Assuring the Reliability of Critical Power Cable Systems

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Some of the technologies described herein are patented and proprietary IMCROP technology.
Executive Summary

- Critical industries have lost 100’s of millions of dollars due to defective cable systems (mostly workmanship) & ineffective tests.
- New extruded cable systems predominately fail by a process of erosion associated with PD, not conduction (leakage detectable by HIPOT).
- High Potential (HIPOT) (AC & DC) tests are intentionally destructive & do not assure reliability.
- Repeating the manufacturers’ off-line 50/60Hz PD QC test in the field is only effective way to assure insulation system meet design life.
- Over the last decade, one diagnostic technology has been demonstrated to effectively reproduce factory test comparable result in the field. (DSD technology)
Question

Which cable system test would you consider best practice to assure the reliability of critical cable systems?

- DC withstand
- VLF AC withstand
- Tangent delta
- On-line PD
- Off-line 50/60Hz PD

What test have manufacturers used to assure product design & production reliability for the last 40 years?
The Strategic Value of Cable Tests

IEEE 400 Definitions
Type 1: Destructive Withstand
Type 2: Non-Destructive Diagnostic Test

Locates & characterizes cable defects

More Strategic

Defect Specific Diagnostics (Type 2)

General Condition Assessment (Type 2)

Destructive Withstand Test (Type 1)
### Evolution of Cable Testing In the Field

<table>
<thead>
<tr>
<th>Early 1900’s</th>
<th>1960’s</th>
<th>1970’s</th>
<th>1990’s</th>
<th>Today</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primarily Paper Insulated Lead Covered Cable (PILC)</strong></td>
<td><strong>Extruded cable insulation (Rubber, HMWPE, EPR, XLPE)</strong></td>
<td><strong>Issues Arise</strong></td>
<td></td>
<td><strong>State-of-the-Art</strong></td>
</tr>
<tr>
<td>- Failure mechanism associated w/ conduction &amp; PD</td>
<td>- Failure mechanism associated predominantly w/PD</td>
<td>- Water testing problems</td>
<td>- VLF HIPOT can’t fail most defects</td>
<td>- Most common HIPOT test still DC test – ineffective</td>
</tr>
<tr>
<td>- Factory test : DC test</td>
<td>- Factory test: 0ff-line 50/60Hz PD</td>
<td>- Can’t fail most defects</td>
<td>- Tangent Delta</td>
<td>- Best practice is off-line power frequency PD</td>
</tr>
<tr>
<td>- Field test : DC test</td>
<td>- Field Test: DC test</td>
<td>- Aged PE fails at higher rate after passing test</td>
<td>- Can’t detect many type of defects</td>
<td>- Comparable w/ factory PD test</td>
</tr>
<tr>
<td>- Simple</td>
<td>- 0.1Hz VLF AC invented</td>
<td>- 0.1Hz VLF AC invented</td>
<td>- Can’t locate issues</td>
<td>- Assures IEEE/ IEC/ICEA/AEIC compliance</td>
</tr>
<tr>
<td></td>
<td>- Fails more defects</td>
<td>- Fails more defects</td>
<td>- PD diagnostic developed for field</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Answer to DC space charge issue</td>
<td>- Answer to DC space charge issue</td>
<td>- Can locate most issues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Tangent Delta developed for field</td>
<td>- Tangent Delta developed for field</td>
<td>- Not comparable to factory standards</td>
<td></td>
</tr>
</tbody>
</table>

“What the industry wants is leading edge technology proven over the past 30 years.”
Question:
What is the most critical part of an MV/HV cable termination?
Stress relief element reduces electric stress significantly at cutback of semiconducting outer conductor (ground)

Basic MV/HV Cable Design

Terminated vs. Unterminated

Electric field - conductor at 30 kV
dark blue = low electric stress
dark red = high electric stress
What is PD?

- An electrical discharge that does not completely bridge the space between two electrodes.
- The apparent discharge magnitude of a PD signal is measured in picoCoulombs (pC).
- The voltage at which PD first appears is the Inception Voltage (PDIV).
- The PD is extinguished when the voltage is reduced below the level called the Extinction Voltage (PDEV).
Modes of Failure

- High impedance defects
  - Workmanship nicks, voids, cuts
  - Aged 20yrs+ old -water/electrical trees
- Low impedance defects –conduction (PILC)
- External Influence
  - Poor mechanical connections
  - Extreme operating temperature
  - Dig-ins, vandalism

Defect Creation → Void → E. Tree → Stress → E. Tree → Partial Discharge Activity → Failure

- DSD test pinpoints defective termination
- Owner did not repair
- Failure 4 mos. later
Typical PD Producing Defects in Extruded cables

