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Symposium Paper

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## Paper information

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| Paper title | The use of partial discharge monitoring and failure analysis of a 275 kV oil filled current transformer |
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## Summary

Powerlink Queensland is the high voltage transmission network service provider in Queensland Australia, responsible for voltages up to 330 kV including over 15,000 km of overhead and underground transmission lines and 140+ substations. This paper examines the failure of a 275 kV oil filled current transformer including the implementation of partial discharge monitoring techniques.

This paper aims to share the knowledge, experiences and challenges of partial discharge monitoring in transmission environments. Using an in-service failure of a 275 kV oil filled current transformer to highlight the need for partial discharge monitoring, while examining the causes and leading factors that resulted in this failure; the paper will also explore the recommendations and learnings that impact asset owners and the challenges of risk based decision making.

## Keywords

High Voltage, Instrument Transformer, Partial Discharge, Failure

## Introduction

High voltage instrument transformers are an integral part of transmission substations, providing input to protection, metering and power quality devices. However, the ongoing maintenance, operation, failure detection and subsequent replacement can become costly for network service providers. As such, understanding of the failure mechanisms and early detection of failures enables preventative intervention to extend the lifecycle and reduce costs of both the affected and associated plant.

This paper aims to share the knowledge, experience and asset owner challenges faced by transmission utilities with respect to instrument transformers. Using laboratory and field based testing techniques for partial discharge, the paper illustrates through a case study the importance of early fault detection and the use of partial discharge monitoring to reduce the network impact caused by instrument transformer failures. The case study focuses on the explosive failure of a 275 kV Oil Filled dead tank current transformer.

## Network & Equipment Overview

Powerlink Queensland is the transmission network service provider (TNSP) for the state of Queensland, Australia. As a TNSP, Powerlink is responsible for the ownership, development, operation and maintenance of the state's high voltage transmission network, comprising of more than 15,000km of lines and 140+ substations with voltages up to 330 kV.

Powerlink has adopted the use of air-insulated switchgear in the vast majority of substations with a significant population of live-tank circuit breakers and oil insulated post type current transformers (CT). Due to safety risks presented by oil insulated post CTs, particularly models with porcelain outer insulation, a transition from oil filled porcelain to oil filled polymer occurred during the early 2000s. Since 2015, the strategic preference has moved to toroidal bushing CTs on dead-tank circuit breakers with gas insulated CTs where this is not practicable.

Current data indicates a population of approximately 2000 oil insulated current transformers (with approximately one third utilising porcelain outer insulation) and 400 gas insulated current transformers in the network.

## Maintenance Practices

### Visual Inspections

Powerlink typically performs visual inspections of substations every 6 months. As part of this inspection, all current transformers are visually assessed and any defects are recorded in an asset management database. These defects are then assessed and any corrective maintenance actions are scheduled based on an assigned priority/risk rating.

### Dissolved Gas Analysis

Powerlink typically performs oil sampling for dissolved gas analysis (DGA) on oil filled current transformers every 3 years. DGA is the primary condition monitoring method applied as it is sensitive to a spectrum of insulation conditions as well as discharging insulation. Examples include insulation or oil overheating and premature insulation ageing, which proceed without significant discharge or hydrogen production. When an oil test is performed, insulation moisture content is also assessed.

### Thermographic Inspections

Powerlink typically performs thermographic inspections of substations every 2 years. As part of this inspection, the temperature rise of current transformers are analysed for localised hotspots or general increases in temperature compared to adjacent phases.

### Partial Discharge Monitoring

Substations which have oil filled current transformers or other plant with an identified increased safety risk due to partial discharge (PD) are monitored for PD using handheld ultra-high frequency (UHF) equipment on a yearly or two-yearly basis.

Whilst the use of radio frequency interference monitoring does not provide a quantitative measure of the level of activity, it is effective in determining if PD activity may be present and further investigation into specific plant is required.

The frequency of this method of PD monitoring is increased when there is increased exposure for personnel, such as during major brownfield replacement or refurbishment projects.

