Power Transformers
failure Modes,
Investigation & Prevention
Techniques

N S Sodha,
Former Executive Director,
POWERGRID Corpn, Gurgaon
POWER TRANSFORMERS

Factory condition
POWER TRANSFORMERS

Site condition
Faults in a Transformer

1. Internal Faults
2. External faults
3. Auxiliary Faults
Transformer failure rates

Acknowledgement

DEVELOPMENT AND RESULTS OF A WORLDWIDE TRANSFORMER RELIABILITY SURVEY


On behalf of CIGRE WG A2.37

Presented at CIGRE SC A2 COLLOQUIUM 2015 during Sep 20-25, 2015 at Shanghai, China
Introduction

WG A2.37 was formed with an objective of

- Review of all existing surveys and study different practice
- Conduct new International survey
- Compiling and analysis of collected data
- Interpreting the results
  - Calculation of failure rates
  - Classification of failure locations
  - Failure causes and modes
Failure definition

- Only transformers/reactors > 60 kV considered
- Major failure
  - Situation requires removal from service > 7 days
  - Involves major repair – factory or repair bay
  - Opening of transformer, tap changer or exchange of bushing
  - < 7 days, but with extensive oil processing
Failure Rates

![Bar chart showing failure rates for different voltage levels.](chart.png)
Failure locations > 100 kV
Substation Transformers (536 Failures)
Failure Locations > 100kV GSUs (127 Failures)

- HV Winding: 28.35%
- LV Winding: 18.90%
- HV Lead Exit: 12.60%
- Tapping Winding: 0.79%
- Winding to Winding Isolation: 2.36%
- HV Bushings: 14.17%
- LV Bushings: 2.36%
- Core and magnetic circuit: 6.30%
- Flux Shunts: 0.79%
- Tap Changer: 11.81%
- Cooling unit: 1.57%
Failure Locations > 100kV
Manufactured before 1980 (333 Failures)

- Winding: 42.94%
- Lead Exit: 9.01%
- Insulation: 2.70%
- Electrical Screen: 0.90%
- Bushings: 15.92%
- Core and magnetic circuit: 4.20%
- Cooling unit: 0.90%
- Tap Changer: 23.12%
- CT: 0.30%
Failure Mode all Voltage class

964 Failures (SS and GSU)

- Unknown: 12.66%
- Dielectric: 36.62%
- Electrical: 16.49%
- Thermal: 10.89%
- Physical chemistry: 3.32%
- Mechanical: 20.02%
Failure Modes all Voltage Class

799 Failures (SS transformers)
## Failure Mode analysis according to Voltage Class

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>69 ≤ kV &lt; 100 (144)</th>
<th>100 ≤ kV &lt; 200 (300)</th>
<th>200 ≤ kV &lt; 300 (229)</th>
<th>300 ≤ kV &lt; 500 (241)</th>
<th>500 ≤ kV &lt; 700 (36)</th>
<th>kV ≥ 700 (14)</th>
<th>All (964)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric</td>
<td>70.14%</td>
<td>25.33%</td>
<td>36.68%</td>
<td>24.89%</td>
<td>72.22%</td>
<td>42.86%</td>
<td>36.62%</td>
</tr>
<tr>
<td>Electrical</td>
<td>12.50%</td>
<td>19.33%</td>
<td>15.72%</td>
<td>17.84%</td>
<td>0</td>
<td>28.57%</td>
<td>16.49%</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.69%</td>
<td>12.00%</td>
<td>10.04%</td>
<td>18.25%</td>
<td>2.78%</td>
<td>0.00%</td>
<td>10.89%</td>
</tr>
<tr>
<td>Physical Chemistry</td>
<td>0.00%</td>
<td>3.66%</td>
<td>4.37%</td>
<td>4.56%</td>
<td>2.78%</td>
<td>0.00%</td>
<td>3.32%</td>
</tr>
<tr>
<td>Mechanical</td>
<td>6.25%</td>
<td>27.33%</td>
<td>22.71%</td>
<td>18.25%</td>
<td>11.11%</td>
<td>7.14%</td>
<td>20.02%</td>
</tr>
<tr>
<td>Unknown</td>
<td>10.42%</td>
<td>12.33%</td>
<td>10.48%</td>
<td>16.18%</td>
<td>11.11%</td>
<td>21.43%</td>
<td>12.66%</td>
</tr>
</tbody>
</table>
Failure Cause
964 Failures

