AMS 10-67 Power Transformers and Oil Filled Reactors

2023-27 Transmission Revenue Reset

PUBLIC

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1 Executive Summary

This document is part of the suite of Asset Management relating to AusNet Services electricity transmission network. The purpose of this document is to outline the inspection, maintenance, replacement and monitoring activities identified for economic lifecycle management of the fleet of terminal station power transformers and oil filled reactors.

The Regulatory Information Notice (RIN) for the 2018-19 financial year reports a total of 165 power transformers and 11 oil filled reactors. Of the listed transformers there are 30 single phase tanks that constitute 10 single phase transformer banks. 16% of the transformer population is installed in the shared market operating at 275kV facilitating large scale generation and state interconnections. The remaining 84% are connection assets directly supplying customers.

Successive transformer replacement projects over the last 15 years mean that 55% of the population of transformers are less than 20 years old and well within their useful life. The condition score reflects this with 68% of these transformers with an overall condition score of C1 and C2. However, specific issues, such as contaminated oil, mean that 32% are condition C4 where addressing the specific issue will improve the condition – early replacement is not feasible. Of the 45% of transformers replacement can be delayed by addressing specific issues such as replacement of deteriorated porcelain bushings, replacing winding temperature indicators

The consequence of a failure – 'Asset Criticality' – assessment is based on community impact due to outages, safety, environment and collateral damage risks. Porcelain housed & oil filled bushings pose a high risk of safety, collateral damage and environmental risk due to the inherent explosive and oil fire risk. The asset criticality methodology is detailed in the asset risk overview document – AMS 01-09.

Risk based assessment on monetised consequence of failure was performed revealed an economically sound replacement program for high risk circuit breakers during the period 2022-27.

Wholesale transformer replacements and treatment of corrosive sulphur contaminated oil are proposed external to this document. The strategies in document are aimed at addressing specific issues by component replacement and additional condition monitoring. This is primarily aimed at extending the life of individual transformers. Proactive management of transformers is required to ensure that stakeholder expectations of cost, safety, reliability and environmental performance are met in a cost vs risk assessment.

The summary of proposed asset strategies is listed in 1.1:

1.1 Strategies

1.1.1 New Installations

- Continue to invest the early stages of procurement continue to have very few early life issues – i.e. specification and auditing of the manufacturing process.

1.1.2 Condition Monitoring

- Install bushing monitoring on selected critical transformers with deteriorated bushings.
- Continue periodic offline HV condition monitoring tests.

- Develop transformer data analysis capability utilising the Information Management platform to optimise maintenance and replacement programs.

1.1.3 Maintenance

- Continue scheduled preventative maintenance as per specific standard maintenance instructions.
- Continue to update/create measurement points in SAP to capture condition information.
- Continue to update maintenance instructions and plans as new deterioration trends become apparent.

1.1.4 Spares Holding

- Continue to hold spare transformers at strategic network locations as per transformer spares holding policies

1.1.5 Refurbishment

- Address risk of diverter switch deterioration due to oil contaminated with corrosive sulphur – specific proposals are outside the scope of this document.

1.1.6 Replacement

- Continue risk-based transformer replacement based on the core and winding intrinsic end of life condition score and transformer asset criticality – specific proposals are outside the scope of this document.
- Replace porcelain OIP (oil impregnated paper) and SRBP (synthetic resin bonded paper) with advanced deterioration.
- Replace the deteriorated PIBs (phase isolated buses) at Hazelwood Terminal Station (HWTS) to prevent transformer failures.
- Replace deteriorated and faulty WTIs (winding temperature indictors) to ensure correct transformer loading.

2 Introduction

2.1 Purpose

The purpose of this document is to outline the inspection, maintenance, replacement and monitoring activities identified for economic lifecycle management of the fleet of terminal station power transformers and oil filled reactors. The document is intended to communicate the basis for asset management decisions.

In addition, this document forms part of the AusNet Services Management System for compliance with ISO 55000 and relevant regulatory requirements. The document demonstrates responsible asset management practices by outlining economically justifiable outcomes.

2.2 Scope

This strategy includes:

- Regulated Transmission Power Transformers with nominal primary winding voltage ranging from 66kV to 500kV.
- Oil Filled Reactors with nominal primary winding voltage ranging from 22kV to 500kV.

The strategy excludes:

- Unregulated Transformers
- Air Core Reactors
- Station Service Transformers
- Special Purpose Auxiliary Reactors (e.g. SVC Transformers)

2.3 Asset Management Objectives

As stated in *AMS 01-01 Asset Management System Overview*, the high-level asset management objectives are:

- Maintain network performance at the lowest sustainable cost;
- Meet customer needs now and into the future;
- Be future ready;
- Reduce safety risks; and
- Comply with legal and contractual obligations.

As stated in *AMS 10-01 Asset Management Strategy -Transmission Network*, the electricity transmission network objectives are:

- Maintain top quartile benchmarking;
- Maintain reliability;
- Minimise market impact;
- Maximise network capability;
- Leverage advances in technology and data analytics;
- Minimise explosive failure risk.

3 Asset Description

3.1 Asset Function

Transformers are required to transfer power between circuits of different operating voltages.

The power transformer fleet has nameplate ONAN (oil natural air natural)[1] ratings ranging from 30MVA to maximum continuous power ratings of 1,000MVA.

3.2 Asset Population

Section 5.2 of the Regulatory Information Notice (RIN) for the 2018-19 financial year reports a total of 165 power transformers and 11 oil filled reactors. Of the listed transformers there are 30 single phase tanks that constitute 10 single phase transformer banks. The following population charts consider three phase banks and three winding transformers as transformer functions and base the percentage splits on transformer functions.

3.2.1 Power Transformers

Figure **1** show the population of transformers against age and voltage.

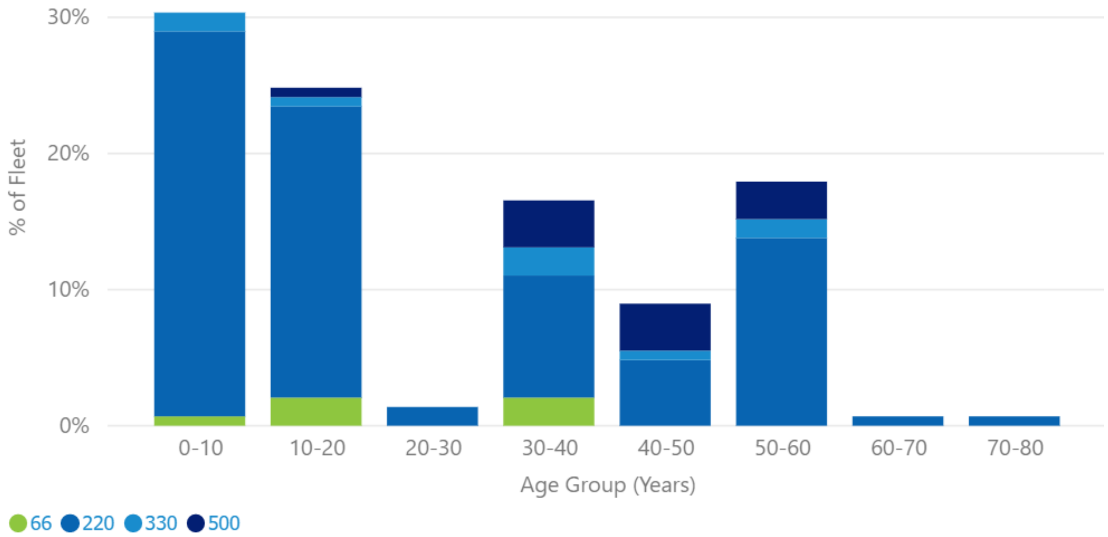

Figure 1 - Age

Transformers with secondary winding with nominal voltage of 66kV and below supplying distribution network operators (DNO's) with a connection agreement are referred to as connection transformers. They include "B", "L", "X" and "U", and are charted against age and voltage in Figure 2.

[1] Refers to the thermal capability of the transformer with an assisted means of cooling – oil pumps and radiator fans.