- Torn insulation shield
- Electrical Tree
- Long Water Tree
- Vented Water Tree
- Vented
- Water Tree
- Electrical Tree
- Protrusion
- Crack
- Space Charge
- Erosion
- Chemical Change
- Effect of PD
- Shield Interruption
- Protrusion
- Torn Jacket/Insulation Shield
- Electrical Tree
- Electrical Tree
- Staple
Typical PD Producing Defects in Joints

- Knife cut
- Delamination
- Void in material
- Rough shield cut-back
- Gap near connector
- Voids and/or contamination
- Tracking
Typical PD Producing Defects in Terminations

- Knife cuts
- Rough Cut-back
- Misalignment

Irregular/ non-radial cut-back
Time scale greatly accelerated ~100 times (e.g. 175mils, 15kV class cable)
Worst case tree growth @3Uo @60Hz (120V/mil) is ~78mils/hour or 0.1mil/5sec test
What is a critical cable system?

Example Categories
- Life support
- 24x7 facilities
- Power generation
- Government facilities
- Military facilities
- Manufacturing facilities
- Transportation facilities
- Large public venues

Example Facilities
- Hospitals, elder care facilities
- Large IT, bio tech
- Nuclear, fossil, renewable
- Gov. buildings, DOE, DOD
- Army, Air force, Navy
- Injection mold, steel, IC chip
- Air & rail support facilities
- Stadiums, arenas
Question:
What is the typical economic impact of a critical cable system failure?

- $100k+
- $10k to $99k
- $5k to $9k
- <$5k
Critical Power Plant Case Study

Excerpt from client’s internal report

- All cable systems pass VLF AC HIPOT acceptance test
- Failure occurs during the first year of operation
- Estimated production lost = $156,212.00
- Emergency fault location labor cost = $44,670.00
- Emergency repair cost = $13,285.00
- Total Loss = $214,167.00
- DSD 50/60Hz off-line PD test performed, several additional cable insulation & accessory defects pinpointed
Case Study
Critical Industrial Plant

- 12 new 15kV cables installed
- DC HIPOT – all cable systems pass
- DSD 50/60Hz Off-line PD diagnostic
- Termination defect pinpointed per IEEE 48
- Stress control material accidentally misplaced
- Repair proven after successful retest
- Client says an outage > USD1 million
Question:

Which test can fail (detect) a higher percentage of cable system defects, a DC HIPOT or an AC HIPOT? (e.g. VLF HIPOT)
How long will massive workmanship defects last under a 2Uo AC HIPOT?

Knife Cut 1/3rd of Insulation Wall

>4 months

Cable Accessory Damage
IEEE 48, IEEE 404, and IEEE 386 Noncompliant

Poor Cleaning -Semicon Residue

Stress Control Misplaced

EPRI Estimation of Future Performance of Solid Dielectric Cable Accessories Report 1001725
What percent of cable defects can an VLF AC HIPOT fail (detect)?

- <5%
- <40%
- >70%
- >95%

What percent can a DC HIPOT fail? <1%
Critical Power Plant Cable System Case Study

- All systems pass VLF AC HIPOT
- 1\textsuperscript{st} failure on energization
- 2\textsuperscript{nd} failure within one year
- DSD PD Test performed
- Defects pinpointed: 1 cable, 1 splice & 10 terminations

In service failure 1
Termination contamination

In service failure 2
Cable damage
Critical Cable System Case Study

- All 12 terminations at substation determined to be defective by DSD
- E. contractor disagreed
- VLF AC HIPOT performed
- All cable systems passed
- Termination fails in 3 weeks time
- All repaired & retested
- Some terminations still did not pass IEEE standards
Critical Plant Case Study

- Client opted not to perform DSD test.
- All cables pass HIPOT commissioning test
- Experienced fault after five months
- Production loss & failure cost = $480K
- DSD 50/60Hz off-line PD tests performed
- Pinpoints additional cable defect & several termination defects
- No failures for 4 years since completion of repairs and successful retests
Question:

What is the likelihood of an on-line PD test detecting a cable defect?

