Smart Transformer for Smart Grid
– Intelligent Framework and Techniques for Power Transformer Asset Management

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Presentation Outline

1. Introduction
2. Research and Development Works
3. SmartBox – A Reconfigurable Platform for Smart Transformer
4. Conclusions
Introduction

Key Objectives:

• To develop online sensor based monitoring techniques to provide total visibility of transformer health condition.

• To develop data centric and machine learning techniques for automatic data processing, information extraction for transformer asset management.
Introduction

System Architecture:

Enterprise Resource Planning System
Transformer Condition Assessment

Data and Information Fusion

Transformation
Recognition
Extraction
De-noising

Historic Database
Field Inspection
Offline Measurements

Transformation
Recognition
Extraction
De-noising

Online Sensor Measurement 1

Historic Database
Field Inspection
Offline Measurements

Online Sensor Measurement n
Research & Development

- Statistical learning techniques for transformer condition assessment
- Signal processing techniques for online monitoring of transformers
- Paper insulation remaining life estimation
- Moisture estimation in transformer insulation
- Dielectric response measurement
- Field testing
Exploits the dependency between transformers’ conditions and measurements (DGA, PD, PDC, FDS) using historic datasets; and then evaluates the condition of transformer under investigation.

Dissolved Gas Analysis (DGA) Results Interpretation

Training dataset → Feature selection → Multiple Class Classification → Probability Computation → Model → Class Prediction

Testing dataset
### Statistical Learning Techniques

**Classification Results: IEEE/IEC scheme VS. Bayesian Classifier**

<table>
<thead>
<tr>
<th></th>
<th>IEEE / IEC Results</th>
<th>Probability of Each Class</th>
<th>Bayesian Classifier Results</th>
<th>On-site Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>NA*</td>
<td>[1.0, 0, 0, 0, 0, 0]</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>T2</td>
<td>NA*</td>
<td>[1.0, 0, 0, 0, 0, 0]</td>
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</tr>
<tr>
<td>T3</td>
<td>NA*</td>
<td>[0, 0.85, 0.15, 0, 0]</td>
<td>MT</td>
<td>DS</td>
</tr>
<tr>
<td>T4</td>
<td>NA*</td>
<td>[0.06, 0, 0.87, 0, 0.07]</td>
<td>MT</td>
<td>MT</td>
</tr>
<tr>
<td>T5</td>
<td>NA*</td>
<td>[0.01, 0, 0.57, 0.42, 0]</td>
<td>HT</td>
<td>HT</td>
</tr>
<tr>
<td>T6</td>
<td>NA*</td>
<td>[0, 0, 0.01, 0, 0.99]</td>
<td>PD</td>
<td>PD</td>
</tr>
<tr>
<td>T7</td>
<td>Normal</td>
<td>[1.0, 0, 0, 0, 0]</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>T8</td>
<td>Normal</td>
<td>[1.0, 0, 0, 0, 0]</td>
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<td>Normal</td>
</tr>
<tr>
<td>T9</td>
<td>DS</td>
<td>[0, 0.75, 0, 0.25, 0]</td>
<td>DS</td>
<td>DS</td>
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<tr>
<td>T10</td>
<td>MT</td>
<td>[0.49, 0, 0.51, 0, 0]</td>
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<td>MT</td>
</tr>
<tr>
<td>T11</td>
<td>PD</td>
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<tr>
<td>T12</td>
<td>HT</td>
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<tr>
<td>T13</td>
<td>Normal</td>
<td>[0, 0.06, 0.01, 0.93, 0]</td>
<td>HT</td>
<td>MT</td>
</tr>
<tr>
<td>T14</td>
<td>MT</td>
<td>[0, 0, 1, 0, 0]</td>
<td>MT</td>
<td>HT</td>
</tr>
<tr>
<td>T15</td>
<td>Normal</td>
<td>[0, 0, 0.01, 0.25, 0.74]</td>
<td>PD</td>
<td>PD</td>
</tr>
</tbody>
</table>

NA* refers no classification of IEEE/IEC due to missing code.

[Normal DS MT HT PD] is the probability of each class, DS - discharge, MT - lower/medium thermal fault, HT- high thermal fault, and PD - partial discharge.

**Probability output**: a certain degree of inaccuracy and uncertainty in data interpretation.

**T15**: high temperature thermal fault - 25% chance; PD – 74% chance.
Signal Processing Techniques

Advanced Signal Processing and Pattern Recognition Technique for Partial Discharge (PD) Monitoring and Diagnosis
Signal Processing Techniques

Signal Processing: PD signals de-noising

DWT – discrete wavelet transform
EMD – empirical mode decomposition
EEMD – ensemble EMD
Signal Processing Techniques

Multiple PD Sources Separation

(a) Top view

(b) Equivalent bandwidth vs. Equivalent time length

(c) Frequency sparsity vs. Time-sparsity roughness

(d) Amplitude vs. Phase angle

[Images of diagrams and graphs related to signal processing and PD sources separation]
Signal Processing Techniques

PD Sources Classification

(a) Floating discharge

(b) Corona discharge

Features:
- Mean
- Variance
- Skewness
- Kurtosis

Fingerprint

54% - internal discharge, 32% - surface discharge, 14% - corona
We are focusing on the Kraft paper insulation within a transformer. During operation this paper slowly degrades to a point when it has reached its end of life.