- External short-circuit: 11.62%
- Design: 9.96%
- Manufacturing: 9.96%
- Improper repair: 6.02%
- Other reasons: 4.88%
- Material: 3.73%
- Improper maintenance: 3.22%
- Lightning: 2.18%
- Abnormal Deterioration: 2.49%
- Installation on-site: 0.83%
- Repetitive through faults: 0.83%
- External Pollution: 0.52%
- Loss of clamping pressure: 0.41%
- Overvoltage: 0.62%
- Overheating: 0.31%
- Collateral Damage: 0.31%
- Improper application: 0.21%
- Loss of cooling: 0.21%
- Corrosive Sulphur: 0.21%
- Unknown: 29.05%
External effect Analysis

- 76.5% of failures did not result into any external effects
- 7.1% failures resulted in Fire
- 5.1% failures are related with explosions or blasts
External Failure effects
964 Failures

- None: 76.56%
- Explosion, Burst: 5.91%
- Fire: 7.16%
- Collateral Damages: 1.24%
- Leakages: 4.25%
- Others: 4.88%
Failures with Fire or explosions

(126 Failures)
External effects of Bushing failures
115 Failures

- None: 45.22%
- Fire: 30.43%
- Explosion, Burst: 10.43%
- Leakages: 5.22%
- Others: 7.83%
- Collateral Damages: 0.87%
Action taken analysis
964 Failures

- Unknown: 13.80%
- Onsite Repair < 1 week: 7.37%
- Onsite Repair > 1 week: 12.97%
- Onsite Repair > 1 month: 2.28%
- Scrapping: 31.74%
- Repair in workshop: 31.85%
Failure location analysis of 242 scrapped transformers
Failure location analysis of 465 repaired transformers
CIGRE WG-Conclusions

- Overall failure rates remained < 1 %
- GSU failure rate marginally higher than SS X’mer failure rate - difference is < 0.5%
- GSU (300-500kV) failure rate exceeded 1%
- Winding, tap changer, bushings followed by lead exits – major contributors
CIGRE WG Conclusions

- GSU contribute higher winding and lead failures
- SS transformers contributed more towards tap changer failure
- Both type had similar contribution in bushing failures
- Bushing and Lead exit failures tend to have increasing trend with higher voltage upto 700 kV
CIGRE WG Conclusions

- Dielectric failures – highest contributors
- Design and manufacturing, ageing and external short circuits - major contributors
- Bushing failures most often result in fire and explosions
- Large contributors being ‘unknown’, results should be treated with caution
POWERGRID, India
Power Transformer/Shunt Reactor Asset Performance & Preventive Actions
Asset Growth in POWERGRID, India

Transformer

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>178</td>
</tr>
<tr>
<td>2010</td>
<td>309</td>
</tr>
<tr>
<td>As on date</td>
<td>692</td>
</tr>
</tbody>
</table>

Reactor

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>273</td>
</tr>
<tr>
<td>2010</td>
<td>435</td>
</tr>
<tr>
<td>As on date</td>
<td>1110</td>
</tr>
</tbody>
</table>
Growth of 765kV Transformers in POWERGRID, India
Growth of 765kV Reactors in POWERGRID, India

- Till 2011
- 2012
- 2013
- 2014
- As on date
## Failures of AC Transformers

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>10</td>
<td>100</td>
<td>135</td>
<td>206</td>
<td>247</td>
</tr>
<tr>
<td>Failure</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>% Failure</td>
<td>-</td>
<td>0.1</td>
<td>0</td>
<td>0.49</td>
<td>0.809</td>
</tr>
</tbody>
</table>