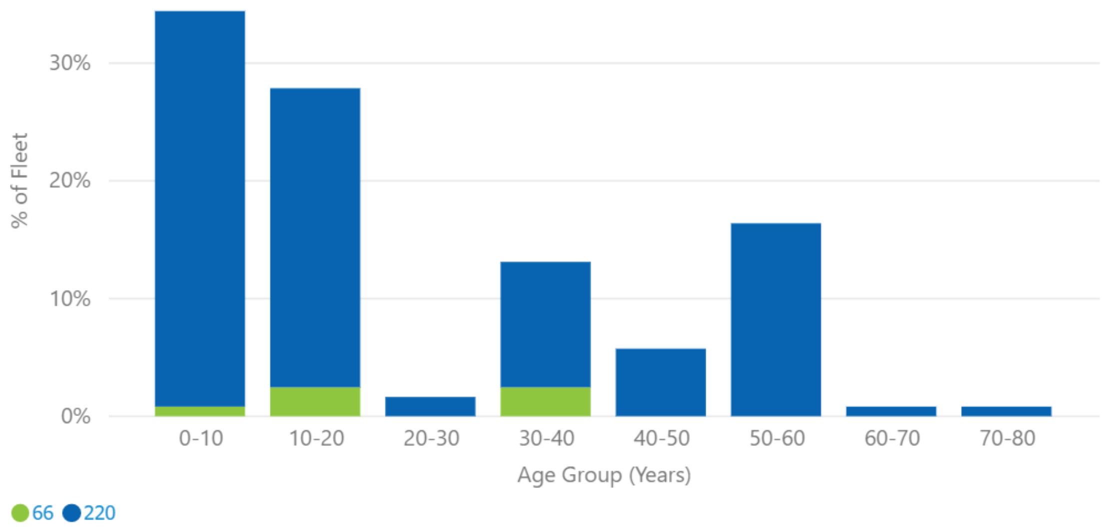

Figure 2 – Age Connection Assets per Voltage

Transformers with nominal secondary winding voltage of 220kV or above contribute to the reliable function of the national electricity market (NEM) – they are main tie transformers within the shared network. They are referred to throughout this document as shared transformers, and include “A”, “F”, “M” and “H” transformers. The population against age and voltage for shared transformers are plotted in Figure 3:

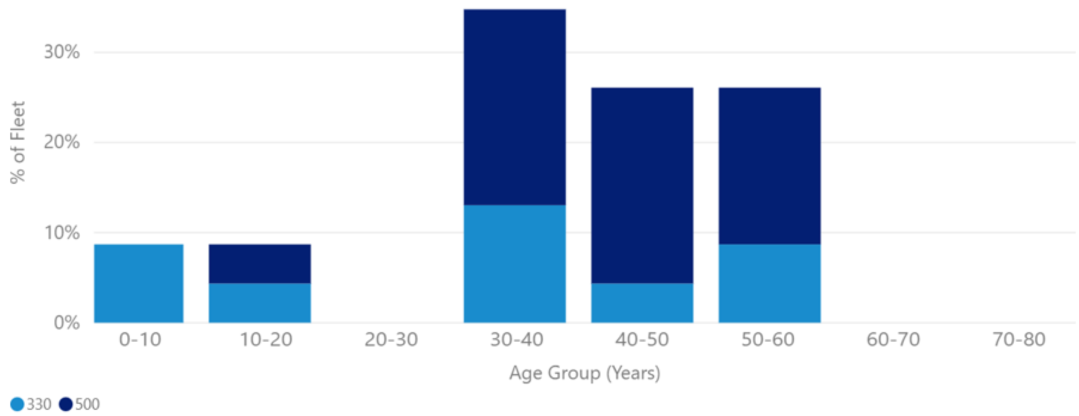

Figure 3 - Age Shared Assets per Voltage

Similarly, Figure 4 plots transformers against winding configuration – three phase transformers or single-phase banks.

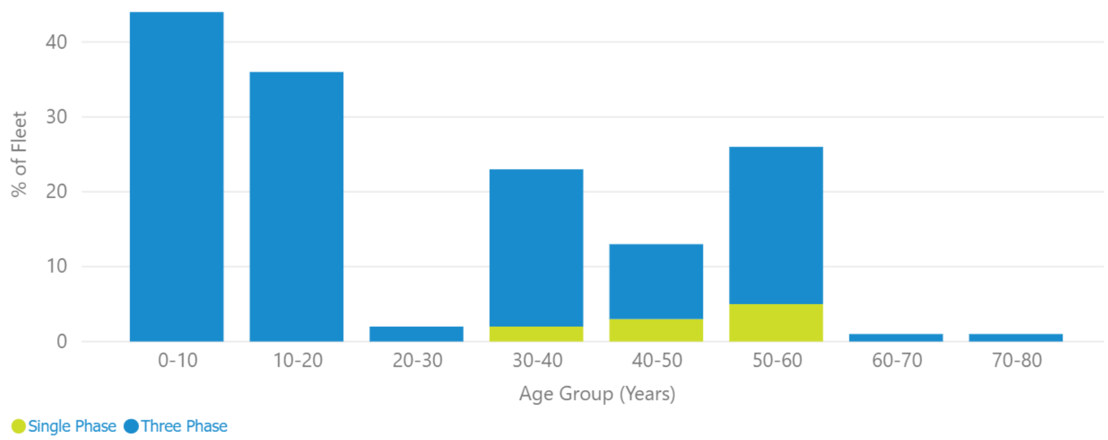

Figure 4 - Age per Winding Configuration

3.2.1 Oil Filled Reactors

The fleet of oil filled reactors are plotted against age and voltage in Figure 5:

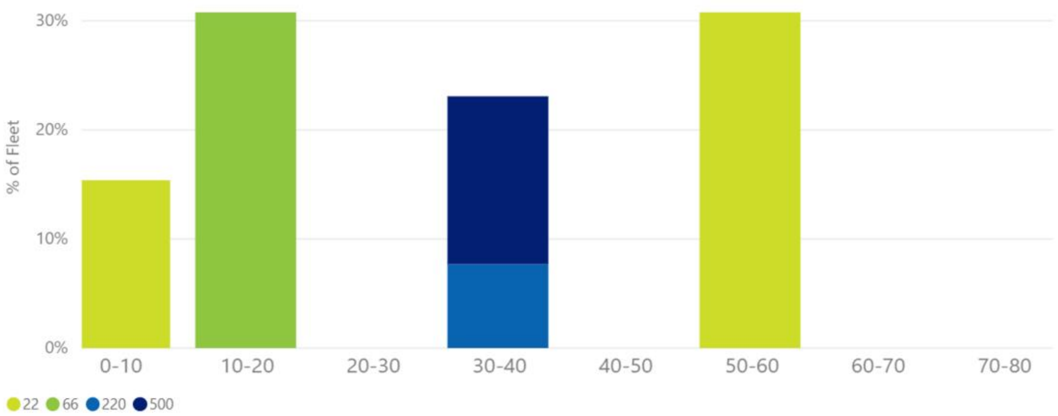

Figure 5 – Oil Filled Reactors per Age and Voltage

In general, the fleet of oil filled reactors are newer than power transformers. The column at 56 years are the L transformer series reactors at WMTS. These reactors are intrinsically linked to the L transformers at WMTS, any will be required until the 22kV switchboard is retired in the medium term.

3.2.2 Manufacturers

Unlike large population fleets, transformers are largely unique in their design and construction. Optimised designs of transformers began in 1960's reaching maturity in the 1980s.

3.2.3 Vector Group

In addition to having different primary/secondary voltages and manufacturers, the fleet of power transformers also have different 'vector groups' as per Figure 6. The ways in which the three-phase windings in a transformer are connected determine which vector group the transformer belongs to.

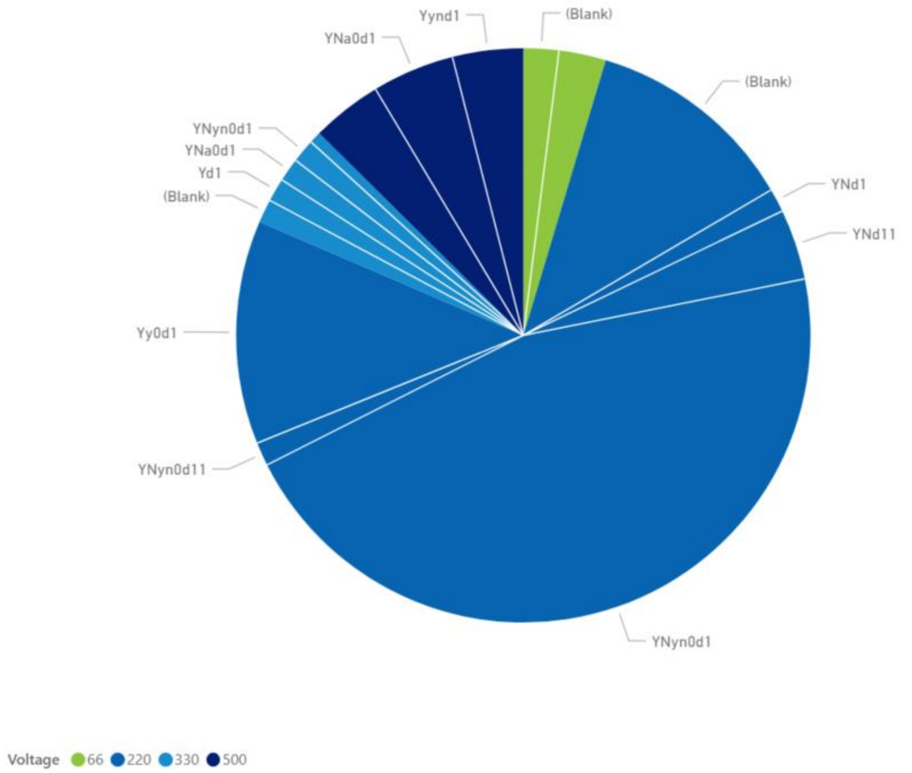

Figure 6 – Percentage of Total Transformer Fleet by Vector Group

3.2.4 Spares

The population of power transformers consists of strategic spares and emergency spares.