## Failure Rates of Oil Filled Current Transformers

Oil Filled current transformer failures in the Powerlink high voltage network are subject to investigation and analysis of root cause. This is aimed at ensuring minimal risk to both people and plant. As such failure rate data and causes allow proactive tasks for the ongoing reliability and safety of the transmission network. There are three main causes of oil filled current transformer failure:

1. Explosive Failure
2. Dissolved Gas Analysis (Evidence of Heating or Internal Arcing)
3. Moisture Ingress

Between 2014 and 2020 the following statistics were recorded for a total fleet of 2000 oil insulated current transformers:

1. 7 Explosive Failures
2. 19 DGA Arcing & Heating Fault Failures
3. 10 Moisture Ingress (where moisture was detected >40 ppm)

## Case study – Failure of 300kV current transformer

In August 2020, the B phase unit of a 300kV oil insulated outdoor Current Transformer (CT) failed explosively during switching activities.

A forensic investigation of the failed unit was completed in cooperation between both Powerlink Queensland and representatives from the equipment manufacturer, as well as additional investigations of both adjacent phases of the CT set.

### Investigation of failed B phase unit

The forensic investigation of the B phase unit provided the organisation with a though understanding of the failure mechanism, including the pressure relief and location of the insulation breakdown. The current transformer was a "Hairpin" style design manufactured in the 2000's. Constructed of graded paper and foil insulation system including partial foil layers. Investigations illustrated three points of dielectric breakdown as shown below.