## Failures of Shunt Reactors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>10</td>
<td>147</td>
<td>218</td>
<td>436</td>
<td>507</td>
</tr>
<tr>
<td>Failure</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>% Failure</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.23</td>
<td>0.395</td>
</tr>
</tbody>
</table>
Transformer and Reactor Failures

- First failure of Transformer was encountered in 2013 and first Reactor was encountered in the year 2015.
- So far, failure of 4 Nos. Transformer and 3 nos. Reactor were encountered.
- All of the failures were attributed due to failure of winding unlike 400kV Transformers and Reactors where most of the failures were due to bushing.
POWERGRID’s Preventive Measures/Philosophy

- Each bank of 765kV Transformer and Reactors are having a dedicated hot stand by spare.
- Charging of spare Transformer and Reactor on rotational basis in every 4 to 6 months.
- Each 765kV Transformers and Reactors are equipped with online DGA monitoring System, Online drying System FO temperature sensors & Digital RTCC.
- Commissioning of Controlled Switching Devices, Online DGA/Dry out System along with Transformers and Reactors and Validation and SCADA Integration of Fiber Optic Temperature Sensors.
- Six Monthly Review of DGA and Oil Test results by Committee of Expert.
- Periodic review of AMP test results by Committee of Expert.
- Monitoring of Bushing Tan delta before expiry of warrantee period.
POWERGRID’s Preventive Measures/Philosophy

Monitoring of oil:

- Norms for DGA Testing of oil:
  - Just after charging,
  - After 24 Hrs. of charging,
  - After one week of charging
  - 15 days of charging
  - One month of charging.
  - On monthly basis till warrantee Period
  - Thereafter 2 monthly basis

- Monitoring of all oil parameter tests (except oxidation stability) within six month of charging and thereafter yearly basis

- Particle counts measurement before and within three months of charging.
POWERGRID’s Preventive Measures/Philosophy

**Further Improvement:**

- Inclusion of UHF PD monitoring System and Self Dehydrating Breathers in TS.

- SCADA integration of on line DGA monitoring System, On line drying System, FO temperature sensors are under progress for remote monitoring.

- Standardisation of Transformer and Reactor design for ease of maintenance

- Inclusion of RIP bushings with polymer housing to avoid catastrophic failure

- Bushing and Transient voltage monitoring system
Water – the worst enemy of a transformer...

- A transformer with low moisture content is like a person in good condition
  - A transformer can be used at high load without risk for catastrophic failure.
  - A person can work hard without risk for heart attack
- A wet transformer is like an overweight person in bad condition
  - The transformer owner has to limit load to avoid bubbling (may lead to catastrophic failure)
  - Moisture in insulation increases the rate of aging
  - The person can not run the marathon...
- Water/moisture and (high) temperature will sooner or later kill the transformer
How Water affects the transformer performance?

- Loading capability
  - Limits the loading capability due to decreased bubbling inception temperature
- Dielectric strength
  - Decreases the dielectric strength of the oil and decreases PD inception voltage
- Aging
  - High temperature and moisture will dramatically accelerate aging that lowers the mechanical strength of the cellulose insulation
Loading capability is limited by high moisture

- Moisture determines the maximum loading/hot-spot temperature for bubble inception
- Knowing moisture content and oil quality allows for correct decision on maximum loading
  - Leave as-is
  - Dry-out/re-generate oil
  - Replace/Relocate
  - Scrap

Temperature limits from IEEE C57.91-1995

Life of a transformer – Moisture and aging

- During manufacturing, the cellulose insulation in the transformer is carefully dried out before it is impregnated with oil.
- The moisture content in the solid insulation of a new transformer is typically targeted to be < 0.5% by weight.
- As the transformer gets older, the moisture content will increase.
  - Open-breathing transformers, typically around 0.2%/year.
  - Sealed conservator transformers, typically around 0.05%/year.
- In an old and/or severely deteriorated transformer, the moisture content can be > 4%.
- The aging process of the insulation is directly related to moisture content.
Moisture accelerates aging

Where does the water come from?

