Outline

- 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
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.

Why do we need diagnostics?

Composition of US MV system

Overview

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

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

- This is the largest coherent study of cable system diagnostics anywhere.
CDFI - 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

Utility Data

- Con Ed
- Com Ed
- PPL
- Alabama Power
- Keyspan
  - DC Withstand
  - Offline PD (60Hz)
  - Online PD
  - Tan Delta
  - VLF Withstand
  - Offline PD (0.1Hz)
  - Tan Delta
  - Offline PD (0.1Hz)
  - Online PD

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>
<tr>
<td>Service Performance</td>
<td>ALL</td>
<td>89,000</td>
<td></td>
</tr>
</tbody>
</table>

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
Rick Hartlein

Failures by Equipment

Major Cable Components

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)
6,7 Splinter/Fiber
8. 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

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.
SAGE Approach to Diagnostic Programs

Nigel Hampton

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

Increasing Failures → Decreasing Failures

When to deploy diagnostics

Cable System Performance

Commissioning
Operational Stress
Condition Assessment

Time (Years)
Context – is important

Global Context
- Comparison with many tests
- Databases
- Standards

Local Context
- Comparisons within one area

Data
- Generation from Diagnostic Measurement

Case Study
Roswell, GA
November 2008 & January 2009

Nigel Hampton
- 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

<table>
<thead>
<tr>
<th>Diagnostic Technique</th>
<th>Action Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC withstand</td>
<td>Replace Small Portion, Replace Segment, Replace Accessories</td>
</tr>
<tr>
<td>VLF 15 mins</td>
<td>Replace Small Portion, Replace Segment</td>
</tr>
<tr>
<td>VLF 30 mins</td>
<td>Replace Small Portion</td>
</tr>
<tr>
<td>VLF 60 mins</td>
<td>Replace Small Portion</td>
</tr>
<tr>
<td>HV DC Leakage</td>
<td>Replace Small Portion</td>
</tr>
<tr>
<td>Monitored Withstand</td>
<td>Replace Segment, Replace Accessories</td>
</tr>
<tr>
<td>PD Online</td>
<td>Replace Segment, Replace Accessories</td>
</tr>
<tr>
<td>PD Offline</td>
<td>Replace Segment</td>
</tr>
</tbody>
</table>

Have a shortlist of three techniques: Monitor Withstand, Offline PD and VLF (30 mins)

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

Monitored Withstand
- If 51,000ft is tested
- <4% fails on test, no customer interrupted
- 70% of loss tests indicate no further action
- Estimate
  - <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.
Overhead and Cabinet Terminations

Monitored Withstand

If this had been a Simple Withstand

Monitored Withstand - Stability
Test Results - Local Perspective

Test Results – Global Perspective

Targeted Offline PD Test – Segment 6

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 4 months from 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) 5 months from 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 reinforcements Planned.

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

Nigel Hampton

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.

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 the diagnostic is imperfect...
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.”
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

More than one technique used
No testing
One technique used

No Testing

Testing

Diagnostic Testing Technologies

Survey of Use of Diagnostics

More than one technique used
No testing
One technique used

No Testing

Testing

Diagnostic Testing Technologies

Lengths Tested

Based on diagnostic data supplied to CDFI

Diagnostic Testing Technologies

Global Context
Comparison with many tests
Databases
Standards

Local Context
Comparisons within one area

Data Generation from Diagnostic Measurement

Context

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>5</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>

Cosine-rectangular and Sinusoidal

Data Generation from Diagnostic Measurement
Test Sequences

Localization of Testing Technologies

Cumulative Length Tested in One Year (Miles)

Withstand Test Outcomes

Time of failure in mins for failures ≥ 15 mins

Simple VLF Withstand to IEEE400.2 levels

Separation with Simple VLF Outcomes

Area 1 is clearly different from the others.

Global Context

Comparison with many tests

Databases

Standards
Withstand Testing Experience

Test Performance for Different Utilities

Service Experience

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.
Dielectric Loss (Tan δ)

Dielectric losses - Tan δ:

- The cable insulation system is represented by an equivalent circuit.
- In its simplest form it consists of two parameters; a resistor and a capacitor [IEEE Std. 400].
- When voltage is applied to the cable, the total current will be the contributions of the capacitor current and the resistor current.

