AMS 10-54 Circuit Breakers

2023-27 Transmission Revenue Reset

PUBLIC

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Disclaimer

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Table of Contents

1 Executive Summary

This document is part of the suite of Asset Management Strategies relating to AusNet Services' electricity transmission network. The purpose of this strategy is to outline the inspection, maintenance, replacement and monitoring activities identified for economic life cycle management of terminal station circuit breakers.

The strategy covers 1065 circuit breakers installed in terminal stations. Approximately 75% of the terminal station circuit breakers are SF6 insulated and about 20% of population are oil insulated, either outdoor bulk oil (CBBO) type or minimum oil (CBMO) type, and remainder a small population of vacuum circuit breakers installed in indoor switchboards.

Condition assessment shows approximately 66% of the total CB population are either in a "very good condition" (C1), "good condition" (C2) or "average condition" (C3). The remaining 34% of the total CB population are either in "poor condition" (C4, 14.0%) or "very poor condition" (C5, 20%).

The consequence of a failure was assessed based on community impact due to outages, safety, environment and collateral damage risks. Porcelain housed & oil filled circuit breakers pose a high risk of safety, collateral damage and environmental risk due to the inherent explosive and oil fire risk.

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.

Proactive management of circuit breakers inspection, condition monitoring and replacement practice is required to ensure that stakeholder expectations of cost, safety, reliability and environmental performance are met. The summary of proposed asset strategies is listed below.

1.1 Asset Strategies

Strategies in the management of circuit breakers include:

1.1.1 New Installations

- Specify outdoor SF_6 insulated dead tank/ polymer insulator circuit breakers up to 220kV and Live tank / polymer insulator circuit breakers for 275kV and above for replacement in outdoor terminal stations.
- Specify SF6 insulated circuit breaker for 66kV and above voltages in Gas insulated switchgear (GIS)
- Specify indoor metal clad /arc fault rated vacuum interrupter or SF6 insulated circuit breaker in indoor modular AIS or GIS for 22 kV indoor installations.

1.1.2 Condition Monitoring

- Continue visual checks of circuit breakers as part of the regular terminal station inspections.
- Continue annual non-invasive condition monitoring scans including the use of radio frequency interference, ultrasonic, infra-red thermal and UV corona camera testing to evaluate the integrity of circuit breaker insulation and external and internal connections.
- Continue to establish the bulk oil CB's SRBP bushing condition through electrical testing

1.1.3 Maintenance

- Continue scheduled preventative maintenance as per specific Standard Maintenance Instructions for each circuit breaker type.

1.1.4 Spares Holding

- Maintain strategic spares holding of CB as per spare holding policies
- Continue to salvage best parts and complete assemblies of obsolete CB to achieve per spare holding policies

1.1.5 Refurbishment

- Use bushing replacements to manage shorter term risk for from the very poor condition bushings of bulk oil CBs, identified during the electrical testing condition monitoring program
- Complete refurbish [C-I-C] 220kV CB mechanisms and [C-I-C] during TRR 2022 -2027 period
- Continue to refurbish/ repair SF6 leaks in live tank circuit breakers and GIS, where economical

1.1.6 Replacement

- Replace 2 off [C-I-C] and 4 off [C-I-C] (associated with very poor condition CT's)

Replace 8 off identified high operation capacitor bank CB reaching their duty limits / C5 condition 2 off 220kV [C-I-C], 1 off [C-I-C] and 4 off 66kV [C-I-C] and 1 off [C-I-C]

2 Introduction

2.1 Purpose

The purpose of this document is to outline the inspection, maintenance, replacement and monitoring activities identified for economic life cycle management of circuit breakers in AusNet Services' regulated electricity transmission network. This document is intended to be used to inform asset management decisions and communicate the basis for activities.

In addition, this document forms part of our Asset Management System for compliance with relevant standards and regulatory requirements. It is intended to demonstrate responsible asset management practices by outlining economically justified outcomes.

2.2 Scope

This Asset Management Strategy applies to all regulated asset base outdoor and indoor type circuit breakers operating at 500kV, 330kV, 275kV, 220kV, 66kV, 22kV and 6.6kV located in terminal stations.

The following related assets are also covered by other strategies;

Circuit Breakers installed in Gas Insulated Switchgear refer to AMS 10 -62.

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

Circuit breakers are electrical switches that, in conjunction with protection relays and SCADA controls, operate automatically to interrupt the abnormal flow of electrical currents and protect people from injury and protect property and the electrical network equipment from damage.

Circuit breakers are also used to energise and de-energise lines, feeders, busses and electrical equipment such as transformers or capacitor banks to enable operation requirements, maintenance or augmentation works.

3.2 Asset Population

AusNet Services has a total of 1065 circuit breakers (CB) installed in the electricity transmission network as reported in 2019 RIN.

3.2.1 Population by Object Type

A summary of the transmission circuit breaker population by voltage class and technology type are shown in figure 1 and 2.