Lelekakis, Martin, Wijaya, *Ageing rate of paper insulation used in power transformers, Parts 1 and 2*, IEEE Transactions on Dielectrics and Electrical Insulation, 2012.
Testing

Three test transformers were set up. Using temperature and WCP their fall in paper DP was modelled, and can be seen to closely match measured values.
Life remaining

The fall in DP can also be plotted as life remaining (where end of life is DP=200).

Blue and trace is using the existing IEEE standard. Insulation can be seen to degrade far faster when oxygen and water are present. Setting oxygen and water to low values in our model gives close alignment with the IEEE one.
Insulation water content

• Because the life expectancy model needs water content of paper, techniques to measure this were investigated.
EXISTING METHODS

• Sensors mounted in pipe at bottom

• Hard to see how the water content of paper can be calculated if the temperature of the paper is not known. A probe mounted at the top is better because there will be a smaller temperature gradient.

• Some devices give water content of oil in ppm, which brings inaccuracy because the equation used does not reflect all oils or all ages.
Dielectric Response Measurement

Frequency Domain Spectroscopy (FDS) Measurements

• Measures capacitance and dielectric losses of transformer insulation at different frequencies

• Condition monitoring of transformers
  ➢ Estimating moisture content in transformer insulation
  ➢ Estimating oil conductivity

Typical FDS response of oil-paper insulation system in of transformer.
Dielectric Response Measurement

Frequency Domain Spectroscopy (FDS) Measurements

Thermal transient effect needs to be considered for properly interpreting dielectric response measurement.
FIELD TESTING: THE FOLLOWING TRANSFORMERS WERE USED
EXAMPLE OUTPUT OF MODEL

Temperature measured by water activity probes

- **Winding temperature calculated from load**
  - Load
  - Top winding temperature

- **Calculated water content of paper insulation**
  - Corrected for winding temperature gradient
  - No temperature correction

- **Temperature measured by water activity probes**
  - Oil at top of tank

- **Measured water activity**
  - Oil at top of tank

- **Water content of paper**
  - Trend line
## Results

<table>
<thead>
<tr>
<th></th>
<th>Tr1</th>
<th>Tr2</th>
<th>Tr3</th>
<th>Tr4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit description</strong></td>
<td>12.5</td>
<td>12.5</td>
<td>25</td>
<td>225/375</td>
</tr>
<tr>
<td>(MVA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Age on test</strong></td>
<td>33</td>
<td>33</td>
<td>29</td>
<td>7</td>
</tr>
<tr>
<td>(years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water content measured</strong></td>
<td>3.9</td>
<td>3.0(^1) – 3.6(^2)</td>
<td>3.7</td>
<td>0.3</td>
</tr>
<tr>
<td>using dielectric response</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water content measured</strong></td>
<td>3.8</td>
<td>3.7</td>
<td>2.7 – 2.9</td>
<td>0.4</td>
</tr>
<tr>
<td>using UQ algorithm and</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water activity sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SmartBox Development

SmartBox: reconfigurable hardware/software platform

1. HFCT - high frequency current transducer
2. AE sensor – acoustic emission sensor
3. Online moisture sensor
SmartBox Development

SmartBox: Functional Components

- PDC
- FDS
- DGA/Oil
- FRA
- Others
  - **Offline Measurement**

- PD
- Acoustic
  - **Online sensor measurement (with DSP and PR)**

- Moisture
- Temperature
- Current etc.
  - **Online sensor measurement**

SQL DB

Diagnosis Console

Real-time DB

Substation Automation
IEC 61850
SmartBox Development

SmartBox: Software Platform - Multi-Agent System

Transformer Health Management Agent

Transformer Diagnosis Decision Fusion Agent

Support vector Machine Agent

Clustering Algorithm Agent

Rule Base Induction Agent

Time Series Analysis Agent

Feature Extraction Agent

Front end Processing Agent

Historic Data, Offline Tests, Expert Knowledge Retrieval Agent

Sensors
Conclusions

• Transformer is a complex system requires a comprehensive solution of condition monitoring and assessment.

• Developed a number of techniques for condition monitoring and assessment of transformers.

• Developed a re-configurable hardware and software platform (SmartBox) for deploying various techniques for condition assessment.
Thank you!

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