# Analysis of Testing Methodologies for High Voltage Transformers

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**Abstract**

*The advent of new testing methodologies has seen Water Corporation evaluate its preventative maintenance strategy for its distributed high voltage ("HV") and low voltage ("LV"), high power electrical equipment. The aim of this project is to assess the efficacy and applicability of testing methodologies for HV transformers in the context of Water Corp's criterion of occupational health and safety (OSH), asset criticality, economics, compliance, skill-set and operating environment and deliver a recommendation.*

*The project develops a framework for the Water Corporation to assess the applicability and efficacy of the testing methodology. Analysis has been carried out in conjunction with ABB ("Asea Brown Boveri") and Downer Group to gauge the practicality and effectiveness of the testing methodologies and an indicative cost schedule for each methodology has been prepared. The results indicate condition monitoring ("CM") in the form of yearly inspections and preventative maintenance ("PM") in the form of dissolved gas in oil analysis ("DGA") and partial discharge analysis ("PD") on 'critical' transformers should be conducted.*

## 1. Introduction

Water Corporation is the principal supplier of water, waste water and drainage services in Western Australia. To ensure reliability of service, Water Corporation has maintenance standards with associated work instructions that are utilised across all metropolitan and regional electrical assets. The Corporation intends to create a stand-alone Maintenance Standard for High Voltage Maintenance that encompasses all assets to ensure standardisation across the business. The current HV and LV, high power maintenance work instructions have been in use over a period of 30 years and reflect testing methodologies in similar industries and in appropriate Australian standards. Following installation of new and more reliable equipment and implementation of new maintenance testing methodologies Water Corporation have commissioned this project to test the efficacy and applicability of these methodologies in the context of assets operated.

### 1.1 Current Maintenance Practices for Transformers

The Water Corporation currently own and maintain approximately 420 transformers across the state. These transformers are primarily step-down transformers with a few step-up transformers. The transformers can further be segmented into dry and oil-filled type, and to pole-top and pad-mounted as shown in Figure 1.

Water Corporation Generic Work Instructions ("GWI") show that maintenance on transformers is carried out yearly. Inspections on each pad-mounted transformer include visually inspecting the mechanical and electrical integrity for signs of overheating and corrosion, integrity of wiring and earthing connections and temperature gauges.

Periodic oil sampling is also undertaken on ground-mounted transformers larger than 300kVa, whereby a sample of oil is obtained and sent to a laboratory (SGS Oil) for analysis. The frequency of this analysis is based on the criticality of the asset with an interval ranging from 1-8 years.

## 2. Approach

The approach taken in this project required an analysis and critical review of various testing methodologies to ascertain applicability to Water Corporation's criterion. Firstly a review of Water Corporation's transformers and the current testing methodologies employed was required to form the basis of analysis. The transformer register was segmented as shown in Figure 1 to simplify analysis and to ensure focus on critical transformers.