- Leaking gaskets and faulty water traps may expose the inside of the transformer to moisture humid air
- Exposure to humid air during site installation/commissioning
- Exposure to humid air during maintenance
- Normal aging of cellulose produces water
- Insufficient drying at manufacturing

Typical moisture content in paper/pressboard:
- New transformer: < 1%
- Aged transformer: 2 - 4%

Normal increase of water content is typically 0.05-0.2%/year
Interpretation of moisture content by various standards and practices

- < 1% - “As new”
- 1-2% - “Dry”
- 2-3% - “Moderately wet”
- 3-4.5% - “Wet”
- > 4.5% - “Excessively wet”

1) Original data in IEC60422, annex A, are presented as relative saturation in percentage. “Dry”, “Moderately wet”, “Wet” and “Excessively wet” are recalculated to percent moisture in cellulose.
2) Original data in IEC60422 for new transformers is presented as percent moisture in cellulose insulation.
3) Original data in CIGRE349 is by categories. “Good”, “Fair”, “Probably wet” and “Wet” are relabeled to “Good/New”, “Dry” and “Wet”.
Transformer drying – Methods/Examples

- Two major techniques are used:
  - Drying the insulation by drying the oil – Field
  - Drying the insulation with heat and vacuum – Field and factory

- Drying the oil
  - Molecular sieves
  - Cellulose filters
  - Cold traps
  - Combined oil regeneration and degassing

- Drying the insulation
  - Vacuum and heat
  - Pulsation drying through oil circulation
  - Hot oil spray drying
  - Low frequency heating
  - Vapour phase drying

A. Gruber, “Online Treatment of Transformers and Regeneration of Insulating Oil”, TechCon AsiaPacific 2009
Tests on Transformer

**Sweep frequency response analysis (SFRA)**

- SFRA test is carried out to obtain initial signature of transformer sweep frequency response.
- The test connections, procedure and connections shall be defined for repeatability.
- The test can be repeated after a major event transportation, short circuit, periodic maintenance, earthquake etc.
Tests on Transformer

Sweep frequency response analysis (SFRA)

Healthy HV & LV windings
Tests on Transformer

Sweep frequency response analysis (SFRA)

U-phase shorted turn
Tests on Transformer

Sweep frequency response analysis (SFRA)

- **WITH OIL-IN GREEN**
- **WITHOUT OIL-IN RED**

Removing oil lowers capacitances and resonances shift to higher frequencies.
Conclusions on moisture/water

- Moisture is the worst enemy of the transformer!
  - Limits the loading capability
  - Accelerates the aging process
  - Decreases dielectric strength

- The water/moisture in a transformer resides in the solid insulation, not in the oil

- Dielectric Frequency Response Measurement is a great technique for moisture assessment as it measures:
  - Moisture content in the cellulose insulation
  - Conductivity/dissipation factor of the insulating oil
  - Power frequency tan delta/power factor, accurately temperature corrected to 20°C reference temperature

- Drying a power transformer can take from days to years depending on drying process & technology
Enhanced Reliability thru. Accessories Monitoring and Control

- Major accessories are Bushings, OLTC, OCTC, Temperature indicators, oil preservation system and CTs
- Bushings are High voltage bushings for HV Windings and high Current bushings for low voltage windings. HV Bushings are mainly OIP bushings. Now the trend is to go for Resin Impregnated Paper (RIP) Bushing.
- Polymer insulation instead of Porcelain for operational safety.
- OLTC have different current and voltage ratings. Most of OLTCs are high speed resistor type. There are OLTC mounted inside the tank and also outside the tank.
- OCTC like OLTC have different voltage and current rating. OCTC are linear/reversing type.
- Trend is to go for Vacuum Type OLTC which has more contact life & less maintenance.
## Comparison between mineral oil and Synthetic Ester & Natural Ester