Strategic spares are designed to be used universally for voltage and a vector configuration. They become the permanent transformer once used unless they are grossly over-specified for the application, and it is economic to shift again to be retained as a spare. Table 1 lists the strategic spare transformers.

Table 1 – Strategic Spare Transformers

Station	Transformer Name	Primary Voltage	Nominal Rating (MVA)	MANUFACTURER	AGE	Vector Group	Overall Condition
MBTS	B1 - HOT SPARE	220	50	[C-I-C]	14	YNyn0d1	
MLTS	SPARE A	500	333.3	[C-I-C]	14	YNa0d1	
HWTS	SPARE A	500	200	[C-I-C]	52		4
KTS	SPARE A	500	250	[C-I-C]	49		3
KTS	SPARE COUNTRY	220	150	[C-I-C]	2	YNyn0d1	1
SMTS	SPARE COUNTRY	220	150	[C-I-C]	3	YNyn0d1	1
SMTS	SPARE F	500	333.3	[C-I-C]	38		3
HTS	SPARE METRO	220	150	[C-I-C]	2	YNyn0d1	1
TTS	SPARE METRO	220	150	[C-I-C]	2	YNynd01	1
BLTS	SPARE U	66	60	[C-I-C]	13	YNyn0d1	4

Emergency spares are intended to be used to temporarily provide service in the event of a failure, until a permanent replacement is implemented. They consist of:

- Retired transformers that remain on site and are maintained to a short-term serviceable state. These are listed in Table 2.
- Retired transformers that remain on site in a disposed or out of service status and are not maintained. This a tactical approach to salvage transformers in an emergency. This is a third tier of spare support and the transformers are not part of the regulated asset base (RAB). They are listed in Table 3.

Table 2 - Emergency Spares (In Service)

Station	Transformer Name	Primary Voltage	Nominal Rating (MVA)	MANUFACTURER	AGE	Vector Group	Overall Condition
RTS	B4 - HOT SPARE	220	150	[C-I-C]	52	Yy0d1	
SMTS	H2 - HOT SPARE	330	233.3	[C-I-C]	52	Yd1	
SMTS	H2 - HOT SPARE	330	700	[C-I-C]	52	Yd1	
SMTS	H2 - HOT SPARE	330	233.3	[C-I-C]	52	Yd1	
SMTS	H2 - HOT SPARE	330	233	[C-I-C]	52	Yd1	
YPS	SPARE	220	54	[C-I-C]	70	YNd11	4
BLTS	SPARE EX - B4	220	150	[C-I-C]	53	Yy0d1	

Table 3 - Emergency Spares (Disposed)

Station	Transformer Name	Primary Voltage	Nominal Rating (MVA)	MANUFACTURER	AGE	Vector Group	Overall Condition
MWTS	Ex B2	220		[C-I-C]	49	Yyn0d1	
DDTS	Ex H1 Bph	330	75	[C-I-C]	57		
DDTS	Ex H1 Wph	330	75	[C-I-C]	61		
DDTS	OOS H Spare Bph	330	75	[C-I-C]	61		
DDTS	OOS H Spare Rph	330	75	[C-I-C]	61		
DDTS	OOS H Spare Wph	330	75	[C-I-C]	61		

The inventory of spare transformers to be configured to match 92% of in-service transformers. Notable exclusions are:

- 330/66/22 X transformers at WOTS
- SVC transformers at ROTS, HOTS, KGTS
- 230/11kV YPS and 66/11kV LYPS Power Station supplies
- 500/275kV M transformers at HYTS
- 500/220kV three phase A transformer at HWTS

The case for purchasing a spare transformer for WOTS is being reviewed.

The asset criticality to date has not driven a spares strategy for the SVC transformers.

The power station transformers are planned to be management with a combination of redundancy.

There are no specific spares for the 500/275kV M transformers at HYTS and the three phase A transformer at HWTS. There is however enough redundancy to sustain the failure of a single transformer for the short term.

3.3 Asset Condition

Asset condition refers to the conditional probability of failure. When combined with asset criticality an asset risk score can be produced. Asset management decisions are not based on condition alone.

Section 3.3.1 provides a view of the conditional failure probably of the fleet of transformers and oil filled reactors. Section 3.3.2 compares the fleet condition profile to the age profile to give an indication of the effectiveness of the transformer and oil filled reactor asset management practices.

3.3.1 Fleet Condition

The asset health report document AHR 10-141 details the condition assessment methodology used to give the transformers and oil filled reactors an end of life condition score (C1 to C5). The end of life condition score gives an asset a distributed probability of suffering a failure, where the economically feasible means of reinstating the asset function is a wholesale asset replacement. Table 4 summarises the meaning of each of the condition scores for transformers.

Table 4 – Condition Score Definition

Condition Score	Condition Scale	Condition Description	Remaining Service Potential
C1	Very Good	Initial Service Condition	95%
C2	Good	Relatively new, no known issues identified.	70%
C3	Average	Average condition, some minor defects identified. Early signs of deterioration and condition or performance.	45%
C4	Poor	Advancing deterioration – life ending failure highly likely within 10 years without remedial action	25%
C5	Very Poor	Extreme deterioration – life ending failure highly likely within 5 years without remedial action	15%

Component scores are then produced for on load tap changer (OLTC), bushings, external components, oil, core and coil. An overall condition score is then produced to show the weighted likelihood of failure due to any of the transformer subcomponents.

Sub-components are worse than the overall condition, because remedial action can be taken to improve their condition. If not addressed, however, they can often result in the unrecoverable failure of the transformer.

For the core and coil there is no feasible means of improving the condition. Some means such as drying paper and oil and re-clamping may slow the rated of deterioration but are high risk activities. Deterioration of paper is therefore considered to be the limiting life factor and as a result provide the greatest weighting for the overall score. Where OLTCs cannot feasibly be retrofitted, failure of an OLTC is also terminal.

The following two sections – 'Power Transformers' and 'Oil Filled Reactors' – plots the overall condition scores, as well as the subsystem condition scores:

- core and winding
- oil
- OLTCs
- bushings
- external components.

Figures 7 to 17 shows the condition profile of major components of 'Power Transformers' and 'Oil filled Reactors'.