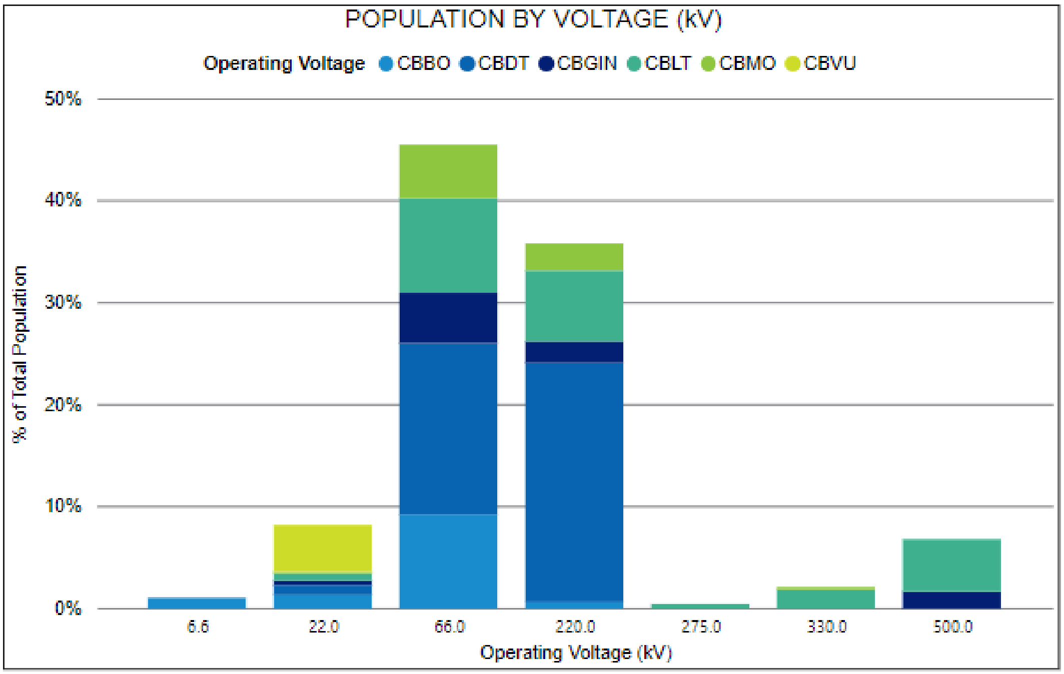

Figure 1 - Circuit Breaker population by Object Type and Voltage

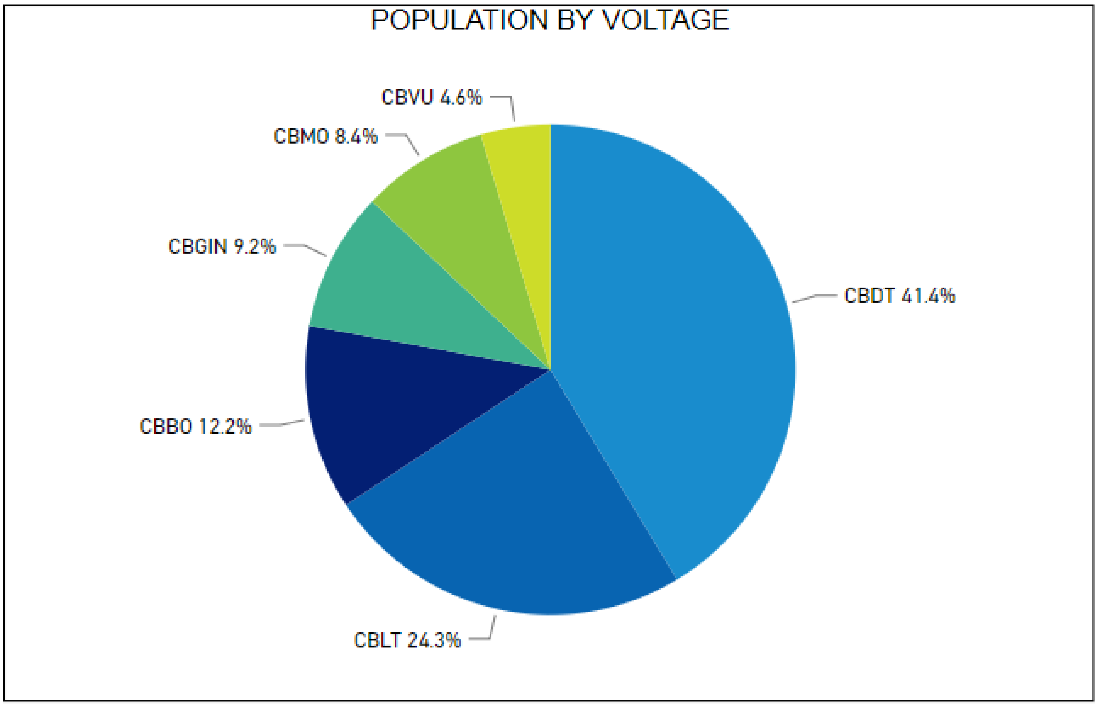

Figure 2 - Circuit Breaker population by Technology Type

The majority of circuit breakers are SF6 insulated, dead tank (CBDT) type, live tank (CBLT) type and GIS (CBGIN) type. Approximately 20.6% of population are oil insulated, either outdoor bulk oil (CBBO) type and minimum oil (CBMO) type. The small remainder are indoor switchboard vacuum type (CBVU).

Approximately 45.5% the circuit breakers 66kV system and comprise of 31% off SF6 insulated and 14.5% off mineral oil insulated circuit breakers.

3.2.2 Population by Manufacturer

Figure 3 ,4 and 5 below provides the population distribution of 220kV and above Live Tank, All Bulk Oil and Minimum Oil circuit breakers by top 10 Manufacturer/Model.