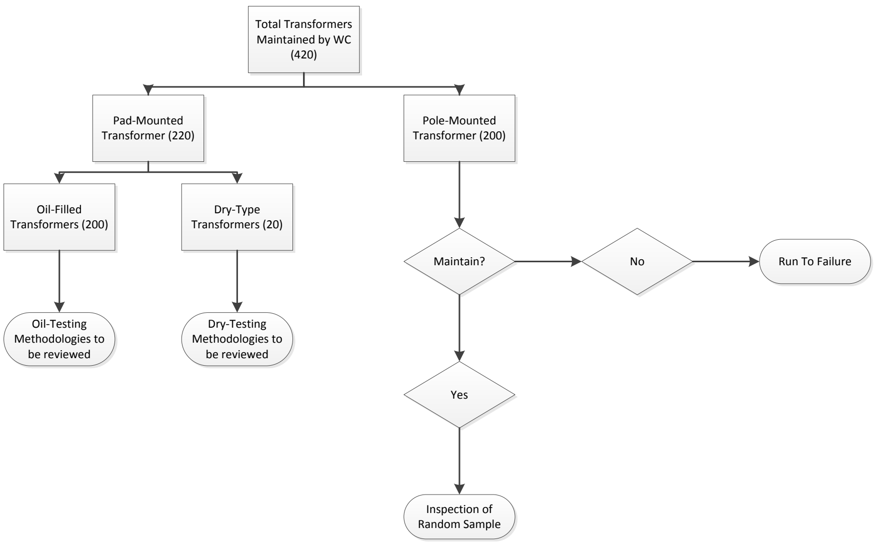


**Figure 1 Summary of Water Corporation Transformers**

Secondly, a literature review was conducted consulting Australian, IEC and IEEE Standards as well as transformer handbooks and journal articles to gauge the testing methodololgies in use today.

Third, main transformer failure causes and the rates of failure was obtained from a paper by the CIGRE working group. This allowed a focus to be placed on maintenance activity that detects such faults. Then the testing methodologies were compared against Water Corporation' criterion using a risk-based framework.

Finally, the frequency of testing is to be modelled and simulated. Transformer maintenance model equations for perfect maintenance and imperfect maintenance as shown in Jirutitijaroen & Singh (2004) will be used to determine optimum frequency.

## 2.1 Economic Analysis

The maintenance data indicates a total of 995 maintenance activities conducted on transformers since the SAP database was implemented by Water Corporation in 1999. It is important to note that this is not an exhaustive list because the maintenance entries recorded on SAP could have been recorded in different category and functional groups. Further, the Perth region group "Aroona" records their data using another database and have site specific GWI. The data on SAP is categorised scheduled preventative, condition based preventative, deferred corrective and emergency corrective.

The table summarises the cost categories and indicative costs. Scheduled (preventative) is cyclical planned maintenance, condition based (preventative) maintenance is maintenance to assess the condition of the transformer along with one-off maintenance based on asset condition. Emergency (corrective) is repairs to a fault done immediately and deferred (corrective) are faults that can be left until the next working day.

| | *Number of Recorded Entries* | *Total Cost ($)* | *Average Cost ($)* |
|---|---|---|---|
| Scheduled (Preventative) | 860 | 622,200 | 723.5 |
| Condition-Based (Preventative) | 83 | 252,818 | 3,046 |
| Emergency (Corrective) | 21 | 125,802 | 5,990.6 |
| Deferred (Corrective) | 31 | 64,822 | 2,091 |
| **Total** | 995 | 1,065,642 | 1,071 |

**Table 1 Transformer Maintenance Cost**

# 3. Testing Methodologies Considered

Ageing of transformers depends on factors such as operating environment, servicing and loading. Paper insulation for example does not regain its original molecular structure when the temperature falls after a period of high transformer loading. A 6-7°C temperature rise can cause a doubling in the chemical deterioration process in cellulose (ABB 2010). As the tensile strength of the paper becomes weaker, the risk increases that the transformer will fail if a short circuit occurs. Other significant variables include presence of water and free oxygen in oil, which have the affect of oxidising oil and thus reducing the dielectric strength of oil. The testing methodologies below describe methods to detect and repair incipient faults.

## 3.1 Dissolved Gas in Oil Analysis ("DGA")

DGA has recently been developed to diagnose fault conditions in oil-filled transformers and involves studying dissolved gases in transformer oil. When insulating oils and cellulose materials within a transformer are exposed to higher than normal electrical or thermal stress, they decompose to produce certain combustible gases (fault gases). The faults that can be detected by DGA include the following:

- Deterioration of Cellulose insulation- Elevated carbon monoxide, carbon dioxide levels
- Excessive oil temperature- Elevated methane, ethane and ethylene levels
- Corona (Partial discharge) – Elevated hydrogen levels
- Arcing – Low levels of acetylene

### 3.2 Partial Discharge ("PD") Testing

Partial discharge is a localised dielectric breakdown of an electrical insulation system under high voltage stress. PD in power transformers can lead to corrosion on solid insulating materials which may breakdown operating components as well as decomposing and polluting insulating oil. Acoustic techniques are used by manufacturers to locate discharges that occur during HV factory testing. To identify discharge location, both electric and acoustic signals from the discharge must be recorded and distance from the sensor calculated. When sensors are mounted externally a low pass filter is employed to remove all 'noise' frequency components. Simultaneous recording of electric and acoustic signals has been proposed as a basis for on-line monitoring where PD is diagnosed through the correlation of acoustic and electrical signals, thereby avoiding false alarms caused by rain and electrical signals caused by corona in air (Lundgaard 1992).