Power Transformers

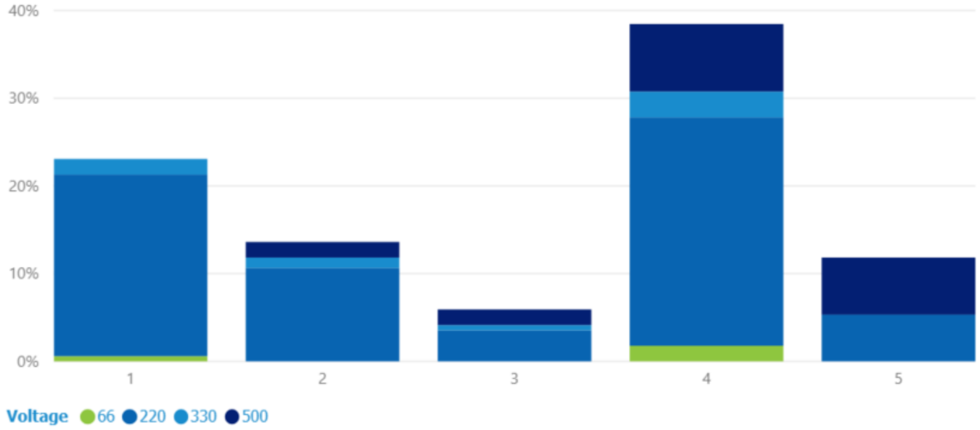

Figure 7 - Transformer Overall Condition per Voltage

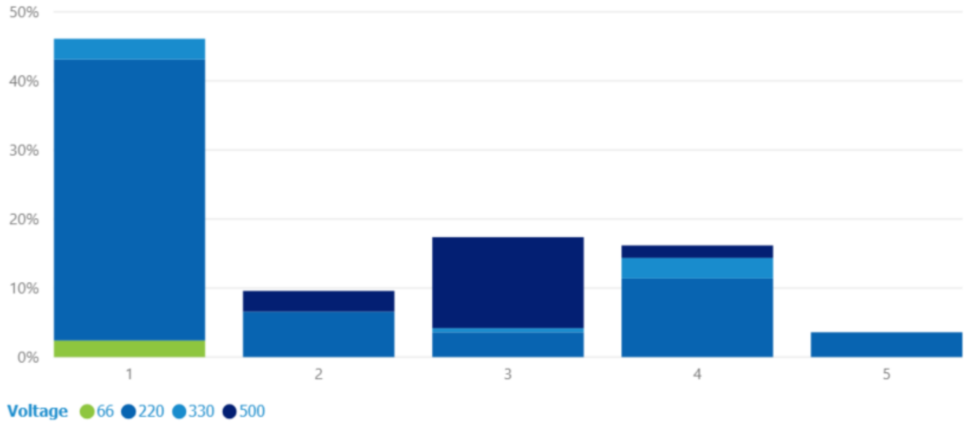

Figure 8 - Transformer Core and Winding Condition Score per Voltage

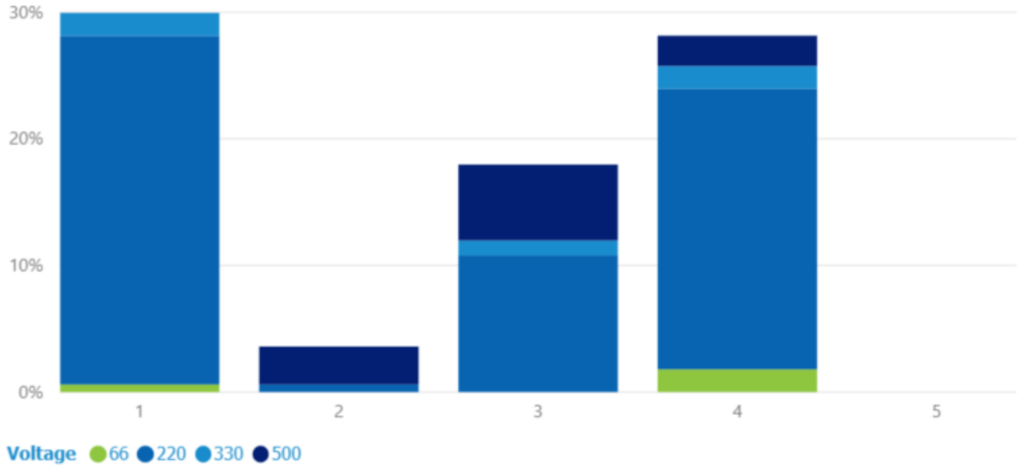

Figure 9 - Transformer OLTC Condition Score per Voltage

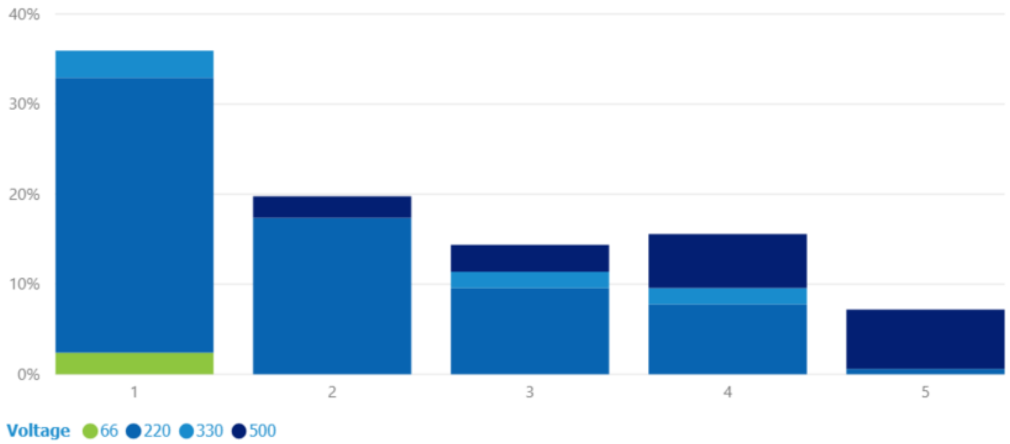

Figure 10 – Transformer Bushing Condition Score per Voltage

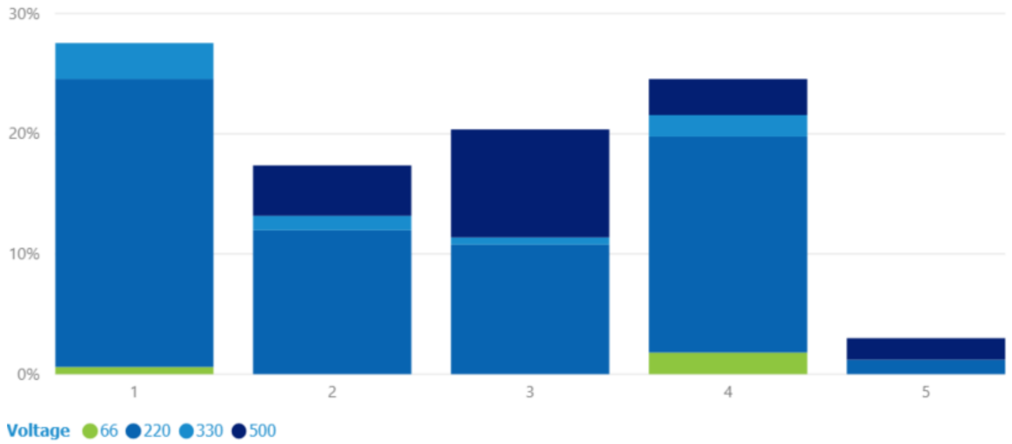

Figure 11 - Transformer Oil Condition Score

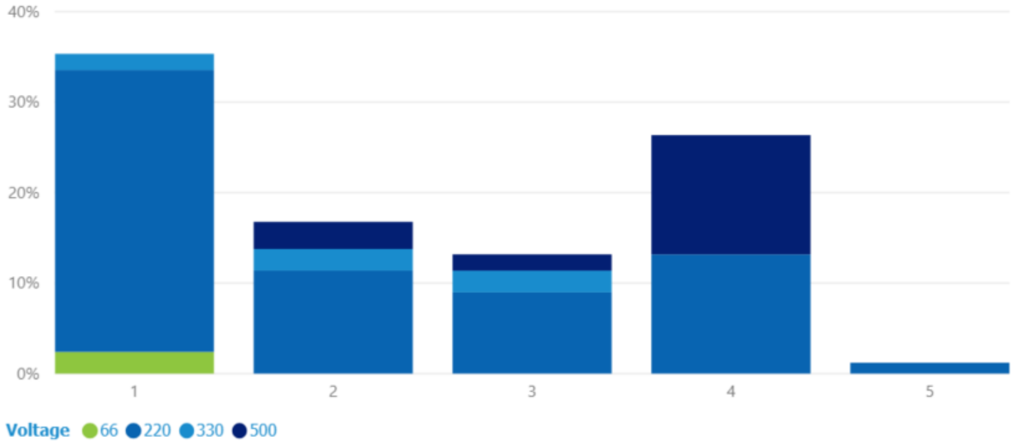

Figure 12 - Transformer External Components Condition Score per Voltage

Oil Filled Reactors

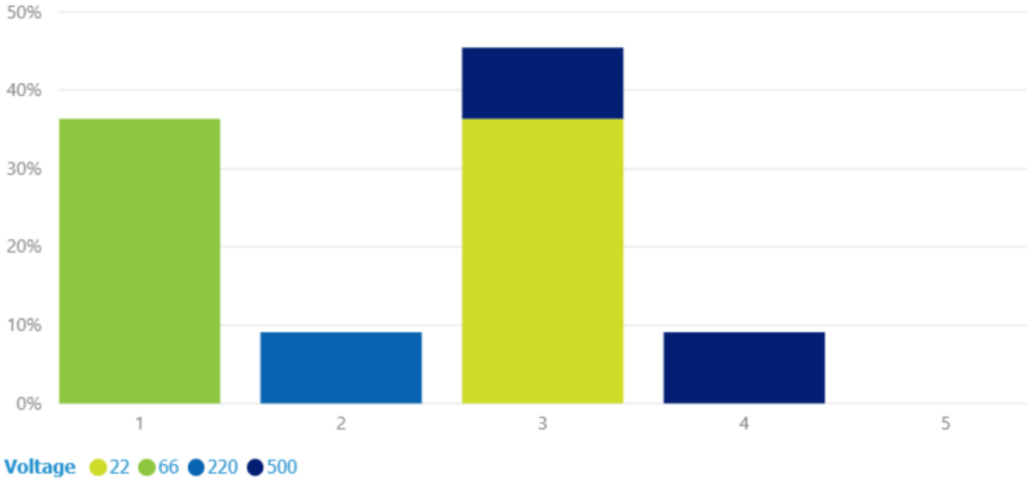

Figure 13 - Oil Filled Reactor Overall Condition Score per Voltage

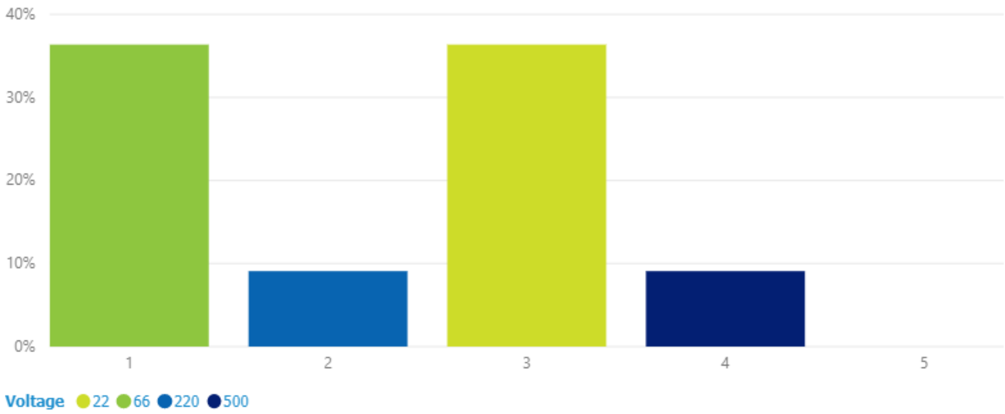

Figure 14 - Oil Filled Reactor Core and Winding Condition Score per Voltage

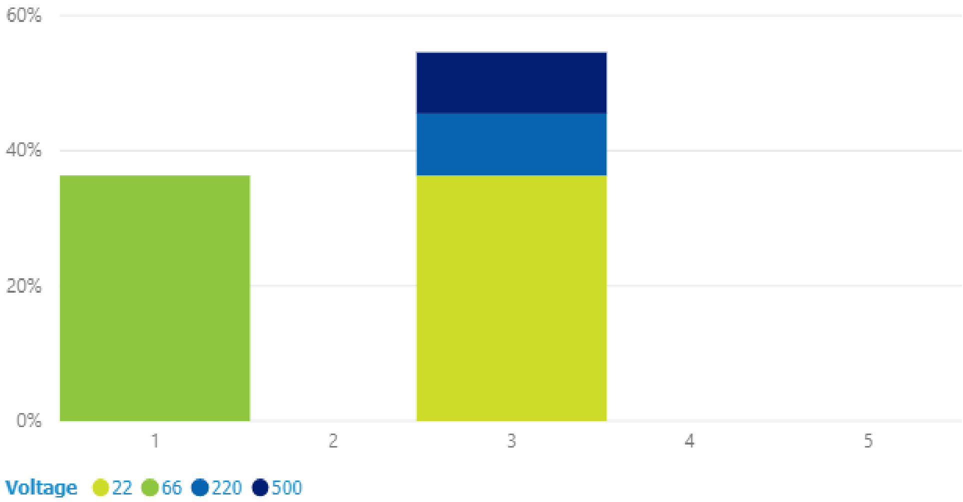

Figure 15 - Oil Filled Reactor Bushing Condition Score per Voltage

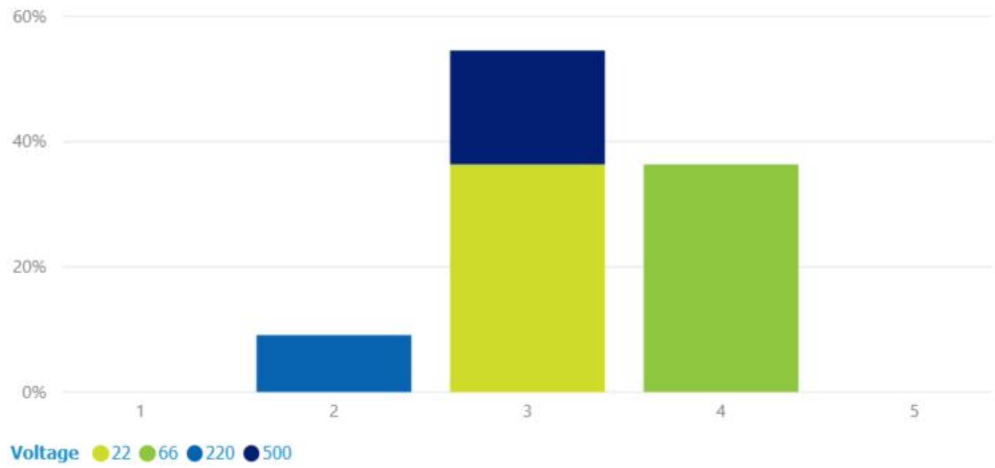

Figure 16 - Oil Filled Reactor Oil Condition Score per Voltage

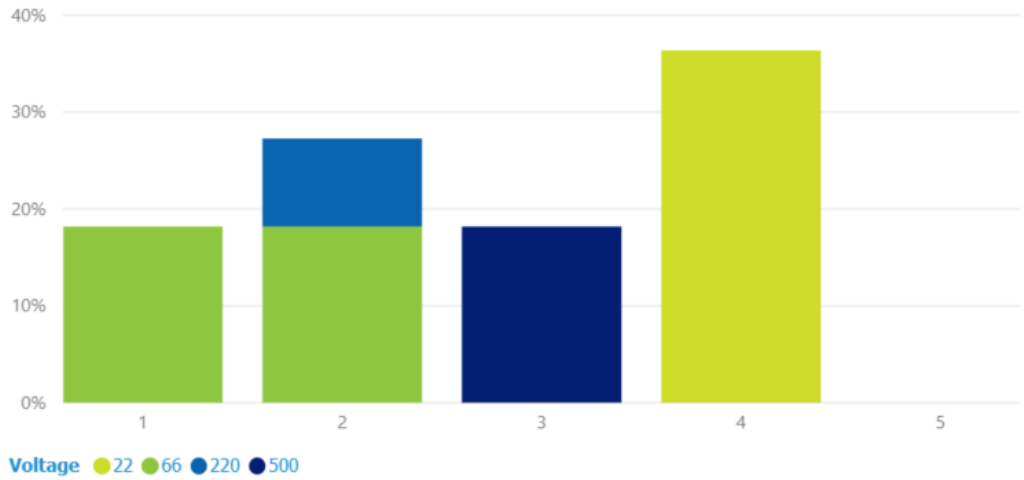

Figure 17 - Oil Filled Reactor External Component Condition Score per Voltage

3.3.2 Age versus Condition

Figure 18 overlays the overall transformer condition over the age distribution:

