Limits of off-line PD measurement to assess quality and condition of HV insulation windings for rotating machines

Werner Ladstätter, Insucon May 2017
Accident in power plant Rodund II / Austria in 2009
Predictive maintenance and residual life time calculation

Total degree of utilisation for critical regions

- Service life time: 40 years
- 5 Start/Stop cycles per day
- 1 load rejection / month

Residual life time prediction of a HV winding
Residual life time of high voltage windings

Statistics of hydro generator failures

Statistic was made in 7 countries with 1199 Hydro generators

Failures are if generator

> 10 MVA

> 10 days outage

> 10 years in operation

Source: Cigre Working Group A1.10
„Survey of Hydro generator Failures“
Residual life time of high voltage windings
Investigations of a 45 Years Old Winding

Fast rotating generator for a storage hydro power plant

- 45 years in operation
- 160,000 operating hours
- 11,000 Starts & Stops
- Rated Voltage 12.5 kV
- Load 100 MVA
- Insulation System
  - Press-Cured Epoxy System
- Very high PD values
Residual life time of high voltage windings
Investigations of a 45 Years Old Winding

Test sequence:
- Diagnostic and destructive tests
  - Detailed PD analysis
  - DC ramp test
  - Scan of stator bore with TVA probe
  - AC VET on installed winding until breakdown
  - PRPD measurement

Goals:
- Estimation regarding possibilities and limits for prediction of residual life time of old stator windings!
- Detection of “weakest point” and correlation between breakdown and PD level of TVA scan
- Detection of any PD activities short before breakdown (PRPD pattern)
Residual life time of high voltage windings

Investigations of a 45 Years Old Winding

Gamut

Intensity [PD/s]

<table>
<thead>
<tr>
<th>Main</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>QIEC</td>
</tr>
<tr>
<td>V</td>
<td>59.74 nC</td>
</tr>
</tbody>
</table>

Freq. integration at 200 kHz ± 150 kHz from: 59 kHz to: 350 kHz
33.761 PDs in 30.01 s

Gated Percentage
static: 0%
static partial: 0%
dynamic: 0%

IEC 60270 status
conforming, Calibrated 11-SEP-2013 18:11:36.5

U1 V W:
- U/√2
- 12.60 kV
- V RMS
- 12.62 kV
- f
- 50.01 Hz

OMICRON
Residual life time of high voltage windings
Investigations of a 45 Years Old Winding

DC Ramp Test up to 32 kV DC performed before AC HIPOT Test

- Absolute normal behaviour up to 1.5 x 1.7 Un
- No signs for serious insulation defects of a looming breakdown recognizable

Charging current / UVW on HV
Ramp Rate: 2.5 kV / min.
Residual life time of high voltage windings

TVA Probe / Scanning of Stator Bore at $U_n = 12.5$ kV

<table>
<thead>
<tr>
<th>Location/Slot where breakdown occurred</th>
<th>Bottom (06:00)</th>
<th>Top (12:00)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very Low TVA level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Medium TVA level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Very high TVA level</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Location/Slot where breakdown occurred
Residual life time of high voltage windings

Breakdown statistic after 20 hours at 1.5 \( U_n \) (18.75kV)

- Two very critical bars
- Two bars with “appropriate” residual life time
- All 4 - top bars (no bottom)
- 284 bars with relatively good residual life expectancy for sufficient operational reliability
Residual life time of high voltage windings

PRPD Pattern / PD Scanning up to breakdown

- No significant change of PD pattern before breakdown
- PD activity was continuous monitored over the whole test duration of 20.5 hours
- At all other 3 breakdowns – not any indication of breakdown by PRPD recognizable
- Even if the weak point is close to the line end (as in this case) there was no indication by PRPD measurement
Investigation on new bars
Investigation on new bars

Bar selection and test set up

New bar production for a large hydro generator
- Power output: > 350 MVA
- Voltage: 18 kV
- Electrical field strength: 2.93 kV/mm
- Total bar number: > 800

