads to reduced reliability (failure in service) or compromised performance (severed neutrals – stray voltage).

In accuracy estimates we have used failures in service and interpreted the diagnostics as “Bad Means Failure.”
**Questions**

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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)

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

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

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

Context

- Data Generation from Diagnostic Measurement
- Local Context
  - Comparisons within one area
- Global Context
  - Comparison with many tests
  - Databases
  - Standards
**Diagnostic Context**

- OK
- Not Proven either way
- NOT OK

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

**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.
VLF Test Voltages

<table>
<thead>
<tr>
<th>Cable Rating (kV)</th>
<th>Test Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Cosine-rectangular | Sinusoidal

- Cosine-rectangular
- Sinusoidal

Test Sequences

<table>
<thead>
<tr>
<th>Cumulative Length Tested in One Year (Miles)</th>
<th>Withstand Test Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Simple VLF Withstand to IEEE400.2 Levels</td>
</tr>
<tr>
<td>20</td>
<td>Time of failure in mins for failures &gt; 15 mins</td>
</tr>
</tbody>
</table>

Local Context

Comparisons within one area
Separation with Simple VLF Outcomes

Area 1 is clearly different from the others.

Expect Failures Increase with Time

Expectation

“Early” Phase Matters

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

DC or VLF

Length Adjusted

Failure as Test: % of Sections Tested
"Early" and "Hold" Phases

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

"Early" Phase – Ramp Entry Example

In this case, 60% of the tests produced a failure before reaching the target test voltage.

"Early" Phase – Hold Entry

"Early" phase accounts for 30% of failures on test.
Test Failures

3-Phase Segments

Performance After Test – Pass/No Pass

Simple Dielectric Withstand

Difference between Passing and not Passing

<table>
<thead>
<tr>
<th>Test Duration [Min]</th>
<th>Time to Failure for 1% of Tested Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Days] Pass</td>
</tr>
<tr>
<td>15</td>
<td>133</td>
</tr>
<tr>
<td>30</td>
<td>36</td>
</tr>
</tbody>
</table>

Segments that fail on test and subsequently repaired perform better in service.

What does this mean for Withstand?

- The technique is widely used by utilities
- Tested circuits display improved reliability
- Circuits normally Pass the tests
- Multiple / cascading failures are rare
- IEEE400.2 recommended times (30 mins) and voltages seem to give good service performance
What does this mean for Withstand?

- Modifications to IEEE400.2 recommendations need to be considered very carefully
- Voltage & test time cannot be determined independently
- Many test fails occur early in the test, useful information is revealed by tracking of these times / voltages of failure
- More failures on test does not mean fewer service fails
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!

Outline

- NEETRAC Overview
- CDFI Background/Overview
- Cable System Failure Process
- SAGE Concept
- Case Study: Roswell
- Diagnostic Accuracies
- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
- Selecting a Diagnostic Testing Technology
- Summary
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

The cable insulation system is represented by an equivalent circuit.
- In its simplest form the equivalent circuit consists of two parameters (IEEE Std. 400):
  - Resistor
  - Capacitor
- When voltage is applied to the cable, the total current is the sum of the capacitor current and resistor current.

\[
\tan(\delta) = DF = \frac{I_C}{I} = \frac{1}{\omega RC}
\]

Cable system equivalent: Cable system (cable, splices, and terminations) is reduced to simple circuit.
Data Generation from Diagnostic Measurement

Local Context
Comparisons within one area

Tan δ Ramp Test Data

Tan δ Data for EPR Cable Systems
Segments within a Feeder

Lengths within a Local Region

Testing at Reduced Voltages

Global Context
Comparison with many tests
Databases
Standards
**Tan δ Interpretation**

Based on 258 Conductor Miles

- **No Action**
- **Further Study**
- **Action Required**

**Tan δ Correlation with VLF Withstand**

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>Fail Subsequent VLF Withstand</th>
<th>Pass Subsequent VLF Withstand</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**What does this mean for 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
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.

---

**Wet Joint**
- Feeder had two splice failures just before the test.
- Water ingress was detected with the TDR.
- Failure on 01/17/2008 at detected water ingress location.
- Water ingress confirmed by tests and repair crew.
What does this mean for TDR?

- All diagnostics rely on the neutral, TDR helps to establish its condition.
- Length and accessory information are very important in establishing the context of diagnostic findings.
- Unusual TDR traces can diagnose unusual features in their own right.
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.
- Testing typically performed by a service provider.
- Different implementations of the overall approach
- Assessment criteria are unique to each embodiment of the technology

Discharge Occurrence

No PD  PD

Local Context
Comparisons within one area
Distribution of PD along Lengths

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

Global Context
Comparison with many tests
Databases
Standards

Where is PD found?