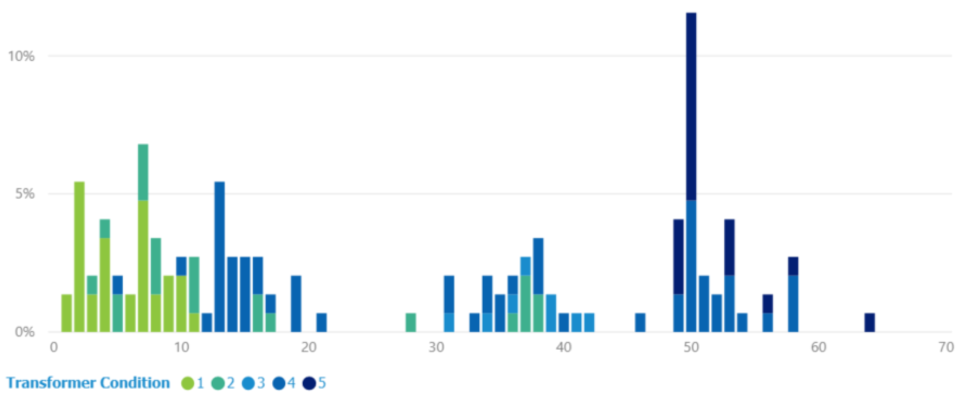

Figure 18 - Transformer Age vs Condition

Condition 1 generally aligns with new transformers and condition 5 with the oldest transformers. Transformers between 30 and 40 vary from condition 2 to 4 depending on the behaviour of the individual transformer.

The major deviation from the expected chart relates to a cluster of condition 4 transformers in the 10 to 20-year age bracket. The poor score in these cases is being driven by the issue of corrosive sulphur contaminated oil, which is discussed in section 4.1.2. Unless mitigated the advanced deterioration to metal components, particularly silver-plated contacts in the OLTC, will deteriorate a transformer well in advance of its years. This runs the risk of an in-service failure.

3.4 Asset Criticality

Asset criticality is a measure of the severity of the consequence of an asset failure. Figure **19** show the percentage spread of transformers and oil filled reactors in a five-point ranking:

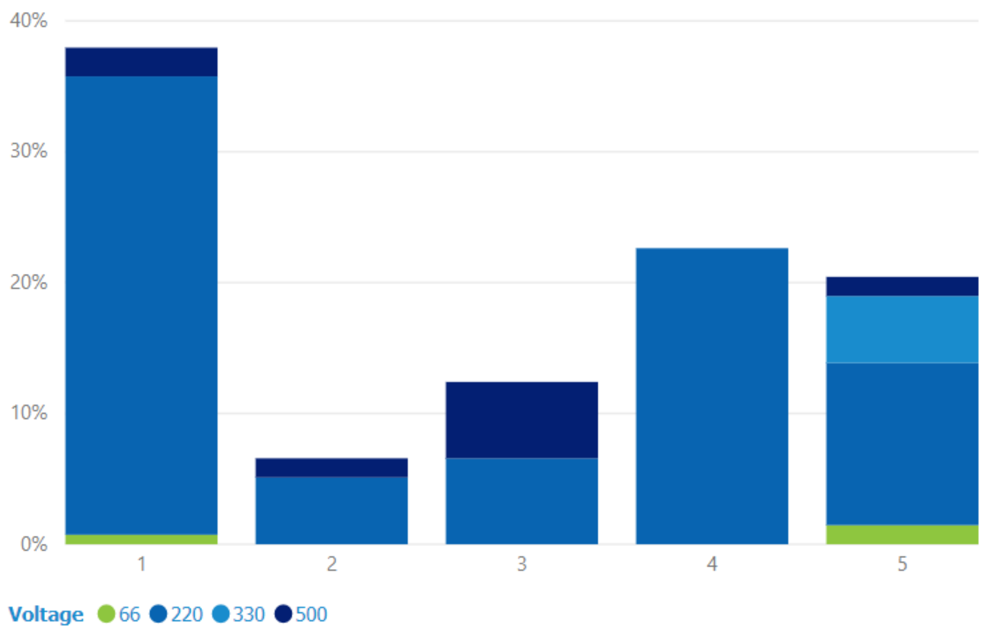

Figure 19 - Transformer Market Criticality per Voltage

The five-point rank is based on the ratio of monetised failure consequence to the cost of replacing an asset. Table 5 shows the ratio, while Table 6 shows the transformer replacement costs used.

