Underground Cable Testing and Life Expectancy Diagnostics

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Overview

- History of Undergrounding and underground cables
- How utilities are approaching replacement of URD systems
- Diagnostic Testing Options
- NEETRAC’s work on Monitored Withstand Test
- Case Study: Martins Landing on Sawnee EMC’s system
Underground Distribution

• For Rural Co-ops starting in 1970 with acceleration in 1980 and 1990
  – New residential developments wanted underground utilities
  – Trend started earlier for urban areas
  – Many local governments require underground service

• Cost in Aid of Construction
  – Cooperatives typically make the developer pay for underground service (some or all of the cost)
  – Better reliability than overhead lines
    • Need to be loop due to long outage time
    • Adds to more cost per home
URD Cable Quality

- 1970s and early 1980s vintage URD cable
  - Not so good
  - Early failures
  - Bare concentric neutrals
  - Directional boring developed
  - Trend to install cables in conduits
- Cables installed in 1980s and 1990s
  - In service age 30 to 40 years
# Oklahoma Gas and Electric

<table>
<thead>
<tr>
<th>Cable Type</th>
<th>Years</th>
<th>Failure Rate</th>
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<td>2 AL (Bare Conc. Neut.)</td>
<td>1970-1983</td>
<td>19.3 Failures/100 miles/Year</td>
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<tr>
<td>2AL (Con. Neut. Jkt.)</td>
<td>1984-2004</td>
<td>2.3 Failures/100 miles/Year</td>
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<tr>
<td>1/0AL (Bare Conc. Neut.)</td>
<td>1970-1983</td>
<td>14.3 Failures/100 miles/Year</td>
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<td>1/0AL (Conc. Neut. Jkt.)</td>
<td>1984-2004</td>
<td>7.9 Failures/100 miles/Year</td>
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Source: “Oklahoma Gas & Electric Underground Cable Failure Data Base and Failure Rates” by Dale Metzinger, IEE/ICC Nov. 3, 2004
<table>
<thead>
<tr>
<th>Generation</th>
<th>Insulation</th>
<th>Semicon (conductor &amp; insulation shields)</th>
<th>Jacket</th>
<th>Barrier</th>
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<td>Jacket</td>
<td>Extruded Lead</td>
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<td>Graphite / Carbon Tape</td>
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<td>3</td>
<td>XLPE or EPR</td>
<td>Graphite / Carbon Tape</td>
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<td>4</td>
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<td>Extruded Thermoplastic</td>
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<td>7</td>
<td>WTR XLPE or EPR</td>
<td>Extruded Thermoset (crosslinked)</td>
<td>Jacket</td>
<td>Conductor Water Blocked</td>
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<td>Conductor &amp; Core Water Blocked</td>
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<tr>
<td>9</td>
<td></td>
<td></td>
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<td>Metal Core Barrier</td>
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</tbody>
</table>
Planned Replacement of Utility Infrastructure

Run to Failure

- Street Light bulbs – could be a reasonable plan
- Copper wire
  - No testing
  - Prioritize repairs based on load/reliability
- Wood poles
  - No testing, wait till it falls
  - Testing, what do you learn?
  - Imminent failure? Strength to 2/3 required when installed
- Power transformers
  - DGA testing
Planned URD Replacement

• Vintage of the cable
• Construction of the cable (bare concentric)
• Number of failures in an area
  – 2 failures, 1 year apart
  – 3 failures
  – Etc.
• Often an entire URD development is replaced on these metrics
• Cost per foot $15 to $85 depending method required.
  – 3 to 10 times original installation cost
Cable Rejuvenation

• Option for not replacing cable is cable rejuvenation
  – RUS will provide load dollars for this application
• Decision for rejuvenation
  – Number of failures in an area
  – Vintage of the cable
• Well over 80 million feet of cable has been rejuvenated
  – With reported failure rates below 1%
• However, not all cables can be rejuvenated
• Does it need to be rejuvenated???
Diagnostics for Cables

- Difficult to demonstrate the value of cable replacement/rejuvenation
  - If very few outages
  - The replacement project prevents future outages
  - But does not improve current reliability statistics
- When a failure does occur, the system is looped
  - URD failures not like a pole or conductor falling on the ground
  - URD failures generally do not endanger the public
- Age and number of failures on a cable
  - Not great tools to determine the need for replacement
Diagnostic Testing per NEETRAC Survey 2014

- 65.0% No Testing
- 4.5% Tan δ (Very Low Frequency)
- 14.9% Simple Monitored Withstand – Very Low Frequency
- 8.3% Monitored Withstand VLF TD
- 4.8% Partial Discharge

• Each test requires a different skill level and provides more or less information
Simple Withstand
Very Low Frequency

• The test calls for voltage above nominal operating voltage be applied to the cable to stress the insulation of a cable system for a set period of time.

