Preamble

Why/How did this happen?
Outline of the presentation

- Introduction to Transformer Bushings
- What Causes A Transformer Bushing to Fail?
  - Impact of bushing design and construction
  - Impact of unusual in-service conditions
  - Impact of bushing selection
- Bushing Failure Mechanisms and Failure Modes
- Learning from Transformer Bushing Failure Investigation
- How to Prevent Transformer Bushing Failure?
  - Ageing indicators and diagnostics
- Conclusions
Introduction to Transformer Bushings

Bushing Standards:

Much like bridges on the motorway, bushings provide a point of interface such that electrical current can pass to and from a transformer without the passage of excess current to ground. They are very critical and the weakest link.
Introduction to Transformer Bushings

They are usually highly reliable... here is a good example of

Three 275kV Bushings after More Than 50 Years!
Introduction to Transformer Bushings

But, when a fault develops and/or its operational conditions change…

the high voltage bushing can fail quickly!
Introduction to Transformer Bushings

Cigré WG A2.43 (2010) Transformer Bushing Reliability
Bushings cause from 5 to 50%, or in average, one quarter of the total number of transformer failures.

Cigré WG A2.37 (2012) Transformer Failure International Survey

- Bushing failures contribute significantly to failure statistics of power transformers, approximately \(17\%\) for substation transformers and \(14\%\) for GSU transformers.
- For the reported 115 bushing failures during 1996-2010, \(30\%\) of transformer bushing failures had fire and around \(10\%\) of these bushing failures had the porcelain exploded.
Introduction to Transformer Bushings

Doble Bushing Survey 1989-1998

Total 939 bushings destroyed in failures, and more than 30% was violent…
So, What Causes A Transformer Bushing to Fail?

The transformer bushings are normally exposed to a variety of dielectric, thermal and mechanical stresses. The condition of the bushings deteriorates gradually right from the start, resulting in

- Reduction in dielectric strength;
- Reduction in thermal integrity;
- Reduction in mechanical strength.

**Failure occurs when the insulation system is no longer able to withstand the stresses imposed on it during operation.**
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

In order to interpret why they fail and how they may fail it is essential to understand how transformer bushings are designed and manufactured.

**IEC 60137 (2008)**

‘Bushing is a device that enables one or several conductors to pass through a partition such as a wall or a tank, and insulates the conductors from it’.
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

Two Key Parts for any bushing:
- **Insulation System** (to prevent a failure mode of over-voltage)
- **Conductor Path** (to prevent a failure mode of over-current)
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

**Capacitor/Condenser Type:**
- ✓ RBP  Resin Bonded Paper (Since 1910s)
- ✓ OIP  Oil Impregnated Paper (Since 1950s)
- ✓ RIP  Resin Impregnated Paper (Since 1960s)
- ✓ RIS  Resin-Impregnated Synthetics (Since 2010s)

**Non-Condenser Type:**
- ✓ Solid
- ✓ Alternate Layers of Solid and Liquid Insulation
- ✓ Gas-Filled
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

<table>
<thead>
<tr>
<th>OIP</th>
<th>RIP</th>
<th>RIS</th>
</tr>
</thead>
</table>
| • Excellent PD  
• Cost effective  
• Overloading capability  
• BUT... |
| • Excellent PD  
• Much safer – no explosion risk  
• Less maintenance  
• BUT... |
| • Same excellent safety & less maintenance  
• Excellent PD  
• Best possible moisture performance  
• Shorter manufacturing time  
• BUT...  
• Less overloading capability  
• Only available up to 170 kV |
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

<table>
<thead>
<tr>
<th>Unusual Service Conditions</th>
<th>Unusual Environmental Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperatures greater than a maximum of 40°C with a 24 hour average of 30°C</td>
<td>Damaging fumes or vapors, Excessive abrasive or semi-conductive dust, Explosive mixtures of dust or gases</td>
</tr>
<tr>
<td>Ambient temperatures lower than -30°C</td>
<td>Stem, salt spray or wet conditions</td>
</tr>
<tr>
<td>Altitudes greater than 1000 meters</td>
<td>Low or moderate or high seismic zone</td>
</tr>
</tbody>
</table>

Both the unusual environmental factors and the in-service conditions may influence the electrical performance of the transformer bushings. - IEEE C57.19.00 (2004)
So, What Causes A Transformer Bushing to Fail?