[C-I-C]

Figure 3 – 220kV and above Live Tank Circuit Breakers by Manufacturer / Make

[C-I-C]

Figure 4 – Bulk Oil Circuit Breakers by Manufacturer / Make

[C-I-C]

Figure 5 – Minimum Oil Circuit Breakers by Manufacturer / Make

Following observations are made:

1. There are very large variety of key makes, models, voltage and current ratings of circuit breakers in service operating at 6.6kV - 500kV across the transmission network. Live tank CBs have the highest number of variations. They are mainly; Bulk Oil - 12, Dead Tank (SF6) -12, CB GIS – 10, Live tank (SF6) – 33, Minimum Oil – 10, Vacuum- 4)

2. Live tank Circuit Breakers (220kV & above): Key types are [C-I-C] (23.4%), [C-I-C] (15.6%), [C-I-C] (12.5%), [C-I-C] (12.5%) and [C-I-C] (7.0%) which contribute to the 71% of the live tank CB population.

3. Bulk Oil Circuit Breakers: Consists of mainly of one key type of outdoor CB, namely the 66kV [C-I-C] (76.1%)

4. Minimum Oil Circuit Breakers: Approximately 65.3% of the minimum Oil CB population consists of [C-I-C] (45.3%) and [C-I-C] (20.0%) CBs.

3.3 Asset Age Profile

The mean service age of all Transmission circuit breaker population is about 25 years.
Table 1 below shows the average age, youngest and oldest circuit breaker age by object type.

Table 1: Service Age Profile of Transmission circuit breaker by Object type

OBJECT_TYPE	Average Age (Yrs)	Youngest Age (Yrs)	Oldest Age (Yrs)
CBBO	52	38	59
CBDT	10	0	19
CBGIN	31	2	41
CBLT	25	1	40
CBMO	40	21	54
CBVU	11	6	14

It is noted that bulk oil, minimum oil circuit breakers and GIS at Newport (NPSD) contribute to the aged circuit breaker population whereas the younger CB population is due to SF6 insulated dead tank, live tank and GIS circuit breakers and modern vacuum circuit breakers.

Figure 6 and Figure 7 provides the population distribution of transmission circuit breakers against the object type and operating voltage.

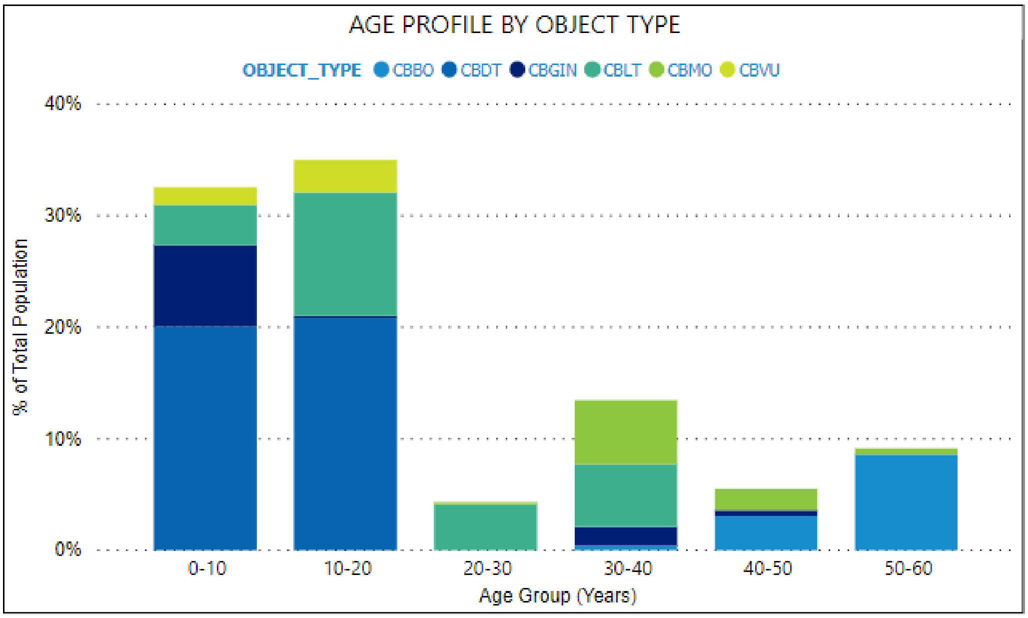

Figure 6 – Service Age Profile by CB Object Type

It is noted that approximately 9.1% of the total CB population is more than 50 years of age and the majority of this group, approximately 8.6%, are due to 66kV bulk oil circuit breakers. This also shown below in Figure 6.