• Test yields pass/fail results
  - Don’t know how close the system was to failure.
  - A failed test requires repairs or replacement at that time.

• Test in accordance with IEEE 400.2
Simple Withstand
Very Low Frequency

- Stress cable at some voltage above $U_0$
  - 1.5 to 2.5 times $U_0$
- Failure on Testing (FOT)
- FOT is GOOD!!
  - Found bad section
  - Repairs made
- No FOT
  - Return to service
  - Hope for the best
  - No Failure in Service (FIS)

Figure from NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016 Page 10-14
Monitored Withstand
Very Low Frequency

• A more sophisticated approach to the simple withstand test is to measure some other system property during the ramp up of the test.
  – Dielectric property or discharge characteristics
  – Possible to stop the test if the monitored values show imminent failure.

• Advances in test equipment that could be deployed in the field
  – Field test equipment available at reasonable prices

• NEETRAC’s research pointed to the value of the Monitored Withstand Test
  – Gathered large datasets to analyze the effectiveness

• This is a relatively new concept to utilities
  – BUT can be an effective tool for analyzing the health of cable sections
Monitored Withstand
Very Low Frequency

NO PASS
1. Dielectric failure
2. No Dielectric Failure but non-compliant data
   • Rapid increase in monitored values
   • Steady upward trend at a moderate voltage level (Tip up)
   • Instability of monitored value
   • High magnitude value
   • Non-acceptable low pass margin

PASS
1. No Dielectric failure
2. Monitored Values
   • Stable
   • Within acceptable ranges

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016  Page 10-12
Monitored Withstand
Very Low Frequency

• Use the ramp up time to monitor values
  – Take reading every 10 seconds with a minimum of 6 readings at each applied voltage level

• Relatively easy to use calculations, compare to set decision matrix
  – Easy to tell really good cable system
  – Easy to tell really bad cable system

• Stop after the ramp up
  – Determine if the Full Withstand Test is necessary
    • Not needed for Really Good Cable system
    • Really Bad Cable System likely to failure at full withstand
Monitored Withstand Very Low Frequency

- Use the ramp up time to monitor values
- Relatively easy to use calculations and decision
  - Good cable system
  - Bad cable system
- Stop after the ramp up
  - Determine if the full Withstand Test is necessary
Monitor Tan $\delta$

- Monitor the Dissipation Factor (aka Tan $\delta$) during the Ramp Up
- What is a Tan $\delta$ test and what can it tell us?
- Tan $\delta$ is the measurement of the phase angle between the charging current and the loss current.

**Dissipation Factor** = **Tan** $(\delta) = \frac{I_R}{I_C}$
Tan δ

- A diagnostic method of testing cables to determine the quality of the cable insulation.
- Cable insulation free of defects (water trees, moisture, electrical trees, etc.)
  - Cable looks like a perfect capacitor (very low Tan δ)
- Test is done at Very Low Frequency (VLF) or 0.1 Hz
  - It takes 600 times less power at 0.1 Hz to energize a cable compared to 60 Hz
  - Tan δ values larger at low frequencies because charging current is smaller.
Advantages of Tan $\delta$

- Basic Tan $\delta$ features at VLF can be ranked in order of importance
  - Discuss these features on next slide
- Overall condition assessment (cable, termination, and joints)
- Indication of overall degree of water treeing in XLPE cable
- Data obtained at lower voltages
- Lower risk of failure on test
- Over time, multiple tests can predict rate of aging
- Test duration is relatively short for good cables
- Works on EPR and XLPE cable systems

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016  Page 6-10
Basic Tan $\delta$ features at VLF

- **Tan $\delta$ Stability**: At a set voltage, Tan $\delta$ should not vary significantly. Often measured as standard deviation.