- Impact of bushing design and construction
- Impact of unusual in-service conditions
- Impact of bushing selection

Reduce the likelihood of making an inappropriate bushing selection---the selected bushing’s BIL ≥ The winding’s BIL; the nameplate rating must be at least 15% above the maximum rated through current of each transformer winding. - IEEE C57.19.00 (2004)
Bushing Failure Mechanisms

- Common Bushing Failure Mechanisms

  - Ageing
  - Contamination
  - Cracking
  - Excessive Moisture
  - Leaking
  - Lightning
  - Partial Discharge
  - Very Fast Transients

*These are actual physical defects or conditions that cause the failure modes to occur.*
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Ageing indicators in a 400kV Bushing After 30 Years Service
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Two sister 235kV OIP bushings failed after only 5-6 years in service due to corrosive oil. - A.D. Ria and K. Ellis, “Investigation of failures of 230kV OIP Copper Conductor Bushings”, 77th Annual International Doble Client Conference 2010.
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Cracking on a 400kV bushing internal clamping plate
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Moisture Ingress and Internal Flashover in 132kV OIP Bushing
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Oil leaks in a 400kV bushing due to broken washer and severe rusting
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Damaged 275kV Bushing  Damaged 132kV Bushing
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Local electrical activity on the innermost partial screen and on the outside of the conductor tube of a 400kV bushing
Bushing Failure Mechanisms

- Ageing
- Contamination
- Cracking
- Excessive Moisture
- Leaking
- Lightning
- Partial Discharge
- Very Fast Transients

Failure of a 230kV Bushing with Insulated Draw Lead
Most of the bushing failures could be classified into either one or a combination of more than one of the following three modes:

- **Progressive Breakdown of Insulation** as a whole, due to severe insulation ageing;
- **Rapid Breakdown of Insulation** by part, due to premature ageing by localised overheating;
- **Porcelain Damage**, due to either lightning or vandalism or others.

There is a Link with Bushing Design and Manufacturer!
Learning from Transformer Bushing Failure Investigation

Case Study: Transformer Bushing Failure due to Porcelain Damage and Moisture Ingress

A visual inspection, external and internal, revealed that the A phase bushing was mechanically damaged, allowing oil to leak out from the main tank and water to leak in. There was clear evidence of free water on frame below the faulted bushing.
How to Prevent Transformer Bushing Failure?

What can we do that is effective in preventing transformer bushing failures in our substations and power stations?

A transformer bushing must be replaced when it no longer meets the requirement of reliability and before it fails. This needs a Bushing Asset Health Review Methodology to analysis and prevent in-service failure.

This involves using information from a wide range of sources, including visual inspections, oil tests, on-line diagnostics and off-line condition assessment tests. In addition, knowledge of transformer bushing designs and of their strengths and weaknesses is essential to understanding the other information. The following three case examples illustrate how developing bushing failures could be managed and even saved by effective DGA analysis combining with effective online diagnostics and offline condition assessment tests.
How to Prevent Transformer Bushing Failure?

Ageing Indicators and Diagnostics
Ageing of bushings can be determined from measurements of DDF/PF and Capacitance.

Change in bushing DDF/PF is indicative of presence of moisture, contamination or the net effect of deterioration. Increase in transformer condenser bushing capacitance is indicative of punctured foils.

<table>
<thead>
<tr>
<th>Insulation System</th>
<th>OIP</th>
<th>RIP</th>
<th>RBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Values at new</td>
<td>0.2-0.4%</td>
<td>0.3-0.4%</td>
<td>0.5-0.6%</td>
</tr>
<tr>
<td>IEEE C57.19.01 (2012)</td>
<td>&lt;0.5%</td>
<td>&lt;0.85%</td>
<td>&lt;2.0%</td>
</tr>
<tr>
<td>IEC 60137 (2008)</td>
<td>&lt;0.7%</td>
<td>&lt;0.7%</td>
<td>&lt;1.5%</td>
</tr>
</tbody>
</table>

Acceptance Limit of DDF/PF and Partial Discharge by IEEE C57.19.01 and IEC 60137
How to Prevent Transformer Bushing Failure?

**Ageing Indicators and Diagnostics**

During 1989-1998 total 5324 bushings removed from service and more than 59% was after Doble Tests. Apparently many bushing failures were prevented due to proactively removing from service which design was recognised as unreliable.
Conclusions

- The failures of bushings are commonly associated with faults, due to several reasons including design/manufacture weakness, defective insulation, ageing, contamination, corrosive attack of the insulation, moisture ingress, and very fast transients.

- Bushing failures can arise in any of the design areas. The identification of the primary cause of each failure and/or design weakness and the subsequent analysis enables enhanced monitoring/investigation to be made on sister bushings built by same manufacturer that hopefully will help in preventing similar failures from occurring and therefore managing the risk of unexpected failure.

- From a utility perspective, it is possible to build up a capability to detect and diagnose the fault(s) inside the transformer bushings before failure. A variety of test methods can be utilised to detect faulty bushings, including Thermovsion, Radio Frequency Interference (RFI) and Dissolved Gas Analysis (DGA). When properly applied, online and offline power factor measurements are powerful method for detecting a wide range of faults in transformer bushings and assisting in determination when to remove the bushing from service for replacement or refurbishment.
Thank you for listening

Don’t forget - It is important to think about the bushing!