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

Cable System Equivalent

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

Tan δ Test Data

<table>
<thead>
<tr>
<th>Voltage (p.u.)</th>
<th>Time [min]</th>
<th>tan(δ) [1e-3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>1.0</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>1.7</td>
<td>3</td>
<td>70</td>
</tr>
</tbody>
</table>

Data Generation from Diagnostic Measurement
Local Context
Comparisons within one area

Segments within a Feeder

Lengths within a Locality
Presented at the Spring 2009 ICC Education Session Copyright GTRC 2009

Global Context
Comparison with many tests
Databases
Standards

Diagnostic Testing Technologies

Testing at Reduced Voltages

Tan-delta @ 2.0 Uo \[1E-3\]
Tan-delta @ 1.5 Uo \[1E-3\]
100.0
10.0
1.0
0.1
1.2
2.2
4
0.7
1.3
2.3

Regression
95% C I
95% PI
PI: Prediction Interval
CI: Confidence Interval

"Cool Wall"

Diagnostic Testing Technologies

Tan δ Interpretation

Based on 258 Conductor Miles

Action Required
Further Study
No Action

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.
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 only be performed by a service provider.
- Assessment criteria are unique to each embodiment of the technology.
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

Diagnostic Results (Overall)
226 Conductor Miles

Diagnostic Testing Technologies
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

![PD Diagram](image)

**PD Pulse**

Data Generation from Diagnostic Measurement

![PD Pulse Graph](image)
**PD Inception Voltage**

![PD Inception Voltage Chart](chart)

**Location of PD**

- 60.6% of PD sites detected in accessories
- 222 Conductor Miles

- Termination: 26.3%
- Cable: 39.4%
- Splice: 34.3%

**Global Context**

Comparison with many tests
- Databases
- Standards

**Offline PD Test Sequence**

- Testing sequence for 16,000 ft.

- No PD
- PD
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.
Combined Diagnostics

Multiple degradation mechanisms mean that two diagnostics are often better than one.
Monitored Withstand Data - Elbow

Optional Ramp Up gives Tan-delta
Tan-delta vs. Voltage
V - 1.5
Voltage

Stability of Tan-delta monitored
Time [min]
Tan-delta [1e-3]

Before Failure
Failure
After Failure

Tan-delta Stability

“Cool Wall”

Monitored Withstand Data - Elbow

Global Context
Comparison with many tests
Databases
Standards
Accuracies Revisited

Why do they matter?

Josh Perkel

Recall the Example...

No Action Required

Action Required

Avoided Corrective Actions

Avoided service failures

Incorrect Diagnosis

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

**Diagnostic Accuracy Complications**

- 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

**Accuracy Over Time – “Bad Means Failure”**

- System Changes
- Additional Aging
- Increased Load

- No Action Required Accuracy
- Action Required Accuracy
The Things We Know Now That We Did Not Know Before

By Diagnostic Technique
CDFI
Dielectric Withstand

Josh Perkel

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

Median Length = 3500 ft

Length Effects

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

Failure

Censored

2000 ft.

500 ft.

500 ft.

500 ft.

500 ft.

0 12000 24000 36000 48000 60000 72000 84000

Circuit Length [Conductor Ft]

Percent
VLF Lab Program

Josh Perkel

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 \( \delta \)
Withstand Testing Periods (variable durations)

Aging Periods

Failures are the primary metric for evaluation

No aging failures for any condition

More failures occur at higher test voltages

No Failures • Before 15 mins • After 60 mins

Percent of 20 ft Samples Failing

Max Time 120 Mins

Testing Voltage (Ub)

Presented at the Spring 2009 ICC Education Session Copyright GTRC 2009
Failure Analyses - Trees & Defects in Cables

- 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 showed two samples without VLF exposure failed during 60 Hz aging @ 2U₀.
- All failures occurred at the appropriate time. i.e. within the VLF testing periods.
- 80% (4 out of 5) of VLF failures between 15 and 60 mins.

Selecting a Diagnostic Technology
Knowledge-Based System

Nigel Hampton

- 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

Short Listing of Diagnostic Approaches
**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>

**Hybrid Cable System**

**Selecting a Diagnostic Technology**

**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.

**Summary**

Rick Hartlein
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 very difficult to predict whether or not the problems/defects detected by PD and Tan δ will lead to failure in the short/medium term.

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.

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.