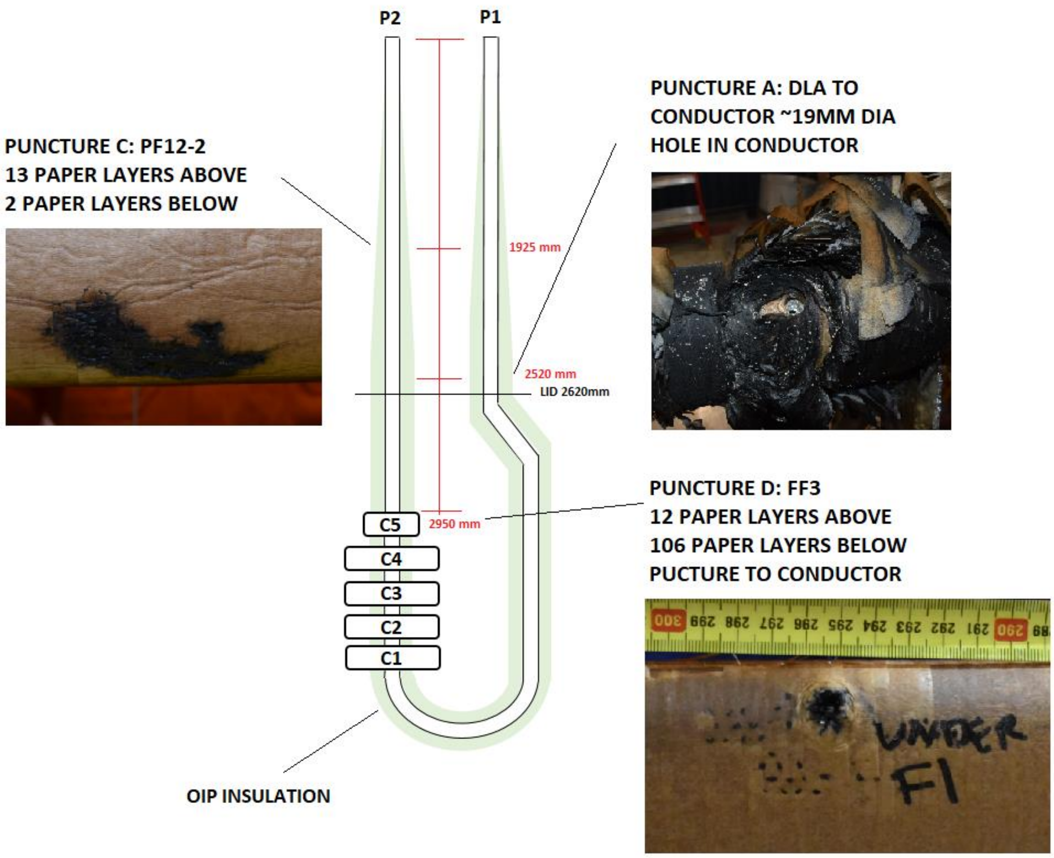


*Figure 1 - Locations of insulation breakdown in failed current transformer. Puncture B (not pictured) refers to a mark on the tank correllating to arcing fault from Puncture A.*

The investigation by both the manufacture and Powerlink concluded the current transformer was subjected to a lightning impulse sometime in the 3 years prior to the failure. Failure was then initiated during a routine switching sequence resulting in a cascade of prior weakened insulation.

## Investigation of adjacent A phase unit

Subsequent to the primary forensic investigation, the adjacent A phase unit was forensically investigated to determine if there were any abnormalities in the construction of the CTs in this batch that may have contributed to the failure.

The inspection did not identify any abnormal condition, the bellows was in acceptable condition and all secondary wiring was neatly arranged and bundled where required. The insulation system closely matched the design specifications and no evidence of poor manufacturing process or workmanship was identified.

Oil samples taken did not result in any identification of abnormal condition, nor was any evidence of partial discharge observed. The investigation concluded the unit remained fit for service.

## Investigation of adjacent C phase unit

The adjacent C phase unit was reserved for further testing to determine if any degradation in performance of the CT was evident which may support the hypothesis of prior stress on the failed B phase unit.

## Laboratory partial discharge measurement

Prior to repeating type and routine tests, partial discharge measurements were taken to establish a benchmark. While Oil samples DGA and Dielectric Loss angle testing returned satisfactory results, off line partial discharge testing detected void type partial discharge arcing, results of which are recorded below:

| | |
|---|---|
| Ambient temperature: | (17.7 ± 0.5) °C |
| Relative humidity: | (76 ± 3) % R.H. |
| Test voltage uncertainty: | ± 2.5 % |
| **Test Voltage ($kV_{rms}$)** | **Maximum PD Magnitude within a 10 Seconds Period (pC)** |
| 173 | 304 |
| 147 | 278 |
| 103 | 128 |
| *Uncertainty* | ± 10 |
| *Coverage factor* | 2.0 |

*Figure 2 - Partial Discharge magnitude results prior to impulse tests*

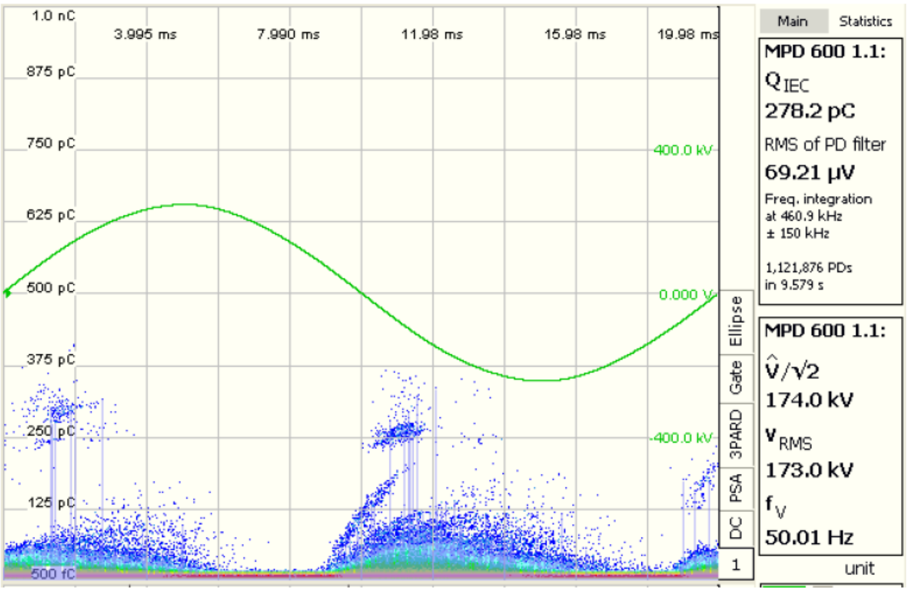


*Figure 3 - Phase resolved partial discharge measurements prior to impulse tests*

