Study on Condition Monitoring Techniques for Low Voltage Electrical Cable

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Nuclear Engineering Ltd. Plant Service Division
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Cable Aging Issue

Cable Structure

Polymer Material: Ethylene-Propylene Rubber, Silicone Rubber, Cross-linked Polyethylene, Vinyl, etc.

Cable insulators gradually degrade due to heat and radiation under normal operating conditions.

⇒ If a design basis accident (inside CV) occurs when cables have degraded to some extent, the cables may lose its function as an insulator.

⇒ It is essential to monitor the condition of cable aging to verify its integrity.

Insulator: after removing sheath & conductor

As aging develops, a cable becomes harder and more brittle.
### Survey on CM Techniques: Primary Screening (29 techniques)

<table>
<thead>
<tr>
<th>Field</th>
<th>NDE</th>
<th>Monitoring</th>
<th>Destructive/Non destructive</th>
<th>CM Techniques</th>
<th>Status factor</th>
<th>Cable type (Relevant detected cables)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>Yes</td>
<td>Entire length</td>
<td>Non destructive</td>
<td>インデンターモジュラス (Indenter Modulus)</td>
<td>機械的指標</td>
<td>高圧ケーブル：EPR, SiR, PVC, XLPE, CSPE, Neoprene</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>表面硬度測定 (Surface Hardness Measurement)</td>
<td>機械的指標</td>
<td>必要</td>
<td>EPR, SiR, エラストマー</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>トルク測定 (Torque Measurement)</td>
<td>機械的指標</td>
<td>必要</td>
<td>全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>超音波診断 (Ultrasonic Diagnosis)</td>
<td>電気的指標</td>
<td>必要</td>
<td>EPR, PE, PVC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>マイクロ波診断 (Microwave Diagnosis, Microwave Absorption)</td>
<td>電気的指標</td>
<td>必要</td>
<td>XLPE, エラストマー</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>フーリエ変換赤外線分光法 (Fourier Transform Infrared Spectroscopy: FT-IR)</td>
<td>化学的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブル</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>レーザーラマン分光法 (Laser Raman Spectroscopy)</td>
<td>化学的指標</td>
<td>必要</td>
<td>ケーブル用途事例確認できず</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>光学診断 (変色): (Optical Diagnosis, Light Reflective Absorbance)</td>
<td>化学的指標</td>
<td>必要</td>
<td>XLPE (FR-XLPE), EPR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>赤外線サーモグラフィー (Infrared Thermography)</td>
<td>(温度)</td>
<td>不要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>照明付きポアスコープ (Illuminated Borescope)</td>
<td>(温度)</td>
<td>不要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>誘電損失 (Dielectric Loss - tan δ, cos δ)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>絶縁抵抗 (Insulation Resistance), 分極指數 (Polarization Index)</td>
<td>電気的指標</td>
<td>必要</td>
<td>熱継続損傷の懸念あり</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>AC 電圧耐圧試験 (AC Voltage Withstand Test)</td>
<td>電気的指標</td>
<td>必要</td>
<td>熱継続損傷の懸念あり</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>部分放電試験 (Partial Discharge Test)</td>
<td>電気的指標</td>
<td>必要</td>
<td>熱継続損傷の懸念あり</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>DC 高電圧試験 (High Potential Test)</td>
<td>電気的指標</td>
<td>必要</td>
<td>熱継続損傷の懸念あり</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>ステップ電圧試験 (Step Voltage Test)</td>
<td>電気的指標</td>
<td>必要</td>
<td>熱継続損傷の懸念あり</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>時間領域反射率測定 (Time Domain Reflectometry: TDR)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>周波数領域反射率測定 (Frequency Domain Reflectometry: FDR)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>時間-周波数領域反射率測定 (Joint time-frequency Domain Reflectometry: JTFDR)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>広帯域インピーダンス・スペクトロスコピー (Broadband Impedance Spectroscopy: BIS)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non destructive</td>
<td>伝送線路共鳴解析 (Line Resonance Analysis: LRA)</td>
<td>電気的指標</td>
<td>必要</td>
<td>低/中圧電気ケーブルの全種</td>
</tr>
</tbody>
</table>