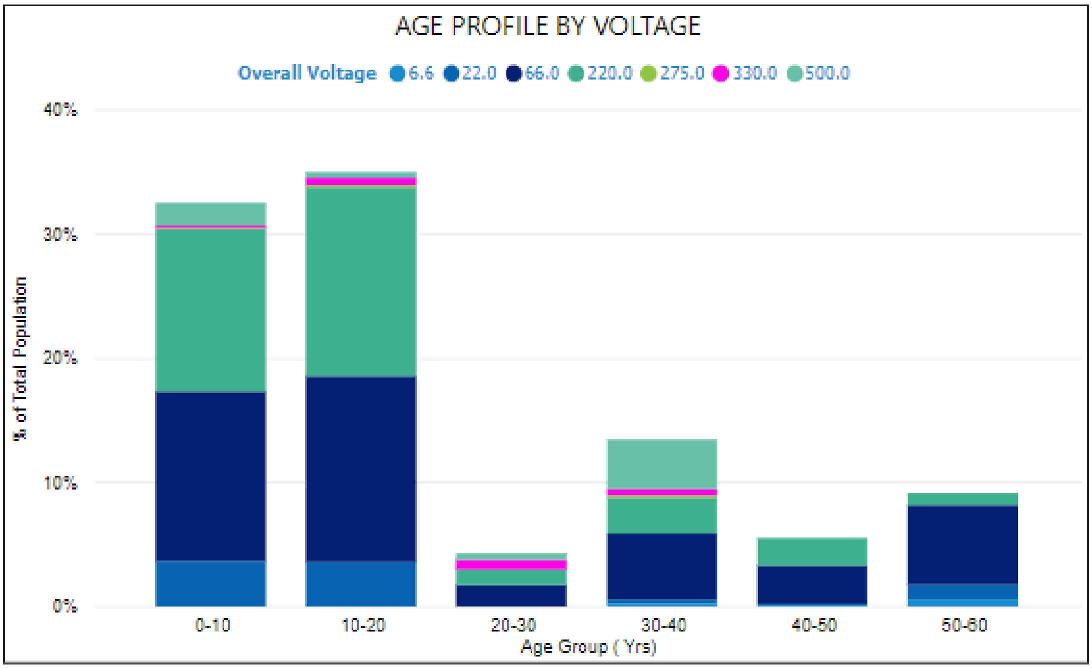

Figure 7 – Service Age Profile by CB by Operating Voltage

3.4 Asset Condition

A circuit breaker CB Health Score has been assessed for each circuit breaker in the electricity transmission network.

CB Health Score of transmission circuit breakers are determined by considering the following factors.

1. Technical obsolescence
2. Environment factors
3. Condition of key components
4. Observations / Measurements
5. Reliability of fleet

Current Health Score is derived by applying weighted asset condition-based factors and weighted reliability factors for each circuit breaker based on above considerations.

The Table 2 provides a definition of the various condition scores and recommended action.

Table 2: Condition Score definition and recommended action

Condition Score	Condition Description	Summary of details of condition score	Remaining Service Potential (%)
C1	Very Good	These CBs are generally in good operating condition with no past history of significant defects or failures. Manufacturer support and spares are readily available for routine maintenance. Routine maintenance and continued condition monitoring is recommended.	95%
C2	Good	This category includes CBs which are in better than average condition. They may have some issues such as minor oil or SF6 leaks from seals, minor corrosion and some mechanism and drive system wear. They do not require intervention between scheduled maintenance nor do they show any trends of serious deterioration in condition or performance other than normal wear. Manufacturer support and spares are available.	70%
C3	Average	This category includes CBs which are with an average condition. They may have developed several issues due to in service related deterioration, such as interrupters wear, oil/SF6 leaks, corrosion, mechanism wear or re- adjustment required. These units typically require increased maintenance. Spares are being used to replace damaged components and manufacturer support for these breakers is becoming limited. The CB's are showing signs of deterioration in condition or performance.	45%
C4	Poor	This category includes CBs which are in worse than average condition. They may have developed an increasing number of issues such as interrupters wear out, worsening oil or SF6 leaks, significant contact and latching mechanism wear. They may also have a history of failures occurring such as bushing failures. Local manufacturer support and spares are typically not available and reverse engineering, salvaging parts from retired equipment or in situ repair are becoming the most practical solution. Specialist targeted maintenance is required to manage specific known defects.	25%
C5	Very Poor	This category includes CBs which are typically maintenance intensive and have history of, problematic interrupters, widespread oil and SF6 unrepairable leaks and repeated top ups, component breakages and typically worn out or unreliable operating mechanisms and significant failures. These CB's have substantial deterioration is approaching the end of economic life. The maintenance that can be performed to restore the condition is very limited due to lack of availability of spare parts and lack of experience and skill required to maintain the asset. They are no longer supported by the manufacturer. The maintenance of CBs in this category is typically no longer economical compared to asset replacement.	15%

Condition profile of transmission circuit breakers by voltage is shown in Figure 8.