- **Differential Tan $\delta$ (Tip Up)**: The algebraic difference of two values at two different voltages 0.5 $U_0$ and 1.5 $U_0$.

- **Differential Tan $\delta$ (Tip Up Tip Up)**: The algebraic difference of two subtractions: Difference of values at two different voltages 1.5 $U_0$ and 1.0 $U_0$ and the difference of values at two different voltages 1.0 $U_0$ and 0.5 $U_0$.

- **Tan $\delta$ Magnitude**: Level of loss. Normally the mean value at 1.0 $U_0$.

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016 Page 6-10
Figure 2: Example of Measured $\tan \delta$ data from a PE Cable System in Service and $\tan \delta$ Diagnostic Features

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016 Page 6-12
Water Trees in Insulation

- Increase in tan $\delta$ over dry insulation
- Tan $\delta$ increases with voltage
  - Drift of the water dipoles is non-linear
- Loss of current waveform distorted
### Assessment of PE-based Insulations (PE, XLPE, TRXLE)

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>No Action</th>
<th>Further Study</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability TD (STD)</td>
<td>&lt;0.1</td>
<td>0.1 to 1.0</td>
<td>&gt; 1.0</td>
</tr>
<tr>
<td>Tip Up TD_{1.5U-TD_{0.5U}}</td>
<td>&lt;6.7</td>
<td>6.7 to 94.0</td>
<td>&gt; 94.0</td>
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<tr>
<td>Tip Up Tip Up (TD_{1.5U-TD_{1.0U}} - (TD_{1.0U-TD_{0.5U}}))</td>
<td>&lt;2.0</td>
<td>2.0 to 50.0</td>
<td>&gt; 50.0</td>
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<tr>
<td>Mean TD at U</td>
<td>&lt;6.0</td>
<td>6.0 to 70.0</td>
<td>&gt; 70.0</td>
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</tbody>
</table>

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016 Chapter 15
# Assessment of Mineral Filled Insulations (EPR)

<table>
<thead>
<tr>
<th>Condition Assessment</th>
<th>No Action</th>
<th>Further Study</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability TD (STD)</td>
<td>&lt;0.1</td>
<td>0.1 to 0.8</td>
<td>&gt; 0.8</td>
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<tr>
<td>Tip Up TD&lt;sub&gt;1.5U-TD&lt;sub&gt;0.5U&lt;/sub&gt;</td>
<td>&lt;2.0</td>
<td>2.0 to 40.0</td>
<td>&gt;40.0</td>
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<tr>
<td>Tip Up Tip Up (TD&lt;sub&gt;1.5U-TD&lt;sub&gt;1.0U&lt;/sub&gt;) - (TD&lt;sub&gt;1.0U-TD&lt;sub&gt;0.5U&lt;/sub&gt;)</td>
<td>&lt;1.0</td>
<td>1.0 to 25.0</td>
<td>&gt;25.0</td>
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<tr>
<td>Mean TD at U</td>
<td>&lt;16.0</td>
<td>16.0 to 75.0</td>
<td>&gt;75.0</td>
</tr>
</tbody>
</table>

Source: NEETRAC Cable Diagnostics Focused Initiative (CDFI) Phase II, Released Feb. 2016 Chapter 15
Tan δ

- Test duration is relatively short less than 5 minutes
  - Once it is set up
  - Simple calculation on data points
  - Automate with a spreadsheet
- Results from Spreadsheet
  - No Action:
    - Stop do not proceed with the Withstand Test
  - Further Action Required:
    - Stop and track cable section for future testing
    - Proceed with Full Withstand Test. May result in a cable/termination failure
  - Action Required:
    - Stop and replace cable or otherwise schedule a replacement
    - Proceed with Full Withstand Test to fail the cable/termination
Condition Assessment of PE-based Insulations (i.e. PE, XLPE, WTR XLPE)

Historical figures of merit within CDFI for US cable systems over a period of 4 yrs.

