On-line PD Monitoring Applications

Motors
Generators
Switchgear
Cables
Transformers
Failure Statistics

Australia & New Zealand

10 Years of Data
457 Failures

Percent - %

Windings, Winding Accessories, Core, Tap Changer, Motor Drive Parts, Bushings, Cooling, Other
Failure Statistics

Eskom

136 Severe Failures
1996 - 2006

- Windings
- Core
- Tap Changer
- Main Tank & Oil System
- Bushings
- Auxiliaries
- Others
Failure Statistics

Canadian Electricity Association

Forced Outages
1997 - 2006

Percent - %

Bushings  Windings  OLTC  Core  Leads  Cooling  Auxiliaries  Other
Failure Statistics

Doble Engineering

1993 - 1998

Bushings, Tap Changer, Tank and Oil, Core, Winding, Other
Failure Statistics

Bushing Monitoring
- Power Factor
- Capacitance
- Partial Discharge

$\Delta T$
- Partial Discharge
- Operations Counters
- Contact Wear
- Control Monitoring

DGA
- Moisture in Oil
- Oil Dielectric
- Partial Discharge
- Leakage
- Reactance
- Online FRA

Cooling System Monitoring
- Fan Current
- Control Failure

Combined Regrouped Data
Issues With Time Based Maintenance

- Time between outages extended
- Many failure modes happen quickly (days, weeks, months)
- Off-line tests cannot simulate actual operating conditions (temperature, voltage, load, mechanical)
- Historical data not sufficient to make a good decision
- Less thorough maintenance
- Can introduce new failure mechanisms
Time to Failure

- Very Difficult to Predict / Forecast
- Studies have shown
  - 80% of all failures are random in nature
  - 20% age related
- If this is true, then current maintenance practices are not all that effective
Time To Failure

- Good Bill of Health
  - Only means there is no clue as to the unit will fail
- Easier to Predict when Failure is imminent
  - Advanced stages of deterioration
- The only true way to capture impending failure is to monitor continuously
Transformer Bushing Monitoring
# Bushing failure statistics

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in C1 Power Factor/Capacitance</td>
<td>53.0%</td>
</tr>
<tr>
<td>Change in C2 Power Factor</td>
<td>7.4%</td>
</tr>
<tr>
<td>Service Advisory</td>
<td>3.4%</td>
</tr>
<tr>
<td>Problems with Taps</td>
<td>2.8%</td>
</tr>
<tr>
<td>Moisture Ingress</td>
<td>2.8%</td>
</tr>
<tr>
<td>Infra-Red Scan</td>
<td>1.9%</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>1.4%</td>
</tr>
<tr>
<td>Other</td>
<td>27.3%</td>
</tr>
</tbody>
</table>

- **Violent**: 52.3%
- **Non-violent**: 47.7%
Facts

- Bushing Failed in June 2001
- Passed Doble testing in Oct 1998
- Investigation confirmed a dielectric failure with a paper insulation puncture through the center draw rod area
  - About 1/3 of the way down from the top terminal

Photos furnished by BC Hydro
Two Capacitances

- C1
- C2
- C1 can be measured On Line
Sensor connects to bushing tap
Transformer Partial Discharge Monitoring
PD is a leading indicator of insulation breakdown.

The higher the voltage the more destructive the activity.

Phenomena that only occurs at higher AC voltages (> 2,000 V). Prefer 3 kV and higher.
Definition - PD

A Localized Electrical Discharge in an Insulation System that does not completely bridge the Electrodes.

Phase to Phase
Phase to Ground
Acoustic Sensors
UHF Type of Sensors
Direct electrical
Key Element on Direct Connection - Bushing Protection

- Bushing are normally grounded at the tap.
- When monitoring, the bushing are now grounded at the instrumentation.
- If ground connection is lost or wire is cut, this can cause a large voltage to build up at the tap and cause a failure.
Not All Bushing Sensors are Equal

- Basically two common types of Sensors
  - Capacitive
  - Resistive

- Protection Elements to Consider
  - Surge Protection
  - Open Circuit protection
  - Possible Fail Safe Circuit
PD Pulse Characteristics

- Generates a High frequency Pulse
  - Rise Time 1 nS to tens of nS
  - Pulse width 1 nS to few hundred nS
  - Frequency Range 0 – 10’s of GHz
  - Usually measured in pC or mV
PD Quantities