These results indicate void type partial discharge, it is possible with continued operation in this condition an additional explosive failure may have occurred. Additional testing in both a field and laboratory environment proved beneficial from a safety and reliability stand point.

## Repetition of withstand and impulse testing

To understand the impact of lightning and switching overvoltage transients. The unit was subjected to a series of chopped and un-chopped lightening impulses and switching impulses.

| Air temperature: (19.0 ± 0.5) °C<br>Relative humidity: (70 ± 3) % R.H.<br>Atmospheric pressure: (1010 ± 2) hPa | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Impulse Voltage Type** | **Wave-form Name** | $U_t$ **(kV)** | $T_1$ **(µs)** | $T_2$ **(µs)** | $T_c$ **(µs)** | $\beta'$ **(%)** | **Occurrence of Flashover** |
| Positive full lightning impulse | LI-p1 | 786 | 1.30 | 51 | - | 4 | No |
| | LI-p2 | 786 | 1.30 | 51 | - | 4 | No |
| | LI-p3 | 792 | 1.29 | 51 | - | 4 | No |
| Negative full lightning impulse | LI-n1 | -420 | 1.47 | 48 | - | 4 | No |
| | LI-n2 | -794 | 1.45 | 48 | - | 4 | No |
| Negative chopped-lightning impulses | LI-cn3 | -794 | 1.45 | - | 4.1 | 4 | No |
| | LI-cn4 | -795 | 1.45 | - | 4.0 | 4 | No |
| Negative full lightning impulse | LI-n5 | -795 | 1.45 | 48 | - | 4 | No |
| | LI-n6 | -794 | 1.45 | 48 | - | 3 | No |
| *Uncertainty (%)* | | ± 3 | ± 8 | ± 6 | ± 6 | ± 2 | - |
| *Coverage Factor* | | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | - |

*Figure 4 - Results of lightning impulse tests*

As shown in the results above, the unit passes all impulse tests with no occurrence of a flashover. While expected, the intent of these tests was to stress the insulation system and re-examine the steady state partial discharge measurements.

## Post-test partial discharge measurement

Post-test partial discharge measurements were taken and comparted to pre-test measurements with results indicated an increase in partial discharge activity within the insulation system. These results support the theory that these current transformers were inherently susceptible to lightning and switching impulses and continued operation would have likely resulted in another failure. An overview of the partial discharge results is below.

| Ambient temperature: (19.5 ± 0.5) °C<br>Relative humidity: (60 ± 3) % R.H.<br>Test voltage uncertainty: ± 2.5 % | |
|---|---|
| **Test Voltage ($kV_{rms}$)** | **Maximum PD Magnitude within a 10 Seconds Period (pC)** |
| 173 | 408 |
| 147 | 379 |
| 103 | 368 |
| *Uncertainty* | ± 13 |
| *Coverage factor* | 2.0 |

*Figure 5 - Partial Discharge magnitude results after impulse tests*

### Forensic investigation

After completion of testing, the unit was returned to Powerlink and forensically investigated to confirm presence of discharge activity. Findings from this investigation found several location where the insulation system was compromised, similar to that of the B phase unit.