### 3.3 Frequency Response Analysis ("FRA")

Frequency Response analysis is a sensitive method to evaluate the mechanical integrity of cores, windings and clamping structures within power transformers. This is measured using electrical transfer functions over a wide frequency range. Electrical networks have unique frequency responses and faults and mechanical shocks can cause deviations. Measurements of different phases can be compared with earlier measurements to get an indication of positional or electrical variation of the internal components. FRA is a reliable technique that a number of sensitive analyses, with the main advantage being the ability to find mechanical damage to the windings that cannot be detected by other means. The swept frequency method for FRA requires the use of a network analyser to generate the signal, make measurements and manipulate the results Ryder (2003). A number of network analysers are commercially available from reputable manufacturers.

### 3.4 Hotspot

The loading capability of transformers is limited by winding temperatures. The temperature of the winding is not uniform, and the real limiting factor is the hottest section (or "hotspot"). The hot spot is located at the top of the transformer and is not accessible for direct measurement using conventional methods. Recent developments on direct measurement of winding hot-spot tecmperatures has seen fibre optic temperature sensors designed that withstand long term transformer oil immersion Berube & Aubin (2012). There are two approaches to installing the sensor, embedding the sensor in a spacer or attaching it directly onto any conductor that should be temperature monitored. This approach requires the removal and restoration of insulation. The other method is to insert the sensor in the spacer between successive disks, which avoids breaking and restoring the conductor insulation. It is evident that this process is most feasible during the manufacturing process and becomes quite an expensive and impractical solution for on-line transformers.

## 4. Results and Discussion

### 4.1 Transformer Failure Causes and Rates

Figure 2 is a survey conducted by "CIGRE" and shows common failures of transformers based on data from 48 utilities around the world. It shows the leading cause of transformer failure are failures of the windings, with tap changers the second most prevalent cause.

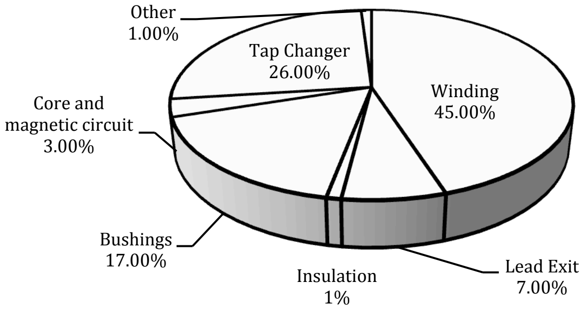


**Figure 2 Transformer Failure Rates (<100kV)**

## 4.2 Framework

The following framework defines the testing methodologies against the criterion of reproducibility, OSH and the need to shutdown the network. Consultation with Tony Chila, the technical services supervisor at Downer and an expert in transformer maintenance revealed some operators choose to conduct their own oil samples for example and in the process contaminate the sample before it is sent to the lab. Hence, it is suggested that testing be conducted by external contractors as they have specialist equipment and expertise that produce required results. Further Tony described DGA and PD Analysis are the services that are the most common in their business and most effective.

| *Testing Method* | *Reproducibility (Contractors)* | *Switching (OSH)* | *Online/Offline* |
|---|---|---|---|
| Dissolved Gas Analysis | Many external | No Switching | Online |
| Partial Discharge Analysis | Many external | No Switching | Online |
| Frequency Response Analysis | Many external | No Switching | Online |
| Hotspot Testing | Limited | Switching | Offline |

**Table 2 Transformer Maintenance Cost**

## 4.3 Criticality and Costing

The criticality of the transformer can be described by the functional assets that it serves. Referring to Figure 3 a single transformer feeding a major pump station is more critical to the business than a pole-top transformer feeding a reticulation asset for example. Judging criticality is important as it will inform the testing conducted on transformer assets.