- **PD Magnitude (mV or pC)**
  - Size or the volume of the defect
- **Pulse Count (PPS)**
  - Number or Growth of defects
- **PD Intensity/Power (mW)**
  - Destructive Power of the PD events
- **PD Signature**
  - Phase of the Defect
  - Type of Defect
Phase Resolved Data

- Phase to Ground
- Phase to Phase
- PD Signature
## Two methods of PD detection

<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acoustic</strong></td>
<td>• Easy to install – External on tank</td>
<td>• Low Sensitivity</td>
</tr>
<tr>
<td><strong>Piezo accelerometer on tank</strong></td>
<td>• Most common on Transformers today</td>
<td>• Depends where defect is located and internal design of transformer</td>
</tr>
<tr>
<td></td>
<td>• Usually can get pulse repetition rate and trend</td>
<td>• Does respond to rain, sleet and other possible disturbances</td>
</tr>
<tr>
<td></td>
<td>• Not susceptible to external electrical noise</td>
<td>• Very Time Consuming</td>
</tr>
<tr>
<td></td>
<td>• Possible location of defect</td>
<td></td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td>• High sensitivity</td>
<td>• Need Outage to install sensors</td>
</tr>
<tr>
<td><strong>Sensor connected to bushing taps</strong></td>
<td>• Can be calibrated in terms of apparent charge</td>
<td>• Sensitive to external electrical noise</td>
</tr>
<tr>
<td></td>
<td>• Approximate location of PD source</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Use of pattern/signature recognition</td>
<td></td>
</tr>
</tbody>
</table>
PD/sparking in transformers

- Will produce gases

- How fast?
  - Depends on size & type of defect
  - Location of defect
  - Temperature at defect
  - Volume of oil
  - Transformer design

- Will range from days to ….
pC levels for insulation

<table>
<thead>
<tr>
<th>Description</th>
<th>pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Free</td>
<td>10 - 50</td>
</tr>
<tr>
<td>Normal deterioration</td>
<td>&lt; 300 - 500</td>
</tr>
<tr>
<td>Developing Defects (Irreversible damage to paper)</td>
<td>1,000 – 3,000</td>
</tr>
<tr>
<td>Breakdown of Oil Gap</td>
<td>10,000 – 100,000</td>
</tr>
</tbody>
</table>
Example of discharge on transformer barrier

Creeping discharge within Pressboard barrier

Discharge in excess of 10,000 pC
External Noise

- Especially on Transformers
  - Floating Potentials
    - Loose bus Insulators
    - Sparking Static Shields
  - Loose Ground connections
  - Radio Transmissions
  - Corona
- Cross Coupled Signals
Noise Cancellation

- This is a key item for in-field / continuous monitoring measurements
- Factories can control noise
- Can not do that in the Field
  - Corona
  - Loose support insulators
  - Radio Stations,
  - Etc.
Noise Cancellation Methods

- Pulse Shape Analysis
- Gating
- Notch Filters
- Pulse Direction
- Pulse Patterns
Pulse Direction is Key

- One needs to determine if the measured signal is coming from
  - Inside the transformer
  - External to the transformer.

- Allows this to be an active system
  - Conditions change
Noise Cancellation

- Time of arrival
- Compares Time of Pulses to reach instrument
Pulse Polarity

- Pulse Polarity (To determine direction)
  - Uses two types of Sensors
    - One Capacitive
    - One Inductive
Pulse Polarity Very Practical Solution

- Bushing Sensor – Capacitive Element
- Rogowski Coil – Inductive Element
Pulse Direction Determination
Case Study 1

- 500 kV – 230 kV, 3 phase transformer
- No Outage
- Only RFCTs on neutral connection and tank ground
Case Study 2

- 500 kV - 3 phase tank
- 6 bushing sensors
- 6 Rogowski Coils
- RFCT on Neutral
- Bushing Monitoring
- PD Monitoring
Case 2 Installation
PD Trends
DGA Results
Case 2 Phase Resolved Data

![Signal](image1)

![Noise](image2)
Bushing Monitoring
Bushing Monitoring
Case 3

- 500 kV – 230 kV - 3 Single Phase Transformers
- 6 Bushing Sensors
- 6 Rogowski Coils
- 4 Acoustic PD sensors per phase
- RFCT on Neutral
- RFCT – Core Ground
- Power Frequency CT On Core Ground
Case 3 Installation
Case 3 – Core Ground Current
Case 3 Bushing Data
Case 3 Bushing Data
Case 3 Acoustic PD
Case 3 Electrical PD
Case 3 Electrical PD
Case 3 Phase Resolved Data
Substation
BAU and Rogowski Coil
Core Ground Current and RFCT
Top and side Aux. Boxes
Acoustic and Load Current Aux. CT
Before and After Pulse Polarity Detection Turned On
Another Recent Install - Indonesia
Another Recent Install
110 kV HVCT’s
# DGA and Tan $\Delta$