Table 5- Criticality Ranking

Criticality Ranking	Economic Impact
1	< 0.3x
2	< 1x
3	< 3x
4	< 10x

5	>10x

Table 6 – Direct Cost Estimates

Task	Transformer Replacement Cost ($k)
Replace > 330kV	27,000
Replace > 220kV	18,000
Replace > 66kV	7,000
Replace <= 66kV	3,000

Monetised criticality for transformers and oil filled reactors is an aggregation of five types of consequences:

- supply
- safety
- bushfire
- collateral damage.

The methodology for determining the asset criticality is detailed in the Asset Risk Overview Document – AMS 01-09.

3.5 Asset Performance

3.5.1 Notification Analysis

Figure 20 shows ZA (condition-based maintenance) and ZK (failure) notifications for power transformers per financial year. There have been on average 111 notifications annually over the last five years.

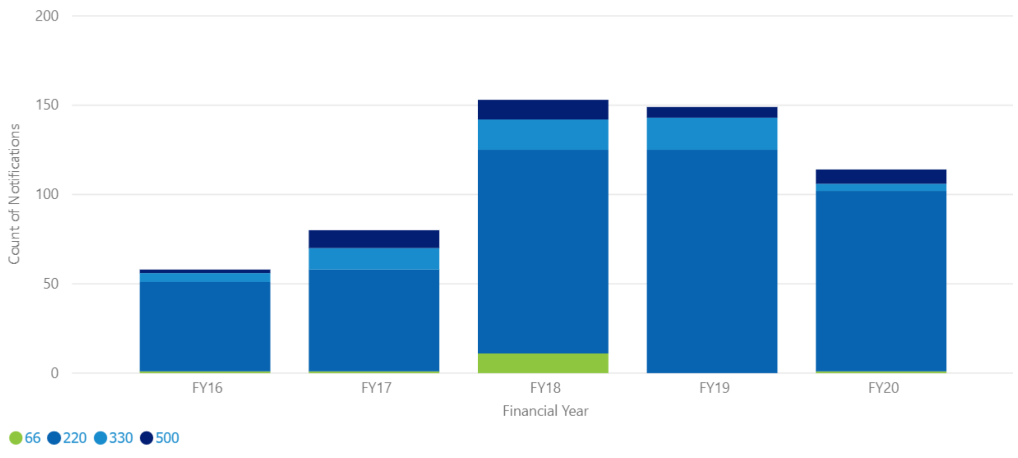

Figure 20 - ZA and ZK Notifications per Financial Year and Voltage

The majority of notifications relate to 220kV transformers. Figure 21 shows the breakdown of notifications over the five-year period (2015-2019) by voltage and notification object type.

Within 220kV power transformers, the majority of failures relate to cooling fans followed by control circuits and oil.

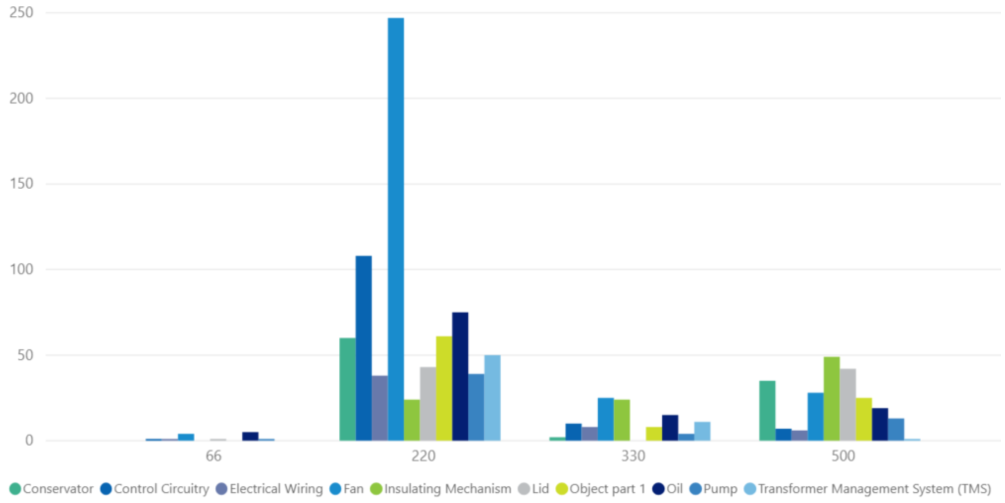

Figure 21 - Top 10 Notifications 2015-2019 per Voltage and Notification Object

3.5.2 Major Failures

Appendix 1 – Major Failures lists major failures that have occurred within the transmission network that in most cases have resulted in the complete replacement of a transformer. Failures since 2015 relate to OLTC contamination and winding displacements resulting from close in faults. In all cases the failures have prompted inspections of the rest of the fleet and a review of the maintenance practices. Headings 4.1.4 and 4.2.1 respectively summarise two issues of fault level incapacity and maintenance intensiveness of OLTCs.

4 Other Issues

The following sections summarise the major issues that require remediation actions within this strategy document, individual replacement program and the corrosive sulphur OPEX plan. More details and specific issues are included in the transformer asset health report AHR 10-141.

4.1 Core, Winding and Tank

4.1.1 Moisture Content

Moisture reduces dielectric strength of oil-paper insulation, which can lead to the inception of partial discharges or dielectric thermal runaway at elevated ambient temperatures. The degradation is pronounced with increased load and moisture levels of greater than 4%.

Free-breathing transformers installed prior 1978 are exhibiting elevated levels of moisture.

The H1 and H2 transformer banks at South Morang terminal station (SMTS) are exhibiting a high transformer oil and insulation moisture level.

4.1.2 Corrosive Sulphur

Oil supplied between 1990 to 2006 potentially contains corrosive sulphur. Corrosive sulphur will lead to premature degradation of copper windings.

Tests on the 66 transmission transformers that potentially contain corrosive sulphur, have shown that corrosive sulphur is present 72% of the time.

Oil passivator has proven successful against copper degradation, however recent industrial findings have indicated that corrosive sulphur can cause corrosion to the silver contacts of OLTC selector. The only way to halt degradation of silver tinned contacts is to process the oil.

4.1.3 Paper Insulation Deterioration

Deterioration paper winding insulation is a function of temperature, moisture, oxygen and certain products of oil oxidation.

Paper insulation with a degree of polymerisation (DP) lower than 200 mechanically weakens the winding to the point it can no longer mechanically withstand through faults to its original specification. This is an unrecoverable condition for a transformer. Any decision to keep a transformer in-service at this point is one based on the probability that a large through fault will not occur.

4.1.4 Fault Levels

Thermal aging of transformers insulation leads to mechanical weakening of the insulation structure and increased risk of damage to due to the sudden electromagnetic forces created by short circuit through currents.

The early pre-computer aided design calculations used for designing transformer to withstand system faults has been found lacking when measured up against present evaluation methods.

[C-I-C] 'B' transformers installed between the 1960s and 1980s in highly loaded stations are vulnerable.

4.2 On Load Tap Changers (OLTCs)

4.2.1 Maintenance intensiveness (oil vs vacuum)

Oil type OLTCs (On Load Tap Changers) are maintenance intensive and present a transformer life ending if not correctly maintained. [C-I-C] OLTCS require assistance from the manufacturer compounding this expense.

[C-I-C] class M and ABB UC oil filled OLTCs installed in the 1990's and early 2000's can be retrofitted with vacuum OLTCS.

Vacuum OLTCs can perform up to 600,000 before invasive maintenance is required. Compared to maintenance every four years for oil OLTCs, vacuum OLTCS potentially won't require invasive maintenance over the life of a transformer.

Oil type OLTCs are maintenance intensive and present a transformer life ending if not correctly maintained. [C-I-C] OLTCS require assistance from the manufacturer compounding this effect. Oil filled OLTCs can be replaced with vacuum OLTCs which required very little maintenance and have a long life.

4.3 Bushings

4.3.1 Deteriorated Bushings

Several oil impregnated paper (OIP) and synthetic resin bonded paper (SRBP) have advanced deterioration of insulation. Three dominant causes are moisture, oil degradation and paper deterioration.

Additionally, due to their construction, SRBP bushings manifest deterioration in core delamination leading to oil leakage into the main tank.

4.3.2 Maintenance and Online Monitoring

The condition of bushings is currently determined by offline electrical tests and oil sampling. Due to generation and interconnection constraints, transformers on the shared network are becoming increasing difficult to take off line for testing. However, the safety consequences of a failure mean the condition still needs to be determined. On solution is to install on-line monitors on 'market' critical transformer that trigger inspection or replacement once acceptable threshold is breached.