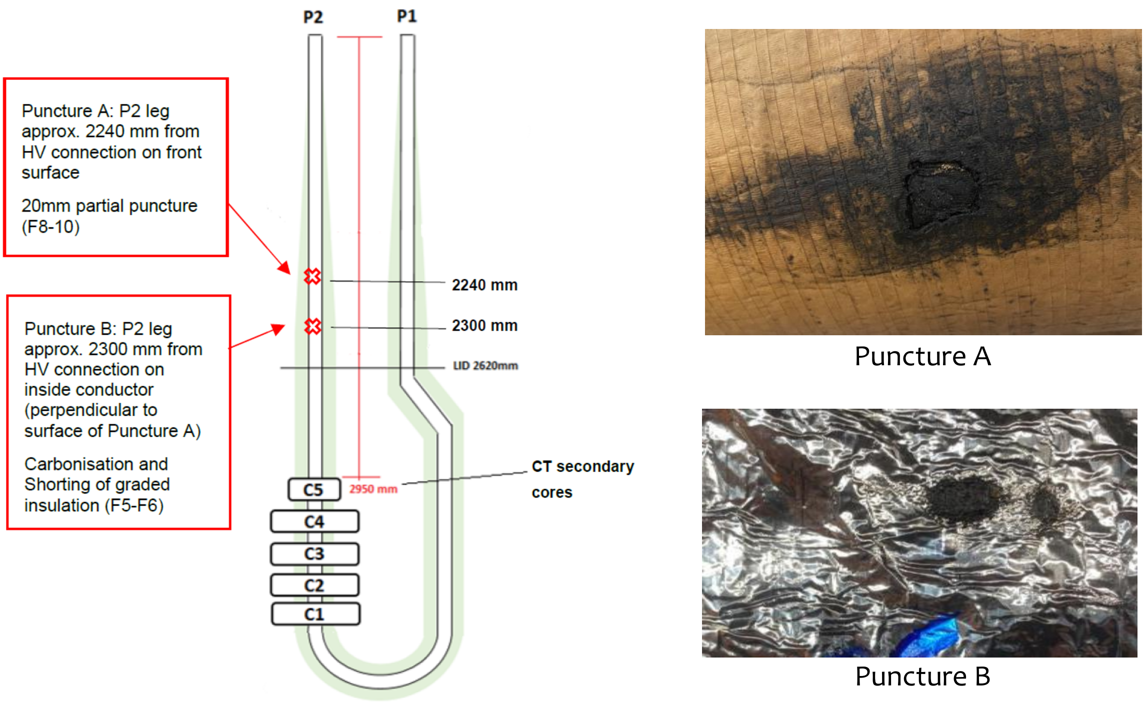


*Figure 6 - Location of PD activity in C phase current transformer*

## Post-incident partial discharge monitoring

As a risk mitigation measure following the incident, additional partial discharge surveillance was implemented at the site where the incident occurred. Several solutions were employed and explored to provide maximum monitoring and alert. The first line of defence was the use of unfiltered AM radios as a way early alert system to field based staff.

Further and more quantitative methods of partial discharge monitoring using both transient earth voltage (TEV) and ultra-high frequency (UHF) were utilised in an online network situation both continuously and ad-hoc.

Due to planned secondary systems replacement works in an adjacent section of the yard, a solution which did not require additional outages for plant was preferred. The chosen method of monitoring consisted of a monitoring unit with online TEV system with automated alerting. This provided asset owners with the ability to use real time data to make dynamic operational decisions and give the most forewarning to field based staff on the development of partial discharges. The system monitored continually for a period of 12 months following the failure, with no indication of further evolving faults. Additionally, the site was scanned manually using UHF technology on a routine bases to monitor for fault evolution.

## Recommendations

Overall this case study provides asset owners and operational organisations with an overview of the investigation following the explosive failure of a 275 kV oil filled current transformer and the implementation of Partial Discharge Monitoring to mitigate risk of further failures.

The forensic investigation of all three phases, including the laboratory testing provided a conclusive root cause analysis that enabled proactive solutions to be implements in order to mitigate risk to people, high voltage plant and the reliability of the network.

This implantation of partial discharge monitoring both continuous and ad-hoc provided operation staff with an additional level of safety confidence and is recommended in scenarios similar to this case study.