- Accessory: 54.0%
- Cable: 46.0%

Variability in PD Location

Percentage of PD (%) vs. Location

- Cable
- Accessory
Level Based Reporting Systems

- Level-based (i.e., “1, 2, 3”, “Defer, Repair, Replace”, “Act, Don't Act” etc.) reporting systems are increasingly common.
- Level systems, on their own, can have limited meaning for utilities.
- 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 “Don't Act” in terms of service performance?
- Comparisons / interpretation of different level-based reporting systems is difficult.

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;&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
What does this mean for Online PD?

- Highly degraded systems most easily differentiated
- Not necessarily easy to deploy – sensor placement and manhole access can be challenging
- Signal analysis is labor intensive
- Data for level interpretation is available
- Trending is likely to be valuable, incorporating this in a level-based reporting system can be a challenge
- Baseline (when new) studies likely to be valuable
- Active failure mechanisms need to involve discharges
- Can localize to accessory and cable segments

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
**PD Charge Magnitude Distributions**

![Graph showing PD Charge Magnitude Distributions for XLPE Offline PD.]

**PD Inception Voltage**

![Graph showing PD Inception Voltage for XLPE Offline PD.]

**Location of PD**

- **Global Context**
  - Comparison with many tests
  - Databases
  - Standards

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

**222 Conductor Miles**
Offline PD Test Sequence

- Testing sequence for 16,000 ft.

PD Location

PD Sites per Length

Service Followup - Cable
What does this mean for Offline PD?

- Highly degraded systems most easily differentiated
- Signal analysis can be labor intensive
- Data for level interpretation could be available
- Trending is likely to be very valuable
- Incorporating trending in a level-based reporting system can be a challenge
- Baseline (when new) studies likely to be very valuable
- Active failure mechanisms need to involve discharges
- Can localize to accessory and within short cable length within a segment

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

Survey of Use of Diagnostics

- 41.7% Tan Delta / PD
- 30.6% VLF / Tan Delta
- 27.8% No Testing
- 0% Testing - one technique
- 0% Testing - > one technique

Multiple Diagnostics

- 25.0% Tan Delta / PD
- 75.0% VLF / Tan Delta
What Diagnostics are Combined

Local

Global

DC Leakage

DC Withstand

PD

VLF Withstand

TDR

Tan δ

Withstand

What Diagnostics are Combined

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

Diagnostic Information

Ease of Utility Implementation

Combined Diagnostics
Tan δ Monitored Withstand

Stability of Tan-delta monitored through the 15 minute withstand.

Tan δ Ramp & Monitored Withstand

Global Context
Comparison with many tests
Databases
Standards

After Repair…
Outline

- NEETRAC Overview
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- Cable System Failure Process
- SAGE Concept
- Case Study: Roswell
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- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
- Selecting a Diagnostic Testing Technology
- Summary

Accuracies Revisited

Why do they matter?
CDFI Meeting - Aug. 19-20 San Ramon, CA

Accuracies Really Matter

---

**Diagnostic Program Costs**

- **Selection**: Diagnostic
- **Corrective Actions**: Consequence
- **Total Diagnostic Program Cost**

---

**Recall the Example...**

- **No Action Required**
  - **Avoided Corrective Actions**
  - Future service failures

- **Action Required**
  - **Avoided service failures**
  - Unneeded Corrective Actions

---

**Incorrect Diagnosis**

- **No Action Required**
  - Future service failures

- **Action Required**
  - Unneeded Corrective Actions

---

**Benefit and Loss**

- **Cost [$]**
  - **Benefit**: Alternate Program 1
  - **Loss**: Alternate Program 2

---

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

- Time is a critical factor in the assessment of accuracy.
  - Failures do not happen immediately after testing.
- Two approaches to computing diagnostic accuracy.
  - “Bad Means Failure” Approach
  - “Probabilistic” Approach
Failures Over Time

Accuracy Over Time – “Bad Means Failure”

Time [Years]

Accuracy [%]

No Action Required Accuracy

Action Required Accuracy

• System Changes
• Additional Aging
• Increased Load

Probabilistic Approach - Tan $\delta$

Accuracies Really Matter
Break

Outline

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The Things We Know Now That We Did Not Know Before

By Diagnostic Technique

- VLF
- DC
- Tan Delta
- PD On
- PD Off
- IRC
- DAC
- TDR

Category:
- No Use
- Occasional
- Standard
- Testing
CDFI Work in Lab and Field

- Dielectric Withstand
  - Simple
  - VLF Laboratory Study
- Dielectric Loss
- VLF Tan δ
  - Monitored Withstand
- Partial Discharge
- Offline 60 Hz.

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 on test and in service.
- Explored the concept of "Monitored" Withstand tests.

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

• Base length must be a meaningful length (50 ft is probably not a useful length).

• Two sets of censored segments:
  – Pass Segments - All segments censored at test duration
  – No Pass Segments
    • 1 failed segment
    • remaining segments censored at failure time

• Multiple failure modes must be dealt with appropriately.

---

Utility I – Hybrid System

Performance at longer test times can be predicted.