- >95%
- >70%
- < 40%
- < 5%

Cable System 731

- 567 - NO PD in cable
- 164 - with PD in cable
- < 5% of cable defects w/PDIV ≤ 1 Uo
Critical Power Plant Cable System Case Study

- All systems pass DC HIPOT
- 9 failures in 3 yrs, >$300k
- All systems pass on-line PD test - 3 failures next yr.
- Total losses >$400k
- DSD PD Test performed
- Defects pinpointed 6 cable, 4 splice & 5 terminations
- After repairs & retests - no failures in 5 yrs.
Case Study
Critical Industrial Plant

- Cable systems routinely pass DC maintenance test
- **Plant historical avg. 1 cable failure/ 3 years**
- Fault records indicates mostly termination issues
- Off-line PD diagnostic test performed in 2000
- 40 repairs recommended
- **No failures since diagnostic & repairs 2000 (8 yrs)**
- Historical failure rate predicted 2 more failures

Plant A: Pareto Analysis

<table>
<thead>
<tr>
<th>Issue</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables Diagnosed (3 phase)</td>
<td>44</td>
</tr>
<tr>
<td>Termination Defects</td>
<td>40</td>
</tr>
<tr>
<td>Splice (joint) Defects</td>
<td>9</td>
</tr>
<tr>
<td>Cable segments recommended for replacement</td>
<td>3</td>
</tr>
</tbody>
</table>
2009 Selected Project Performance

Percentage of components **NOT** passing manufacturers’ standards
Critical Client Experience
2003-2009

- Failures after (no DSD)
  - DC HIPOT
  - VLF HIPOT
  - VLF Tangent Delta
  - On-line PD >150

- Defects pinpointed by DSD after other tests
  - ‘pass’ cable >403

- Failures after DSD 1*

*Based on over 20,000 tests; excluding post test damage such as dig-ins, thermal design issues
IEEE 400-2001
Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems

“If the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition”.

Cable defect was location matched within 6 inches on a 1400’ Cable
ANSI/ICEA S 97-682 Noncompliant
## Insulation Defect Defined by IEEE, ICEA, IEC & VDE Standards

### Standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Joints</th>
<th>Terminations</th>
<th>Separable Connectors</th>
<th>MV Cable</th>
<th>HV Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDE DIN</td>
<td>0278_629_1</td>
<td>0278_629_1</td>
<td>0278_629_1</td>
<td>0276_620</td>
<td>-</td>
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<tr>
<td>IEC</td>
<td>60502_4</td>
<td>60502_4</td>
<td>60502_4</td>
<td>60502_2</td>
<td>62067</td>
</tr>
</tbody>
</table>

### Thresholds

<table>
<thead>
<tr>
<th>Standard</th>
<th>Joints</th>
<th>Terminations</th>
<th>Separable Connectors</th>
<th>MV Cable</th>
<th>HV Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE/ICEA</td>
<td>&lt;3 pC @ ≥ 1.5Uo</td>
<td>&lt;5 pC @ ≥ 1.5xUo</td>
<td>&lt;3 pC @ ≥ 1.3xUo</td>
<td>&lt;5 pC @ ≥ 4.0xUo*</td>
<td>&lt;5 pC @ ≥ 2.0xUo</td>
</tr>
<tr>
<td>VDE DIN</td>
<td>&lt;10 pC @ ≥ 2.0Uo</td>
<td>&lt;10 pC @ ≥ 2.0xUo</td>
<td>&lt;10 pC @ ≥ 2.0xUo</td>
<td>&lt;2 pC @ ≥ 2.0xUo</td>
<td>-</td>
</tr>
<tr>
<td>IEC</td>
<td>&lt;10 pC @ ≥ 1.7Uo</td>
<td>&lt;10 pC @ ≥ 1.7xUo</td>
<td>&lt;10 pC @ ≥ 1.7xUo</td>
<td>&lt;10 pC @ ≥ 2.0/1.7xUo</td>
<td>&lt;10 pC @ ≥ 1.5Uo</td>
</tr>
</tbody>
</table>

- Uo is cable system’s voltage at **50/60Hz**
- All pC values are in **apparent charge**
- * actually 200V/mil (7.87kV/mm)
Design/Specification Best Practices

- Follow manufacturer standards: IEEE, ICEA, IEC
- Adequate neutral/metallic shield size ≥1/6, concentric wire
- Avoid cross-bonding
- Limit cable lengths to 8,500 ft.
- Minimize number of in-line joints (splices)
- Specify quality cable and accessories
- Specify joints with crimped neutral connector
- Off-line 50/60Hz PD Test on complete site & substation
- Specify No HIPOTs > Uo
- Termination preparation: Bag & tape, position & support
Summary

- 100’s of millions of dollars have been lost due to inept tests and cable system defects –primarily workmanship
- Modern cable systems fail by a process of erosion associated with PD (not conduction detected by a HIPOT)
- High Potential (HIPOT) (AC & DC) tests are destructive & do not assure reliability
- Repeating the manufacturers’ PD diagnostic test in the field is only way to assure insulation system design life
- The off-line 50/60Hz PD diagnostics (Defect Specific Diagnostics -DSD) is the only technology which can repeat the manufacturer's QC test in the field
- Where:
  - financial risk is significant
  - contractor warranties are involved
  - reliability is critical
  - significant assets need to be prioritized for replacement

DSD technology can assure cable system reliability at the lowest cost.