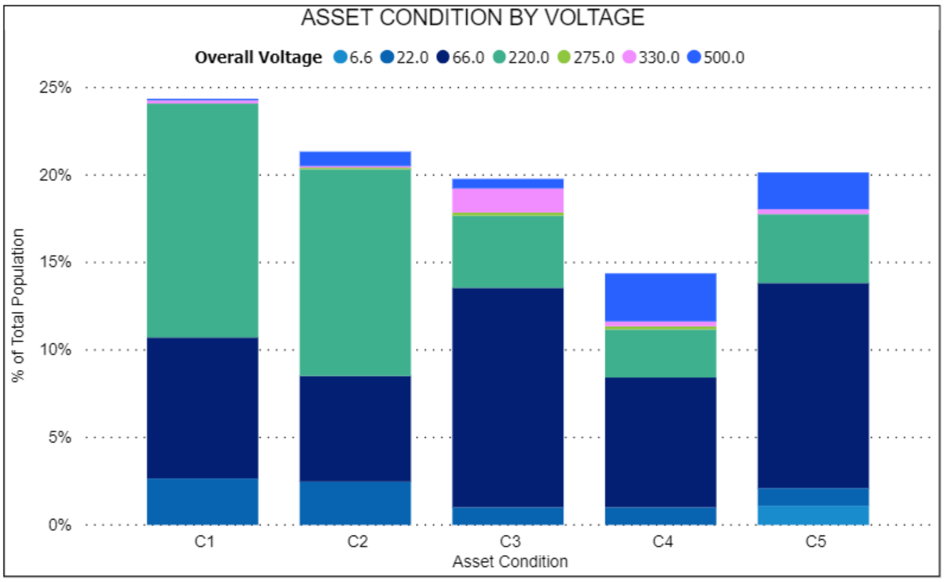

Figure 8 - Condition Profile of Circuit Breakers by Voltage Class

Approximately 20% of the CB population are in very poor condition (C5) and approximately 12% and 4% are due to 66kV and 220kV respectively.

Asset Condition Score vs age profile is shown in Figure 9.

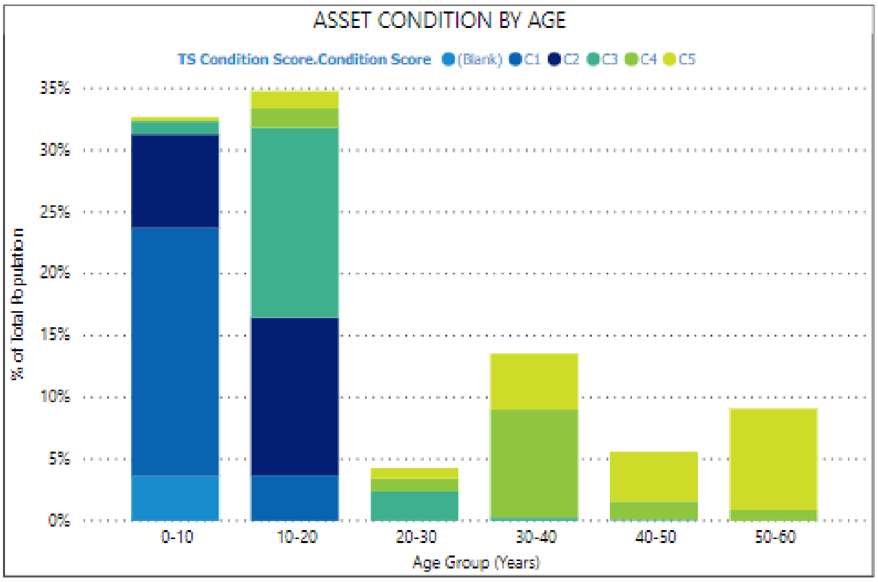

Figure 9 – CB Asset Condition vs Age

It is noted that a small percentage of circuit breakers are found to be in very poor condition (C5) or poor condition (C4) at ages below 20 years are mainly due to high operating capacitor bank circuit breakers which have exceed the manufacturers recommended operating duty needing refurbishment /replacement.

Asset Condition Score vs object type is shown in Figure 10.

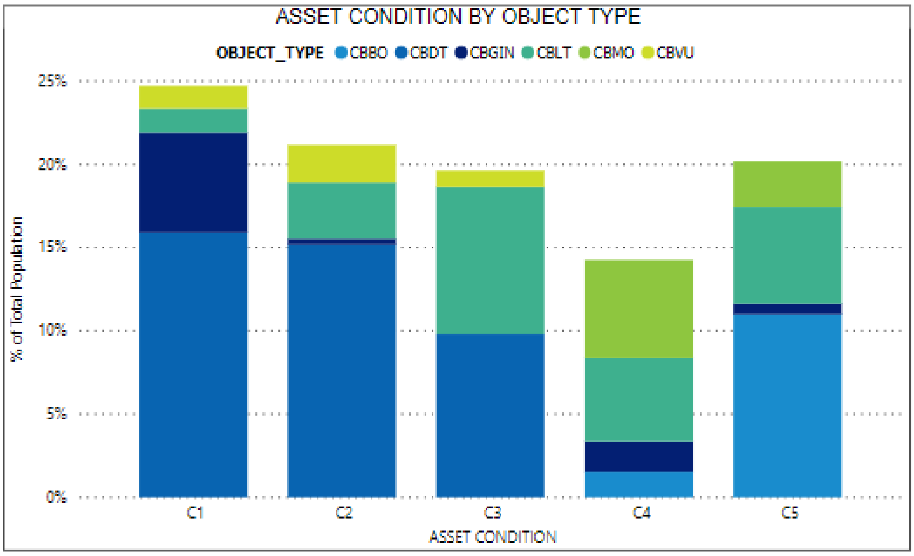

Figure 10 – CB Asset Condition vs Object Type

The majority of the total population are in very poor condition (C5) are bulk oil and minimum oil circuit breakers. They are mainly 66kV [C-I-C] and [C-I-C] circuit breakers. Currently a bushing testing and replacement program is underway for LG4C circuit breakers and a refurbishment program for [C-I-C] circuit breakers.

3.5 Asset Criticality

Asset Criticality was determined by considering the following consequences of circuit breaker failure with the failure effects mentioned below.

1. Safety impact,
2. Community impact due to outages (unserved energy)
3. Environment
4. Collateral damage

Asset criticality is the severity of consequence in a major failure of a circuit breaker at a certain location due to above failure effects irrespective of the likelihood of the actual failure. This gives an idea of circuit breaker types, located critical locations which represent the total value of risk $.