4.4 Protection, Control and Auxiliary Components

4.4.1 Winding Temperature Indicators and Cooler Control

'Thermal Image' used in transmission transformers are sensitive to changes in ambient temperature in the sensing pocket. This may result in inaccurate winding temperature readings.

There are 10 [C-I-C] transformers currently in service. They have a thermal performance design deficiency that results in accelerated winding deterioration at elevated loading. There is evidence of extreme winding deterioration on the [C-I-C] transformers at WMTS, HTS and SVTS.

There are still several transformers that do not have winding temperature control of the transformer-forced cooling system. Winding temperature control allows cooler start settings to be optimised slowing deuteriation of solid insulators.

4.4.2 Phase Isolated Bus (PIB)

PIBs (Phase Isolated Buses) are installed on the A transformers at HWTS and KTS, SMTS F2 and MLTS A1. The PIBs on the A2, A3, and A4 single phase transformers at HWTS are condition C4. Water leaks will eventually lead to an earth short that's causes a winding failure in one of the phases. The transformers are a critical as they supply power from the generators in the La Trobe Valley and damage to an A transformer phase will result in generation constraint for a period of at least 6 weeks.

Deterioration PIBs at HWTS is exacerbated in comparison to other installations as their construction contains many vertical intersection expansion joints. This allows elevated rate of moisture ingress.

5 Risk and Option Analysis

5.1 Risk Assessment

The following four risk matrices display the relative criticality and condition based on the entire transformer, the core and winding, bushings, and OLTCs. Section 5.1.3 and 5.1.4 don't include planned and approved projects and component risk will be reduced by the complete replacement of a transformer.

5.1.1 Overall Transformer

The overall transformer risk uses the weighted overall condition. This shows the current risk with a probability of transformer failure that can be reduced by refurbishment, component replacement, and revised maintenance strategies, and addition to overall replacement. Figure **22** doesn't necessarily show the terminal risk where replacement is the only feasible strategy to reduce the risk. However, it is an accurate reflection of risk if no actions were taken over and above BAU.

Examples of this include:

- Poor Condition Porcelain bushings – they represent a small component of an unrecoverable transformer failure, but a greater risk of injury to personnel in the event of a failure. Replacement of the bushings will reduce this risk without the need to replace the whole transformer.
- Oil containing corrosive sulphur – show up Figure **22** with elevated risk. Processing of the oil will return the transformer to a moderate risk without the need to replace the whole transformer.

Crit. / Cond.	C1	C2	C3	C4	C5
5	3	7	4	14	0
4	8	4	3	14	2
3	1	1	1	12	2
2	4	1	1	3	0
1	21	8	1	13	9

Figure 22 - Transformer Risk Matrix

Assets in risk band 4 (red) present the highest risk to the network. Where transformers are also in condition 4 and 5, then remedial works including replacement and refurbishment will mitigate risk. For transformers in risk band 4 in condition 3 will benefit little from remedial work, station reconfiguration or augmentation will mitigate risk in these instances. Approximately 20% of transformers are in risk band 4 with an overall condition of C4 or worse.

Generally, OLTCs in transformers in the transmission network can be replaced, meaning that, unlike the distribution network, OLTCs don't represent the terminal risk of a transformer.

5.1.2 Core and Winding

The life of a transformer is limited by the condition of the core and winding - thus, the only feasible risk mitigation strategy is transformer replacement. Figure **23** show approximately 8% of the transformer fleet should be considered for replacement within the 2021-25 TRR period – risk band 4, condition 4 and 5.

Crit. / Cond.	1	2	3	4	5
5	18	2	4	4	0
4	18	2	3	7	1
3	4	2	7	4	0
2	6	3	0	0	0
1	31	5	4	7	5

Figure 23 - Risk Matrix based on Core and Winding Condition

The considerations for replacement are documented in individual planning reports.

5.1.3 Bushings

Figure **24** shows the risk matrix for bushings. Bushings in risk band 1 are new polymer clad resin impregnated paper (RIP) that represent a very minor safety risk, and a high probability of preventing an oil leak in the event of a failure. Risk band 3 and 4 porcelain clad oil OIP and synthetic resin bonded paper (SRBP) with an elevated probability of safety risk. The former has a relatively higher chance of preventing an oil leak in the event of a failure.

Crit. / Cond.	C1	C2	C3	C4	C5
5	9	0	3	0	0
4	3	6	10	18	2
3	60	29	8	20	20
2	132	117	80	45	3
1	271	38	4	13	0

Figure 24 - Bushing Risk Matrix

Bushings in risk band 4 and condition C4 and C5 present the greatest safety and unserved energy risk, where bushing replacements are required by the end of the 2021-26 TRR period. Most bushings in this category are of porcelain oil impregnated paper (OIP) construction with elevated probability of safety hazard and oil leak that could damage the transformer.

Two groups of bushings are showing up as emerging risks, where increased deterioration will place them in the highest risk category. The groups are:

- risk band 4 and condition C3
- risk band 3 and condition C3
- risk band 3, condition C4, and criticality 3

The band is illustrated in Figure **25**:

Crit. / Cond.	C1	C2	C3	C4	C5
5	9	0	3	0	0
4	3	6	10	18	2
3	60	29	8	20	20
2	132	117	80	45	3
1	271	38	4	13	0

Figure 25 - Emerging Bushing Risk

Given they are all criticality band 3 or above, outages may be hard to obtain, meaning offline DDF tests aren't undertaken as often, and the rate of deterioration is not well understood. These bushings are candidates for the installation of on-line monitors. On-line monitors if correctly installed will provide a much more detailed view of bushing risk and may allow AusNet Services bushings to remain in service with greater confidence.

5.1.4 On Load Tap Changer

Figure **26** shows that approximately 14% of the transformer population may have a risk that is reduced with remedial works – diverter switch replacement of increased maintenance.

Criticality	C1	C2	C3	C4	C5
5	7	1	6	11	0
4	12	0	9	9	0
3	2	1	5	3	0
2	4	2	0	2	0
1	25	0	5	17	0

Figure 26 - OLTC Risk

Specifically, replacement of [C-I-C], [C-I-C] and [C-I-C], oil filled diverter switches with vacuum diverter switches are considered as an OLTC risk reduction activity.

5.2 Options

5.2.1 Bushing On-line Monitoring

Periodic electrical testing is not practical on many shared network transformers as planned outages are difficult. Installation of online monitors would allow continual condition assessments on critical transformers, where planned outages are impractical, and failures are intolerable.

The strategy is to install on-line monitors on 19 bushings on three main system transformers, which are:

- EHV bushing on critical shared network transformer where the cost of a forced outage is high and planned outages are difficult to achieve
- Porcelain bushings advanced in their lifecycle

5.2.2 HWTS Phase Isolating Bus

The C4 rating for external components on the A2, A3, and A4 transformers at HWTS are driven by poor condition of phase isolating buses (PIBs).

Due to the closure of HWPS and the fact there are four transformers, the market criticality of each is currently low. However, if large scale renewable energy connects to HWPS, then at least three transformers will become critical. In this case refurbishment of the PIBs will be required.

This strategy is to refurbish all three PIB's in sequence over the course of the 2021-25 TRR period, with the potential to do less if directed by AEMO.

5.2.3 OLTC Corrosive Sulphur Processing

This program to mitigate the risk of corrosive sulphur is outside the scope of this strategy.

5.2.4 Secondary Systems

Winding Temperature Indicators (WTIs) that a faulty or incorrectly calibrated may cause the transformers to be incorrectly loaded. In the worst case unknowingly overloading of transformer will lead to early replacement or failure.

Two projects - TD-0003521 and TD-0003374 – have previously been approved to replace 34 WTIs. There remain 11 transformers with 13 tanks (one 3 phase transformer) that are excluded from the two projects that:

- were installed prior to 1990
- are not planned for replacement.

This program allows to the completion of WTIs that are likely to be faulty or cannot be correctly calibrated.

5.2.5 Bushing Replacement Program

Program to replace bushings that pose a safety hazard to personal and/or risk of collateral damage to transformer. The two types of potential consequences result in two bushing programs:

Risk Based

This list of bushings is prominently driven by the potential unrecoverable damage to transformers in critical network nodes, due to:

- **Fire** - OIP bushings present the risk of oil leak and pool fire, the fire risk is lower for SRBP bushings as the main tank tends to remain sealed after a bushing failure.
- **Winding Displacement** – Close in through faults due to secondary winding bushing failures may shift and damage the winding to the point that replacement is the only viable recovery. Any poor condition bushing – C4 or C5 – presents and elevated probability of failure. Poor condition bushings comprise of porcelain clad OIP and SRBP bushings that also have a safety risk.

Poor condition bushings will be replaced in advance of the justified replacement to reduce the safety risk for personnel working on the transformer replacement project.

Condition Based

For C5 bushings that are not included in the risk-based replacement a qualitative risk-based approach is adopted. Explosive failure of a bushing is intolerable therefore bushings with a high conditional probability of failure shall be replaced.

Three 220kV OIP bushings are to be replaced under this scenario.