<table>
<thead>
<tr>
<th>Properties</th>
<th>Mineral Oil</th>
<th>Synthetic Ester</th>
<th>Natural Ester Envirotemp FR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion coefficient (°C)</td>
<td>0.00075</td>
<td>0.00075</td>
<td>0.00075</td>
</tr>
<tr>
<td>Kinematic Viscosity at 40°C (mm²/s)</td>
<td>8-10</td>
<td>34</td>
<td>32-33</td>
</tr>
<tr>
<td>Specific Heat at 20/25°C (J/kg·K)</td>
<td>1860</td>
<td>2065</td>
<td>1880</td>
</tr>
<tr>
<td>Thermal conductivity at 20/25°C (W/m·K)</td>
<td>0.126</td>
<td>0.161</td>
<td>0.167</td>
</tr>
<tr>
<td>Pour point (°C) in accordance with ISO 3016</td>
<td>-57</td>
<td>-60 to -57</td>
<td>-20 to -26</td>
</tr>
<tr>
<td>Breakdown voltage after treatment (kV)</td>
<td>&gt;70</td>
<td>&gt;75</td>
<td>89</td>
</tr>
<tr>
<td>Dielectric dissipation factor</td>
<td>&lt;0.001</td>
<td>&lt;0.03</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Permittivity</td>
<td>2.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Reference Standard</td>
<td>IEC-60296</td>
<td>IEC-61009</td>
<td>IEC-62770</td>
</tr>
</tbody>
</table>
RIP Condenser Bushing

- RIP condenser bushing with Polymer (Silicon Rubber) Insulator
- Fire Resistance & explosion proof
- Plug in type up to 420kV
Enhanced Reliability thru. Accessories Monitoring and Control

- Oil preservation systems
- Conservator with silicagel breather, air cell conservator, N₂
- Sealed conservator, Dry Col breather
- Thermometer
- Thermal image type OTI and WTI. Fiber optic thermal sensors
- Monitoring Device for oil, winding temperature, cooler, OLTC, bushing, oil ppm, gas, PD
- Trend
- Substation automation with control for system operation complying with IEC 61850 communication protocol standard
Transformer Monitoring System

Field Bus Technology

MS 3000 Server

Field bus

Monitoring Module

Sensors
Assets Health Information flow

- Dispatching Centre: Overload assessment
- Operation Dep.: Condition assessment
- Maintenance Dep.: Planning of maintenance

Network Diagram:
- Local Area Network
- Intranet
- Internet
- Firewall
- Power Station A: MS 2000 Server
- Substation A: WEB Server
- Substation B: Web Server
Fiber Optic Temperature Sensor

Accurate measurement of Winding temperature for protection & utilization of transformer
IEC 60076-20 covers to choose a transformer with an appropriate level of energy efficiency, according to the loading & operating conditions. The total capital & the estimated lifetime operating and maintenance cost (TCO = total cost of ownership) are also significant consideration in determining the most suitable transformer for the intended application.
Conclusion

- In future, Power transformer will have to meet increasingly stringent environmental and safety requirement. Replacement of mineral oil by biodegradable natural/synthetic Ester oil
- Energy efficient transformers as per IEC60076-20
- Di-electrical design and appropriate analytical tool will need enhancement to support the next generation transformers such as HTS transformers, Flexible AC Transmission System (FACTs) and Phase Shifting Transformers.
- Factory capability assessment as per Cigre Guide TB530
- Design Review as per Cigre Guide line TB529
On Line DGA

- Transformer faults detection in early stage
- Safe & optimized utilization
- Prediction of ageing
- Fault classification from results
- Gases measured
  - Hydrogen
  - Methane
  - Ethane
  - Ethylene
  - Acetylene
  - Carbon monoxide
  - Carbon dioxide
  - Oxygen
- Nitrogen
- Water
Future Transformers

- Mobile transformers.
- Large capacity three phase transformer.
- Phase shifting transformer.
- Tapless transformer.
- Mobile test system.
- Green Transformer.
- Site assembled transformer.
- Energy efficient transformers

Figure showing Mobile power transformer and substation

Figure showing compact 3 phase 930 MVA 550 kV GT
Milestones in Indian Power Transformer Industry

333MVA, 1200kV ULTRA HIGH VOLTAGE POWER TRANSFORMER
Thank you for your Kind attention!