Bar selection
- 6 bars with lowest PD value
- 6 bars with medium PD value
- 5 bars with highest PD value
Investigation on new bars
Dielectric test at new stage

Standardised PD values (1000 – 4000 pC) according Q\textsubscript{IEC}

<table>
<thead>
<tr>
<th>bar no.</th>
<th>at U\textsubscript{N}</th>
<th>at 2 U\textsubscript{N}</th>
<th>bar no.</th>
<th>at U\textsubscript{N}</th>
<th>at 2 U\textsubscript{N}</th>
<th>bar no.</th>
<th>at U\textsubscript{N}</th>
<th>at 2 U\textsubscript{N}</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>2.3%</td>
<td>13.9%</td>
<td>211</td>
<td>4.2%</td>
<td>12.1%</td>
<td>192</td>
<td>5.6%</td>
<td>32.8%</td>
</tr>
<tr>
<td>68</td>
<td>2.4%</td>
<td>10.4%</td>
<td>352</td>
<td>4.5%</td>
<td>14.8%</td>
<td>291</td>
<td>5.7%</td>
<td>18.5%</td>
</tr>
<tr>
<td>329</td>
<td>3.0%</td>
<td>18.9%</td>
<td>304</td>
<td>4.5%</td>
<td>13.6%</td>
<td>75</td>
<td>6.0%</td>
<td>21.6%</td>
</tr>
<tr>
<td>269</td>
<td>3.5%</td>
<td>14.8%</td>
<td>98</td>
<td>4.6%</td>
<td>19.1%</td>
<td>141</td>
<td>6.4%</td>
<td>15.2%</td>
</tr>
<tr>
<td>271</td>
<td>3.6%</td>
<td>28.8%</td>
<td>225</td>
<td>5.3%</td>
<td>44.0%</td>
<td>306</td>
<td>19.1%</td>
<td>26.6%</td>
</tr>
<tr>
<td>309</td>
<td>3.9%</td>
<td>18.7%</td>
<td>227</td>
<td>5.4%</td>
<td>19.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dissipation factor in ‰

<table>
<thead>
<tr>
<th>bar no.</th>
<th>tan(\delta) at 0.2 U\textsubscript{N}</th>
<th>(\Delta) tan(\delta) / 2 at (0.6 U\textsubscript{N} - 0.2 U\textsubscript{N})</th>
<th>bar no.</th>
<th>tan(\delta) at 0.2 U\textsubscript{N}</th>
<th>(\Delta) tan(\delta) / 2 at (0.6 U\textsubscript{N} - 0.2 U\textsubscript{N})</th>
<th>bar no.</th>
<th>tan(\delta) at 0.2 U\textsubscript{N}</th>
<th>(\Delta) tan(\delta) / 2 at (0.6 U\textsubscript{N} - 0.2 U\textsubscript{N})</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>6.40</td>
<td>0.10</td>
<td>211</td>
<td>6.50</td>
<td>0.05</td>
<td>192</td>
<td>7.10</td>
<td>0.05</td>
</tr>
<tr>
<td>68</td>
<td>8.10</td>
<td>0.10</td>
<td>352</td>
<td>7.10</td>
<td>0.10</td>
<td>291</td>
<td>6.00</td>
<td>0.20</td>
</tr>
<tr>
<td>329</td>
<td>6.00</td>
<td>0.05</td>
<td>304</td>
<td>6.50</td>
<td>0.05</td>
<td>75</td>
<td>8.70</td>
<td>0.30</td>
</tr>
<tr>
<td>269</td>
<td>6.90</td>
<td>0.10</td>
<td>98</td>
<td>6.80</td>
<td>0.05</td>
<td>141</td>
<td>6.70</td>
<td>0.05</td>
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<tr>
<td>271</td>
<td>4.70</td>
<td>0.10</td>
<td>225</td>
<td>7.70</td>
<td>0.05</td>
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<td>6.70</td>
<td>0.15</td>
</tr>
<tr>
<td>309</td>
<td>7.30</td>
<td>0.05</td>
<td>227</td>
<td>7.90</td>
<td>0.10</td>
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</tr>
</tbody>
</table>
### Standardised PD values before and after thermal cycling according Q\textsubscript{IEC}