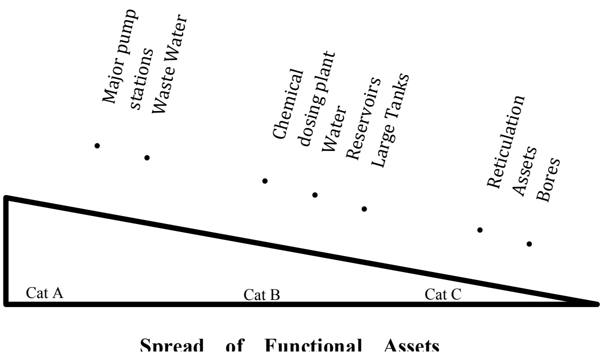


**Figure 3 Ranking of Business Criticality of Functional Assets**

The costings provided are indicative costing schedules provided by Downer Group and will vary depending upon location of the transformer, size and time required. Figure 4 illustrates the cost of each methodology relative to the current PM costs.

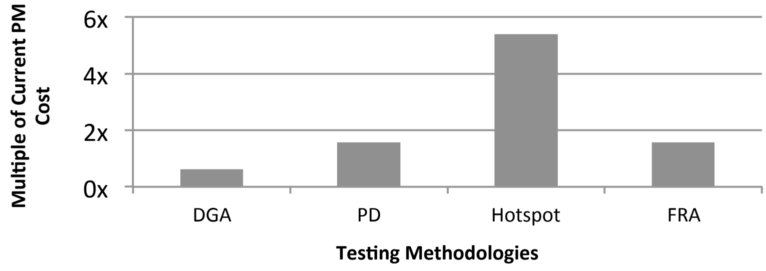


**Figure 4 Indicative Testing Methodology Costing**

# 5. Conclusions and Future Work

The findings of this project indicate that the Water Corporation are currently undertaking the industry standard maintenance strategy. Water Corporation currently do not conduct maintenance on pole-top transformers due to low criticality and relatively cheaper replacement costs. The recommendation for transformer testing based on the results is to conduct condition monitoring assessment in the form of visual inspections on all 200 or so pad-mounted transformers. Further to gauge the condition of the 'critically' defined transformers, DGA testing should be conducted as it will provide indication of oil condition and can also indicate useful life. If the results of the oil sample indicate further inspection, then PD testing should be conducted. The required frequency of the testing is to be determined using simulations on MATLAB.

Work on this project is still ongoing; further work includes verifying results through the use of simulations and case studies. Problems have been encountered so far with data collection, however further attempts will be made. Future analysis of testing methodologies must also be completed on Water Corporation's HV, LV, high power motors and aerials.

# 6. Acknowledgements

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# 7. References

ABB Power Products Division 2010, *ABB Transformer Handbook*, ABB Ltd., Zurich.

Cigre Working Group A2.37, 2012, 'Transformer Reliability Survey', *Electra*, no. 261, p. 48-49

Jirutitijaroen, P & Singh, C 2004, 'The effect of transformer maintenance on reliability and cost: a probabilistic model', *Electric Power Systems Research*, vol. 72, pp. 213-224.

Lundgaard, L.E., 1992, 'Partial Discharge. XIV. Acoustic partial discharge detection-practical application', *Electrical Insulation Magazine IEEE,* vol. 8, no.5, p. 34-43

Nor Asiah, M, Ali Saeed, A & Abubakar, AS '( Regular Papers : DGA Interpretation of Oil Filled Transformer Condition Diagnosis )', *Trans. Electr. Electron. Mater. (TEEM),* vol. 13, no. 5, p. 229.

Ryder, S.A., 2003, 'Diagnosing transformer faults using frequency response analysis', *Electrical Insulation Magazine, IEEE,* vol. 19, no. 2, p 16-22