Please fill the fields highlighted in yellow

<table>
<thead>
<tr>
<th>U/Uo</th>
<th>Mean TD [e-3]</th>
<th>STD</th>
<th>[%]</th>
<th>STD [e-3]</th>
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<tr>
<td>0.5</td>
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<td>1.0</td>
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<tr>
<td>1.5</td>
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</table>

A minimum of 6 measurements should be made at each voltage level to determine the values of the Mean TD [e-3] and STD [%] (parameters highlighted in yellow)

Acronyms:
- V: Test voltage
- V0: Nominal voltage
- TD: Tan delta
- STD: Standard deviation

Condition Assessment Parameters:

- TD Stability @ V0
- Differential TD (TU)
- Mean TD @ V0
Further Study/ No Action

- NOT always a bad cable: Check for potential testing irregularities
- Review data for a rogue measurement
  - STD at $U_0$ or Tip Up calculation
- Re-clean terminations and repeat measurements
- Compare to other phases of the cable or adjacent sections
- If filled insulations are tested, check specific variety of material
- Conduct IEEE 400.2 Withstand VLF for 30 minutes
Testing a Collection of Cables Sections

• Provides a priority for replacement
• Not 100% replacement
• Budget for Action Required
  – To be replaced
• Budget for Further Study
  – Near future testing
  – Replacement of key cable sections
Diagnostic Testing is Available

- NEETRAC work developed a new diagnostic tool
- Provides actionable information on service of life of URD cables
- Before wholesale replacement or rejuvenation
  - Consider testing cables
Case Study – Martins Landing
Sawnee EMC

- North of Atlanta
- Residential area built in the late 80s and early 90s
- 12kV cable 2/0 AL XLPE and 1000 AL XLPE jacketed cable
  - Direct buried
  - Cable 30 or more years old
- Some failures in the area
  - Budgeted millions for replacement of cable
Case Study – Martins Landing

- Direct Buried cables
- No conduit
- Directional Boring required
- Preventing outages before they happen
- Members see lawns and landscaping distributed for “no apparent reason”
Case Study - Martins Landing

• Learned about Monitored Withstand Testing
  - Cable Diagnostic Focused Initiative documentation
• Consultation with NEETRAC
  - Contract through GRESCO who has a relationship with NEETRAC for cable testing and other testing needs.
• After learning more, Sawnee determined cable testing had merit
• Purchase test equipment from a Local Atlanta Manufacturer
  - Also received training from the Manufacturer
• Used NEETRAC’s simple spreadsheet tool to track Tan δ values
  - Calculates Tip Up, median values,
  - Compares to values in No Action, Further Study, and Action Required.
Case Study – Martins Landing

• Decided to a TDR test on the cable prior to Monitored Withstand Test
  – Checked for gross problems in cable system
  – Frequent direct buried splices
  – Verified concentric neutral was reasonably intact – needed for Tan δ test to work
• Monitored Withstand Test
  – Tan δ test at 0.5 $U_O$, 1.0 $U_O$, and 1.5 $U_O$
• Record Tan δ values in spreadsheet
• Often No Action Required
• If Further Study or Action Required
  – Sawnee’s protocol is to proceed with VLF Withstand test
Case Study – Martins Landing

- Approximately 159 cable sections tested
- 151 cable sections scored **NO ACTION**
- 8 cable sections scored **FURTHER STUDY**
  - 7 cable sections failed on Withstand Test with $2.2U_0$
  - All failures occurred at direct buried splices
  - Not cable failures
  - Splices replaced and cable back in service
- 1 Cable Section from **FURTHER STUDY**
  - Tree root grew into the cable
  - Pushed concentric neutral in toward the phase conductor
Splices/Terminators
Have a failure rates
Sawnee’s splice failure may or may not be consistent with these failure rates
Next occurrence at Sawnee
Isolate splice
Send to NEETRAC for Autopsy prior to failure due Withstand Test
Solution for Termination Failures (not Sawnee EMC)
Case Study - Martins Landing

• Testing done by in-house linemen/technicians
  - Learning curve was short
• Typically expect to test 2 to 5 cables per day
  - Broken elbows required repair
  - Time to switch and isolate cable section
• 4 Men and two vehicles about $560 per hour
  - Cost per test ranges from $380 to $112
  - Plus cost of test equipment about $20-40 per test over the life of the unit
• To date no cable sections required replacement
  - Reduced capital expenditures
Wrap Up

• Monitored Withstand Testing
  – New testing method developed in the last 5 years
• Relatively easy to test
• Relatively low cost for testing
• Results provide actionable information

http://www.neetrac.gatech.edu/cdfi-publications.html