Length Weighted Average FOT

- 30 Mins: 2.7%
- 60 Mins: 5.0%
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 2.2$U_0$, DAC), Tan $\delta$
Voltage Effect on Times to Failure

Both curves show that higher voltage leads to increased failure rate.

Phase I & II - Uo / RT ageing, Sine

Test Voltage (Un) vs. Time to 10% Failure (mins)

Phase III - 2Uo / 45°C ageing, Cosine

Voltage Effect on Times to Failure

Failure Analyses - Trees & Defects in Cables

Distance Along Cable (ft)

Failed Samples

DEFECT
LARGE WATER TREE
MEDIUM WATER TREE
SMALL WATER TREE

Dielectric Withstand

VLF Test Program Summary

• Analysis of Phase A is complete.
• Phase B (2Uo aging, 45°C Cosine Rectangular) underway.
• Phases A & B show that no VLF exposed samples have failed under 60 Hz aging @ Uo & 2Uo.
• Phase B tests shows two samples without VLF exposure failed during 60 Hz aging @ 2Uo.
• VLF failures on test:
  – Less than 15 mins: 12 % (2 failures)
  – 15 – 60 mins: 71 % (12 failures)

Dielectric Withstand

Tan δ

CDFI Dielectric Loss

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Prevailing View – Tan Delta

Importance

Tan δ

Tip Up

[2U₀ – 1U₀]

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Tan δ 261

CDFI Suggestion – Tan Delta

Importance

Tan δ

Time Stability

Tip Up

[1.5U₀ – 0.5U₀]

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Tan δ 262

Tan δ Time Stability

Breakdown Frequency

Percent

Filled Paper

PE

Line Class

650 segments
Mean Length 2000 ft
Total length >250 conductor miles

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

VLF Tan Delta of Cable Systems

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Tan δ 263

Tan δ

Breakdown Performance Rank

Percent

0.1
1.0
10.0
100.0
1000.0

Tan Delta at U₀ (E-3)
Cable System – Global Assessment

Unfilled Polyolefin Insulations

Action Required
Further Study
No Action

Tip Up (1e-3)

Service Performance / Accuracy

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

Percent

Action: Action REQUIRED
Further Study: FURTHER STUDY
No Action: NO ACTION

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**

- **Charge Magnitude [pC]**
- **Percent**
- **Variable**
  - Cable_Failed_PC
  - Cable_NOFailed_PC

---

**PD Inception Voltage**

- **Inception Voltage [U0]**
- **Percent**
- **Variable**
  - Cable_Failed_IV
  - Cable_NOFailed_IV

---

**Multi Feature Classification**

- **Criterion 1**
- **Criterion 2**

---

**Classification - PD Magnitude & PDIV**

- **Success Rate [% of Tested]**
- **Neighbors Used in Classification [#]**
- **Variable**
  - fail_success
  - nofail_success
  - Overall_success

- pC and PDIV are not sufficient to get high classification accuracy.
Selecting a Diagnostic Technology

Knowledge-Based System

- 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

- Type of Cable
  - Electrical Action
  - Jacketed?

Suggested Methods Based on Ease of Use (%)

Suggested Methods Based on Time (%)

Suggested Methods Based on Cost (%)

Suggested Methods (%)
KBS Example

**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>
What we have learned about diagnostics (1)

1. A developing database of field failure diagnostic data shows that different diagnostic techniques can provide some indication about cable system condition.

2. Even if the diagnostics themselves are imprecise, diagnostic programs can be beneficial.

3. Benefits can be quantified, however this is not simple and requires 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, VLF, DC and Tan δ & VLF withstand tests detect problems in the field 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 assessments are good at establishing groups of cable system segments that are not likely to fail.

9. Tan δ measurements provide a number of interesting features for assessing the condition of cable systems.

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.

---

**Diagnostic Information**

<table>
<thead>
<tr>
<th>Diagnostic Information</th>
<th>Voltage</th>
<th>Time</th>
<th>Information Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td></td>
<td></td>
<td>Simple</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td>Difficult</td>
</tr>
</tbody>
</table>

**Ease of Utility Implementation**

- DC
- DAC
- VLF

**Combined Diagnostics**

<table>
<thead>
<tr>
<th>Combined Diagnostics</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD Ramp</td>
</tr>
<tr>
<td>PD Ramp</td>
</tr>
</tbody>
</table>

**Diagnostic Information**

<table>
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<th>Time</th>
<th>Information Content</th>
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<td></td>
<td>Simple</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td>Difficult</td>
</tr>
</tbody>
</table>
**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**
  - Simple
  - Some Skill
  - Difficult

- **Voltage**

- **Time**

- **Information Content**
  - High
  - Low

**Combined Diagnostics**
Reflections

- Approach to data analysis established in CDFI
- Many questions answered, there still remain gaps in our understanding of:
  - Benefits
  - Distinguishing anomalies from weaknesses
- 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

Phase II Participants

Current CDFI:
- EPRI
- DOE

New entrants

QUESTIONS