Safety impact is assessed on catastrophic failure risk and it depends mainly on explosive failure mode of porcelain CB bushings associated with older oil filled outdoor CBs, mainly bulk oil and minimum oil circuit breakers. Modern dead tank SF6 insulated circuit breakers and live tank circuit breakers, when fitted with polymeric insulators, have much lower risk. Most vacuum circuit breakers are installed in indoor switchboards and the safety consequence of failure is much lower than for equivalent outdoor circuit breakers.

The Figure 11 shows the Relative asset criticality based on CB Technology, Service Voltage, and Asset Condition of CBs.

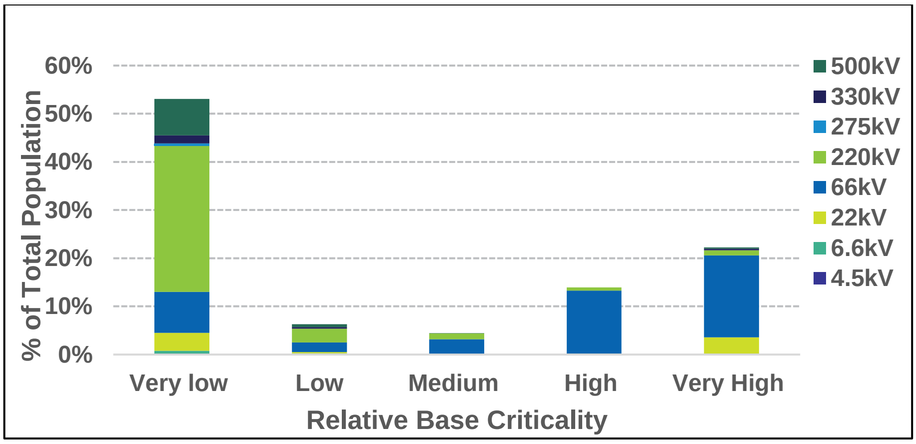

Figure 11 – Relative base criticality by Service Voltage

The applied interpretation of relative base criticality is shown in Table 3.

Table 3: Interpretation of Relative Base Criticality

Relative Base Criticality	Criticality Banding	Definition
Very low	1	Total failure effect cost < 0.3 times Replacement Cost
Low	2	Total Effect Cost is between 0.3 – 1.0 times of replacement cost
Medium	3	Total Effect Cost is between 1 - 3 times of replacement cost
High	4	Total Effect Cost is between 3 -10 times of replacement cost
Very high	5	Total Effect Cost exceeds 10 times of replacement cost

Following observations are made on asset criticality:

- Approximately 40% of the CB population contribute to medium to very high criticality on the relative base mainly due to 66kV circuit breakers (33%). (Refer figure 11)

3.6 Asset Performance

AusNet Services routinely analyses the root cause of unplanned work undertaken on circuit breakers and investigates all major failures, and tracks customer outages due to CB failures.

3.6.1 Corrective Maintenance

Records of unplanned maintenance work undertaken on circuit breaker population on the CB population are maintained in the Asset management system, SAP.

It is noted that there is only a marginal improvement of the total number of condition-based notifications (ZA) raised per CB object type from 2015 to 2019 (Refer figure 12) except for circuit breakers installed in older GIS installations where a marked increase was noticed in SMTS and SYTS due to defects in hydraulic systems etc. Refer AMS 10-62 -GIS installations for details.

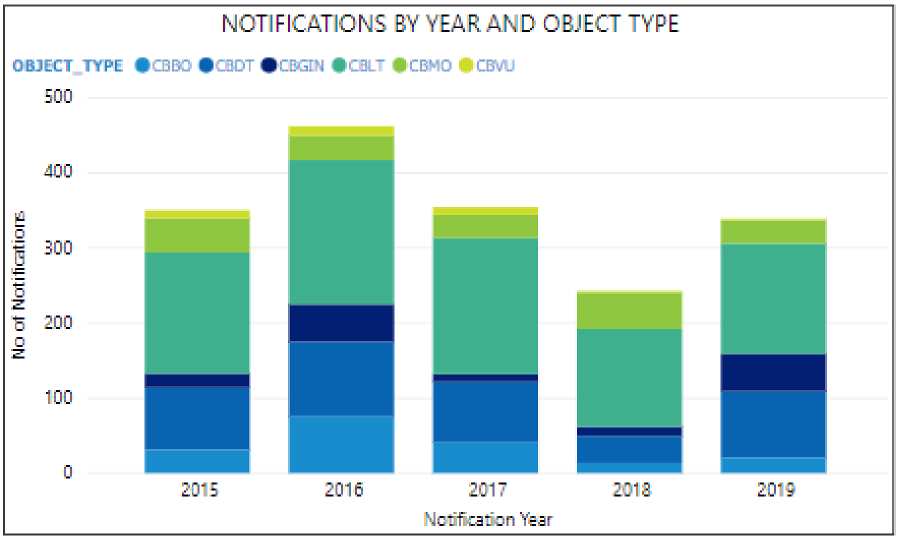

Figure 12 – Number of ZA Notifications per CB object type 2015 – 2019

Table 4 and Table 5 below shows the ZA Notifications vs CB Object type and notification rates per switch type and annual rate for 66kV and below circuit breakers and 220kV and above circuit breakers respectively. It is noted that ZA notifications for 220kV and above live tank circuit breakers and bulk oil circuit breakers were higher than for circuit breakers operating at 66kV and below voltages.