<table>
<thead>
<tr>
<th>Phase</th>
<th>R</th>
<th>Y</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>% PF – 10 kV</td>
<td>.891</td>
<td>12.17</td>
<td>2.05</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>639</td>
<td>567</td>
<td>595</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>113</td>
<td>19,432</td>
<td>595</td>
</tr>
<tr>
<td>Methane</td>
<td>5</td>
<td>12,637</td>
<td>595</td>
</tr>
<tr>
<td>Ethane</td>
<td>3</td>
<td>2,234</td>
<td>595</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3</td>
<td>21</td>
<td>595</td>
</tr>
<tr>
<td>Acetylene</td>
<td>1</td>
<td>1</td>
<td>595</td>
</tr>
<tr>
<td>CO2</td>
<td>401</td>
<td>251</td>
<td>595</td>
</tr>
</tbody>
</table>
Bushing Monitoring

- Can see the Power Factor is changing on two of the bushings.
Second Location

<table>
<thead>
<tr>
<th>Phase</th>
<th>R</th>
<th>Y</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>% PF – 10 kV</td>
<td>4.041</td>
<td>3.302</td>
<td>2.610</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>341</td>
<td>350</td>
<td>329</td>
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<tr>
<td>Hydrogen</td>
<td>12024</td>
<td>18714</td>
<td>15881</td>
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<tr>
<td>Methane</td>
<td>9400</td>
<td>11524</td>
<td>8216</td>
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<td>Ethane</td>
<td>7214</td>
<td>2675</td>
<td>1852</td>
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<tr>
<td>Ethylene</td>
<td>20667</td>
<td>224</td>
<td>.01</td>
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<tr>
<td>Acetylene</td>
<td>87</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>CO2</td>
<td>236</td>
<td>260</td>
<td>140</td>
</tr>
</tbody>
</table>

Circled areas are noise – Floating Potentials
2 hour Period – No bushing monitoring performed
## Third Location

<table>
<thead>
<tr>
<th>Phase</th>
<th>R</th>
<th>Y</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>% PF – 10 kV</td>
<td>31.48</td>
<td>28.33</td>
<td>14.45</td>
</tr>
<tr>
<td>Capacitance (pF)</td>
<td>511</td>
<td>485</td>
<td>542</td>
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<tr>
<td>Hydrogen</td>
<td>6</td>
<td>6</td>
<td>4</td>
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<td>Methane</td>
<td>6</td>
<td>4</td>
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<td>Ethylene</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Acetylene</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CO2</td>
<td>668</td>
<td>356</td>
<td>356</td>
</tr>
</tbody>
</table>

Little to No PD – Mostly Noise

2 hour Period – No bushing monitoring performed
Transformer Applications

- Transmission
- Distribution
- GSU
- Generator / Bus Duct / GSU

Only supplier that can offer a single solution
Transmission Transformer
GSU
Diagnostic Transformer Monitor (DTM)
Standalone System With Acoustic PD Module
Integrated Bushing and PD Modules
## Partial Discharge Monitor

**Device Status:** OK

**Alarm Status:** Warning

**Alarm Cause:** Maximum amplitude

### Last Measurement: Sep 7, 2009 | 11:41

<table>
<thead>
<tr>
<th>Channel</th>
<th>pC</th>
<th>Q (mV)</th>
<th>PD Intensity (mW)</th>
<th>Pulse Count (PPS)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>810</td>
<td>81</td>
<td>74</td>
<td>19187</td>
<td>Active</td>
</tr>
<tr>
<td>2</td>
<td>1050</td>
<td>105</td>
<td>81</td>
<td>16450</td>
<td>Active</td>
</tr>
<tr>
<td>3</td>
<td>1050</td>
<td>105</td>
<td>84</td>
<td>16455</td>
<td>Active</td>
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<tr>
<td>4</td>
<td>1050</td>
<td>105</td>
<td>83</td>
<td>15791</td>
<td>Active</td>
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<tr>
<td>5</td>
<td>1050</td>
<td>105</td>
<td>80</td>
<td>15594</td>
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<td>1050</td>
<td>105</td>
<td>70</td>
<td>14424</td>
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<td>0</td>
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<td>0</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>InActive</td>
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</table>