<table>
<thead>
<tr>
<th>status of measurement</th>
<th>PD range</th>
<th>bar no.</th>
<th>at (U_N)</th>
<th>at 2 (U_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>before cycling</td>
<td>low</td>
<td>37</td>
<td>2.3%</td>
<td>13.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>329</td>
<td>3.0%</td>
<td>18.9%</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>304</td>
<td>4.5%</td>
<td>13.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98</td>
<td>4.6%</td>
<td>19.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>227</td>
<td>5.4%</td>
<td>19.1%</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>192</td>
<td>5.6%</td>
<td>32.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>141</td>
<td>6.4%</td>
<td>15.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>306</td>
<td>19.1%</td>
<td>26.6%</td>
</tr>
<tr>
<td>after cycling</td>
<td>low</td>
<td>37</td>
<td>13.0%</td>
<td>14.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>329</td>
<td>14.8%</td>
<td>22.9%</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>304</td>
<td>21.8%</td>
<td>31.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98</td>
<td>7.4%</td>
<td>16.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>227</td>
<td>5.5%</td>
<td>12.6%</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>192</td>
<td>21.3%</td>
<td>20.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>141</td>
<td>12.0%</td>
<td>12.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>306</td>
<td>17.9%</td>
<td>14.0%</td>
</tr>
</tbody>
</table>

- PD values at \(U_N\) and before TC are recognisable lower
- High voltage system appears as TC and 2*\(U_N\) resistant
Investigation on new bars
Ageing via VET

Correlation between standardised PD level and voltage endurance at 2.17 \( U_N \)

- No correlation of PD values at \( U_N \)
- No difference if bars are thermo-cycled of PD values at \( U_N \)
- No difference if bars are thermo-cycled of PD values at \( 2*U_N \)
Investigation on new bars
Residual life time after thermal and electrical ageing

Standardised PD values according $Q_{\text{IEC}}$ after ageing for 2400 h at 2.17 Un

<table>
<thead>
<tr>
<th>low</th>
<th>medium</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>bar no.</td>
<td>at $U_N$</td>
<td>at 2 $U_N$</td>
</tr>
<tr>
<td>37</td>
<td>417%</td>
<td>837%</td>
</tr>
<tr>
<td>68</td>
<td>21%</td>
<td>50%</td>
</tr>
<tr>
<td>329</td>
<td>294%</td>
<td>564%</td>
</tr>
<tr>
<td>269</td>
<td></td>
<td></td>
</tr>
<tr>
<td>271</td>
<td>19%</td>
<td>47%</td>
</tr>
<tr>
<td>309</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All 8 TC bars survived 2400 h in the VET
- PD values for TC bars are remarkable higher

Correlation between standardised PD levels and residual life time aged at 2.17 $U_N$ after pre-ageing of 2400 h at 2.17 $U_N$

- No correlation of TC bars
- Long residual life time for 83% of all bars
Residual life time of high voltage windings

Summary

- Even slot resolved local PD measurement (TVA probe) could not reveal any correlation between PD level and residual life time for a 45 year old hydro generator.
- If 4 weakest bars could have been detected and removed more than 10 years of operation is statistically possible, but no state of the art detection method available.
- A simple low, medium and risky winding judgement based on PD levels seems OK.
- PD levels after new bar production do not give any correlation to thermal and electrical lifetime.
- TC in laboratory and temperature in operation increase the average VE life time.
- Residual life time estimation (based on PD) after 2400 h VE and 500 TC is not possible with new bars from production – same as for old bars after 45 years of real operation.

- Andritz Hydro will continue to find a way to estimate better residual life of HV windings.
- Request to RR and other VPI manufactures to start a similar investigation for comparison.