Notable exclusions from this list are the 66kV bushings on the B1B and B2B at RCTS as they have been scored as condition C4. As part of the planning report for RCTS, these two transformers are going to be retained in place of the existing L transformers, and the existing L transformers are going to be retired. Even though the 66kV winding will not be used in the reconfigurations, the 66kV bushings will still be energised and still pose a safety risk. Replacement of these bushings should be considered as part of the station reconfiguration.

5.2.6 Vacuum Divertor Switch Retrofits

[C-I-C] and [C-I-C]

Replacing oil diverter switches with vacuum diverter switches increases the interval between class 2 OLTC maintenance from every 4 years to up to 600,000 operations, which is comparable to the life of a transformer. This would allow maintenance costs to be offset.

This was considered for 19 compatible [C-I-C] series and 24 [C-I-C] series OLTCS. However, with a replacement cos 10 times the costs of class 2 maintenance the economics didn't stack up.

The strategy is to continue to maintain the oil diverter switch as business as usual.

[C-I-C]
The TGTS B2 OLTC is unique on the network with no local parts or expertise.

The estimated cost for the retrofit is around twice the cost of class 2 maintenance. Being a 42 year old transformer with a condition score of C2 means the TGTS B2 is statistically going to have a long life – i.e. above average. Notwithstanding, the transformer is only likely to have 20-25 years of useful life remaining. Replacing the OLTC for twice the price of a maintenance overhaul needs to offset a second overhaul, which is unlikely over the predicted remaining life.

The strategy is to continue to overhaul and maintain the existing OLTC for the remainder of its service life.

6 Asset Strategies

The following section summarises the strategies. The itemised program of work is presented in Appendix 2.

6.1.1 New Installations

- Continue to invest in specification and manufacturing auditing to continue to have very few early life issues.

6.1.2 Condition Monitoring

- Install bushing monitoring on selected critical transformers with deteriorated bushings.
- Continue periodic offline HV condition monitoring tests.
- Develop transformer data analysis capability utilising the Information Management platform to optimise maintenance and replacement programs.

6.1.3 Maintenance

- Continue scheduled preventative maintenance as per specific standard maintenance instructions.
- Continue to update/create measurement points in SAP to capture condition information.
- Continue to update maintenance instructions and plans as new deterioration trends become apparent.

6.1.4 Spares Holding

- Continue to hold spare transformers at strategic network locations as per transformer spares holding policies

6.1.5 Refurbishment

- Address risk of diverter switch deterioration due to oil contaminated with corrosive sulphur – specific proposals are outside the scope of this document.

6.1.6 Replacement

- Continue risk-based transformer replacement based on the core and winding intrinsic end of life condition score and transformer asset criticality – specific proposals are outside the scope of this document.
- Replace porcelain OIP and SRBP with advanced deterioration.
- Replace the deteriorated PIBs at Hazelwood Terminal Station (HWTS) to prevent transformer failures.
- Replace deteriorated and faulty WTIs to ensure correct transformer loading.

Appendix 1 – Major Failures

Station	Transformer	Manufacturer	Failure Date	Age at Failure	Nature of Failure	Extent of Damage	Remedial Action
TTS	[C-I-C]	[C-I-C]	8/09/1978	11	Tap changer operated beyond end tap resulting in a tap change from tap 1 to tap 10 – flashover in diverter switch.	Failed tapping windings, 66 kV windings and tertiary on two phases, tertiary on one phase faulted to core – fault current extensively through core – core had to be complexly dismantled.	Transformer repaired at a high cost.
DDTS	[C-I-C]	[C-I-C]	31/12/1986	27	220 kV bushing failed resulting in a fire.	This is a shell type design – Windings completely burnt out, foundations damaged, connecting busbars & conductors damaged, adjacent Surge arresters and one bushing damaged, cubicles burnt.	Transformer repaired using spare winding. Foundation, etc was rebuilt.
SVTS	[C-I-C]	[C-I-C]	6/04/1995	35	Inter-strand fault in “b” phase 66 kV winding resulted in gassing when on load. No other damage	Conductor insulation burnt at site of failure at a transposition point.	Transformer repaired at a cost of $650k using a spare winding to affect a quick return to site. Then later repaired the failed removed winding.
MTS	[C-I-C]	[C-I-C]	April 95	26	Winding failure following external short circuit – LV and tertiary winding damage (in hindsight we believe some movement occurred during a similar fault about 15 years earlier	LV and tertiary winding damaged and had to be replaced	Transformer repaired at a cost of $260k
BATS	[C-I-C]	[C-I-C]	12/12/2000	30	Open circuit developed on one connection in the diverter switch resulted in a	Selector Switch barrier boards ruptured and the tapping windings on “W” phase damaged.	Transformer repaired at a cost of approximately $1.3 Million using Spare

Station	Transformer	Manufacturer	Failure Date	Age at Failure	Nature of Failure	Extent of Damage	Remedial Action
					fault of the "W" phase selector switch.		windings to replace "W" phase windings to effect quick return to site.
DDTS	[C-I-C]	[C-I-C]	17/12/2000	37	Transformer taken out of service due to collection of gas in Buchholz relay. DGA sample suggest Partial discharge/ sparking fault	Extensive on-site testing has confirmed partial discharges but could not locate.	Transformer retired and replaced with a three-phase spare. Held old H2 bank as a spare transformer. Estimated cost was $310~ 390 K.
MBTS	[C-I-C]	[C-I-C]	30/03/2004	49	Internal earth fault on tertiary of White Phase Unit	Winding Damaged.	Replaced with single phase spare.
MBTS	[C-I-C]	[C-I-C]	14/02/2005	50	Internal earth fault on tertiary of White Phase Unit. This is the spare unit installed in the previous failure on 30/3/2004. This failure is also similar to the previous failure.	Winding Damaged	Transformer bank was already being planned to replace due to lack of fault capability. Therefore, temporarily replaced with the 150 MVA country spare. Later replaced with 2 off 50 MVA Transformers (Tie plus spare).
TTS	[C-I-C]	[C-I-C]	31/03/2007	45	Transformer tripped on gas protection followed by gas alarm due to a through fault.	Site testing confirmed winding failure with winding faults on LV and Tertiary and winding displacement. Also winding displacement in white phase "C" unit.	Replaced with a new 3 phase transformer. Also new foundations, etc.

Station	Transformer	Manufacturer	Failure Date	Age at Failure	Nature of Failure	Extent of Damage	Remedial Action
TTS	[C-I-C]	[C-I-C]	4/03/2009	23	Transformer tripped on gas protection followed by gas alarm approximately 1.5 hours after a close- in through fault.	DGA confirmed internal arcing fault and site tests indicated “A” phase LV and TV winding displacement and winding faults. Transformer removed from location. Fault found in “A” phase 66 kV winding. It was established that TV winding has inadequate short circuit strength for TV faults and Phase to Earth through faults. Neutral reactor helps.	Replaced with a new transformer.
MWTS	[C-I-C]	[C-I-C]	31/01/2010	44	Transformer tripped on gas protection due to a close-in through fault. DGA was conducted and DGA was OK. Tripped from diff protection with gas alarm when re-energised.	Tapping winding displacement.	Replaced with the country spare and retired the failed transformer.
KTS	[C-I-C]	[C-I-C]	4/05/2011	40	Transformer tripped on gas protection and gas alarm came up. DGA confirmed an internal fault. High resistance found in the “A” leg common winding	Fault in “A” leg common winding – turn to turn and disc to disc within top 10 discs confined between two spacer blocks.	Replaced with a spare transformer (single phase) and failed transformer was repaired at Alstom Rocklea (Queensland) replacing all windings with spare windings. The cost was $2.3 million.
BATS	[C-I-C]	[C-I-C]	2015	45	OLTC internal flashover due to surface discharge between phases and cellulose based insulation. Contaminated oil.	The failure resulted in damage to the diverter, selectors and the B phase windings and possibly the core. Tapping winding damage.	Replaced with the SMTS Country Spare transformer.

Station	Transformer	Manufacturer	Failure Date	Age at Failure	Nature of Failure	Extent of Damage	Remedial Action
FBTS	[C-I-C]	[C-I-C]	2016	45	Internal tapping winding fault.	Extensive damage of A phase winding and OLTC.	Replaced with FBTS Metro Spare transformer.
RWTS	[C-I-C]	[C-I-C]	2016	44	Internal fault due to deflection from short circuit forces. Paper was displaced during an oil change. The aged transformer was incapable of withstand short circuit force rating.	Unrecoverable internal damage.	Replaced with TTS Metro Spare.

Appendix 2 – Program of Works

Table 7 - Program Summary

Option	Power Transformers	Unit Rate	Quantity
5.2.1	Bushing Monitor Installation (SMTS F2, DDTS H3, HYTS M1)	667	3
5.2.2	PIB Replacement - HWTS A2, A3 & A4	700	3
5.2.4	WTI Replacement	84	13
5.2.5	500kV OIP Bushing Replacement (HWTS A3, HYTS M2, KTS A2, KTS A3, KTS A4)	321	14
	275kV OIP Bushing Replacement (HYTS M2)	321	3
	220kV OIP Bushing Replacement (HWTS A1, KTS A2, KTS A3, KTS A4)	168	12
	Neutral SRBP Bushing Replacement (HYTS M2)	131	1