- **備考**: 表中の○印は調査した文献中で取り上げられている技術 (本文に示す技術には種々のバリエーション/類似の技術があり、ここに示すものが全てではない)
## Survey on CM Techniques: Secondary Screening (abstract)

<table>
<thead>
<tr>
<th>CM Techniques</th>
<th>Applicability to NPP</th>
<th>Advantages</th>
<th>Problems</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indenter Modulus (IM)</td>
<td>applicable to EPR, SiR, PVC, XLPE</td>
<td>• detect embrittlement (elasticity) • easy measurement, trending is possible (ex. INSS prototype)</td>
<td>• not sufficiently applicable to PE series insulators • not applicable to insulators with sheath (depending on cable structures)</td>
<td>A</td>
</tr>
<tr>
<td>Surface Hardness Measurement</td>
<td>applicable to EPR, SiR</td>
<td></td>
<td>• large dispersion, low accuracy</td>
<td>C</td>
</tr>
<tr>
<td>Ultrasonic Diagnosis</td>
<td>applicable to EPR</td>
<td></td>
<td>• large dispersion, low accuracy</td>
<td>C</td>
</tr>
<tr>
<td>Fourier Transform Infrared Spectroscopy (FT-IR)</td>
<td>• detect embrittlement (changes in molecular binding) • easy measurement, trending is possible (Portable system has been developed.)</td>
<td></td>
<td>• limited information on surface • no cable data (limited to some PEs) • need much skill for spectrum analysis</td>
<td>B</td>
</tr>
<tr>
<td>Laser Raman Spectroscopy</td>
<td>• detect embrittlement (changes in molecular binding) • easy measurement, trending is possible (Portable system has been developed.)</td>
<td></td>
<td>• limited information on surface • not sensitive to carbonyl, no cable data • laser beam excites additives • need much skill for spectrum analysis</td>
<td>D</td>
</tr>
<tr>
<td>Time Domain Reflectometry (TDR)</td>
<td>• applicable to all insulation materials • location information on crack/failure/break/short circuit/branching/shave, etc. • commercially available • for judgment of acceptance, diagnosis</td>
<td></td>
<td>• not sensitive to embrittlement (detect crack, mechanical failure, etc.) • need much skill</td>
<td>C</td>
</tr>
</tbody>
</table>

EPR: Ethylene-propylene rubber  
SiR: Silicone rubber  
PVC: Polyvinyl chloride  
XLPE: Cross-linked polyethylene 
PE: Polyethylene

**Evaluation Ranking**  
A: applicable to field measurement, & trending is possible (data available)  
B: applicable to field measurement, but experience is very limited (no data)  
C: applicable to field measurement, but very difficult to improve accuracy  
D: under development / could damage cable material
Conventional Equipment $\Rightarrow$ stationary/not portable (large) = laboratory use

Conventional FT-IR cannot be used for CM of actual plant cables.

Except for the limited laboratory study, FT-IR has not been used for the measurement of various types of cable insulators.

Investigation has been started with the development of compact/portable FT-IR equipment.

A$_2$ Technologies (U.S.) has developed field-portable FT-IR.

$\Rightarrow$ Spec. satisfies NEL requirements.
Field-Portable FT-IR : EXOSCAN
(A_2 Technologies in U.S.)

Measurement Condition

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>4 cm(^{-1})</td>
</tr>
<tr>
<td>Cumulated Number</td>
<td>50 cycles</td>
</tr>
<tr>
<td>Measuring Method</td>
<td>Attenuated Total Reflection ATR Crystal : Diamond</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>4000(\sim)650 cm(^{-1})</td>
</tr>
</tbody>
</table>
Field-Portable IM : (INSS Prototype)