Table 5 shows the overall CB fleet ZA notifications for all voltage classes. It is noted that live tank circuit breakers reported an overall ZA notifications more than twice than that for bulk oil circuit breakers due to SF6 leaks.

Table 4: Number of ZA Notifications per CB (66kV and below) Object Type 2015 – 2019

Object Type	Total Count of ZA Notifications 2015-2019	Number of CBs with Notifications	Total Number of CBs	Average Notifications /Object type /CB population	Average Notifications /Object type /year/ CB population	Percentage of CBs with ZA Notifications/CB Population
CBMO	106	42	62	1.71	0.342	68%
CBLT	178	68	120	1.48	0.297	57%
CBDT	206	77	202	1.02	0.204	38%
CBBO	121	67	131	0.92	0.185	51%
CBVU	23	14	52	0.44	0.088	27%
CBGIN	6	4	59	0.10	0.020	7%

Table 5: Number of ZA Notifications per CB (220kV and above) Object Type 2015 – 2019

Object Type	Total Count of ZA Notifications 2015-2019	Number of CBs with Notifications	Total Number of CBs	Average Notifications /Object type /CB population	Average Notifications /Object type /year/ CB population	Percentage of CBs with ZA Notifications/CB Population
CBLT	556	124	191	2.91	0.582	65%
CBMO	62	25	33	1.88	0.376	76%
CBBO	12	4	7	1.71	0.343	57%
CBGIN	56	19	49	1.14	0.229	39%
CBDT	158	98	285	0.55	0.111	34%

Table 6: Number of ZA Notifications per CB (Overall) Object Type 2015 – 2019

Object Type	Total Count of ZA Notifications 2015-2019	Number of CBs with Notifications	Total Number of CBs	Average Notifications /Object type /CB population	Average Notifications /Object type /year/ CB population	Percentage of CBs with ZA Notifications/CB Population
CBLT	734	192	311	2.36	0.472	62%
CBMO	168	67	95	1.77	0.354	71%
CBBO	133	71	138	0.96	0.193	51%
CBDT	364	175	487	0.75	0.149	36%
CBGIN	62	23	108	0.57	0.115	21%
CBVU	23	14	52	0.44	0.088	27%

Figure 13 below shows the number of ZA Notifications per CB Vs Operating voltage 2015 – 2019. It is noted that approximately 69.6% of total ZA notifications in 2019 were related to circuit breakers operating at 220kV and above.

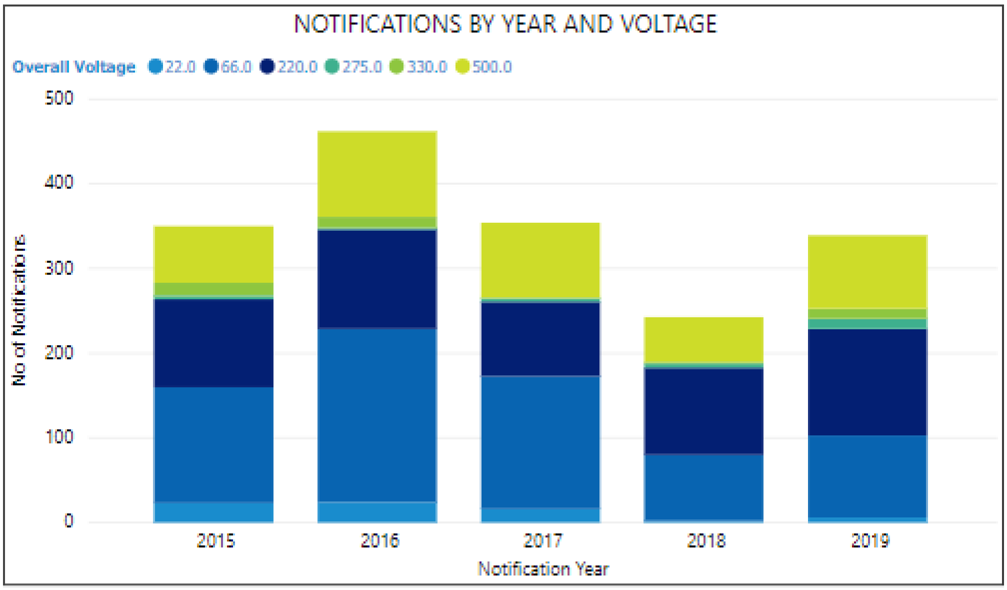

Figure 13 – Number of ZA Notifications Vs Operating voltage 2015 – 2019

Table 7 below provides the list of top 15 transmission circuit breakers by the manufacturer/model and their work order performance sorted in the descending order. (Worst performing CBs on top).

Table 7: Number of ZA Notifications per CB Manufacturer / Model 2015 – 2019 (Top 15)

[C-I-C]

Table 7 – Number of ZA Notifications per CB Manufacturer / Model 2015 – 2019 (Top 15)

Figure 14 below shows the ZA notifications during 2015-2019 against the defect type. It is observed that 41.7% of the total ZA notifications in year 2019 were due SF6 leaks (26.6%) and oil leaks (14.7%) in circuit breakers.