**Measurement Condition**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading at the start of measurement</td>
<td>1.5 N</td>
<td>1.0 N</td>
<td></td>
</tr>
<tr>
<td>Loading at the end of measurement</td>
<td>3.5 N</td>
<td>3.0 N</td>
<td></td>
</tr>
<tr>
<td>Indenter inserting speed</td>
<td>0.08 mm/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Shape of Indenter**
  - Shape : Frustum of a cone
  - Top Dia. : 0.79 φ (mm)

- EP : Ethylene-propylene
- FR : Flame-retardant
FT-IR Spectrum Analysis

Example

Peaks used for normalization in this report

before ageing

after ageing
FT-IR Blind Test Results: ACA Project

Correlation between Peak Area and EAB (% Elongation at Break)

**Peak Area [C=O+Additives]**

- **Maker C, FR-EP rubber**
  - R = 0.78
  - C=O + Add (1750 - 1520) / C-H

- **Maker B, FR-EP rubber**
  - No correlation

- **C社難燃EPゴム**
  - 黒芯
  - 白芯
  - 赤芯

**Peak Area [Carbonyl (C=O)]

- **Maker C, EP rubber**
  - R = 0.74

- **C社EPゴム**
  - 黒芯
  - 白芯
  - 赤芯

**Peak Area [Siloxane bond (Si-O)]

- **Maker C, Silicone rubber**
  - R = 0.77

- **C社シリコーンゴム**
  - 黒芯
  - 白芯
  - 赤芯
  - 緑芯

**Correlation between Peak Area [C=O] and EAB (%)**

- **Maker C, EP rubber**
  - R = 0.74

- **C社EPゴム**
  - 黒芯
  - 白芯
  - 赤芯

- **Maker B, EP rubber**
  - No correlation

- **C社難燃EPゴム**
  - 黒芯
  - 白芯
  - 赤芯

- **C社シリコーンゴム**
  - 黒芯
  - 白芯
  - 赤芯
  - 緑芯

**EAB (%)**

- **EAB (%)**
  - 500
  - 400
  - 300
  - 200
  - 100
  - 0

**Peak Area**

- **Peak Area**
  - 5
  - 4
  - 3
  - 2
  - 1
  - 0

- **Peak Area**
  - 0.20
  - 0.15
  - 0.10
  - 0.05
  - 0.00

- **Peak Area**
  - 30
  - 25
  - 20
  - 15
  - 10
  - 0
## Correlation between Measured Data and Ageing Time

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Insulation</th>
<th>Jacket</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material / Color</td>
<td>Ageing Method</td>
</tr>
<tr>
<td></td>
<td>Indenter</td>
<td>Thermal</td>
</tr>
<tr>
<td>Changzhou</td>
<td>EPR / Black</td>
<td>✓</td>
</tr>
<tr>
<td>Shanghai</td>
<td>XLPO / Black</td>
<td>✓</td>
</tr>
<tr>
<td>EUPEN</td>
<td>EPR / 4 Color</td>
<td>✓ (4 colors)</td>
</tr>
<tr>
<td>Rockbestos</td>
<td>XLPE / Gray</td>
<td>×</td>
</tr>
<tr>
<td>Habia</td>
<td>PEEK / Black &amp; Colorless</td>
<td>×</td>
</tr>
</tbody>
</table>

✓: Correlation between measured values and ageing time can be seen.

∆: Degradation products can be seen in a spectrum, but correlation with ageing time cannot be seen.

? : Need more data points to determine correlation.

×: No meaningful change with ageing time.
### Applicability of IM & FT-IR to CM Program

<table>
<thead>
<tr>
<th></th>
<th>Advantage</th>
<th>Weak Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IM (mechanical)</strong></td>
<td>・Applicable to almost all rubber type insulation material</td>
<td>・Poorly applicable to some type of XLPE insulation material</td>
</tr>
<tr>
<td><strong>FT-IR (chemical)</strong></td>
<td>・Applicable to most of rubber type insulation material ・Applicable to XLPE type insulation material</td>
<td>・Not applicable to some type of rubber insulation material</td>
</tr>
</tbody>
</table>

Mutually complementary relationship between IM & FT-IR

CM Program using IM & FT-IR could be practical in the field.