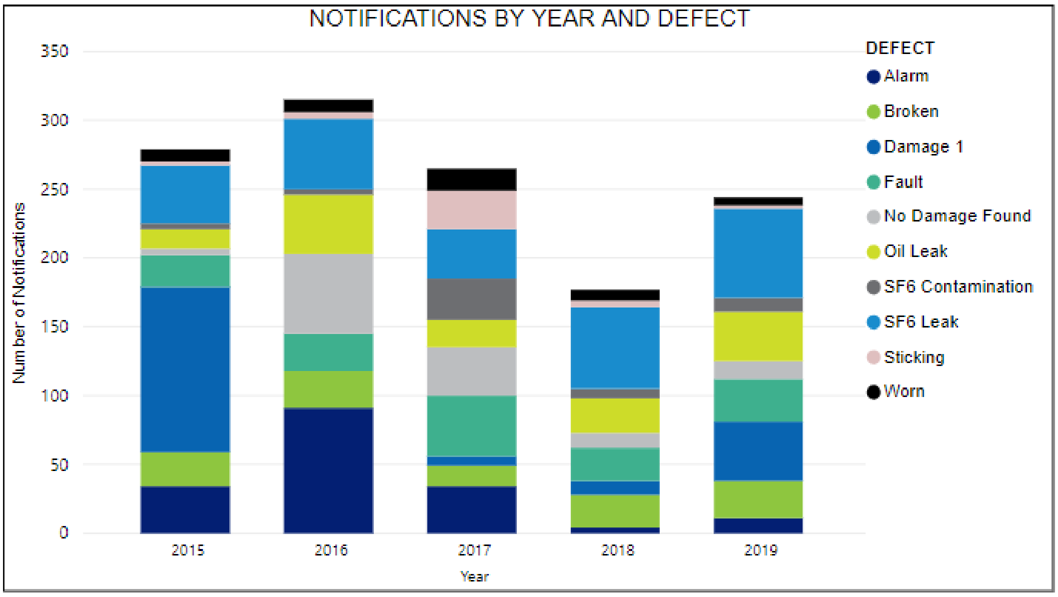

Figure 14 – Number of ZA Notifications Vs Defect type (Top 10) 2015 – 2019

Figure 15 below shows the ZA notifications during 2015-2019 against the CB component part. It is observed that 33.6% of the total ZA notifications in year 2019 were associated with CB secondary systems such as heaters, controls and wiring and approximately 44.6% were associated with the CB insulation medium mainly due to SF6 insulation system including pressure gauges (40.1%) and insulating oil system (4.5%).

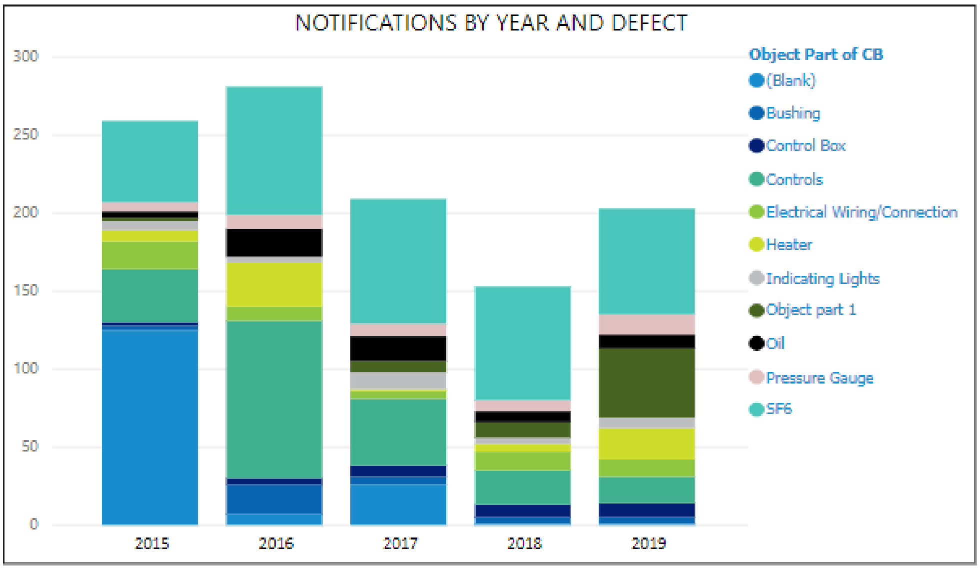

Figure 15 – Number of ZA Notifications Vs CB Component (Top 10) 2015 – 2019

Figures 16 ,17 and 18 show Number of ZA notifications during 2015-2019 against the object part for bulk oil, minimum oil and live tank circuit breakers revealed the following issues.

1. Bulk Oil CBs: Oil leaks and bushing failures were the dominant object failure components in bulk oil circuit breakers which contributed to 56% of the total bulk oil CB ZA notifications in year 2019. Number of notifications have reduced over the years due to extensive condition-based maintenance carried out in them. (Ref Figure 15)
2. Minimum Oil CBs: Dampers and dashpot failures were the dominant object failure components in minimum oil circuit breakers which contributed to 44% of the total minimum oil CB ZA notifications in 2019. 24% of the notifications were caused by flange corrosion and interrupter wear out. (Ref Figure 16)

3. Live Tank CBs: SF6 insulation system failure is the dominant component which contributed to about 50.5% of the total live tank CB ZA notifications recorded in year 2019. Approximately 16.7% contributed to flange corrosion.

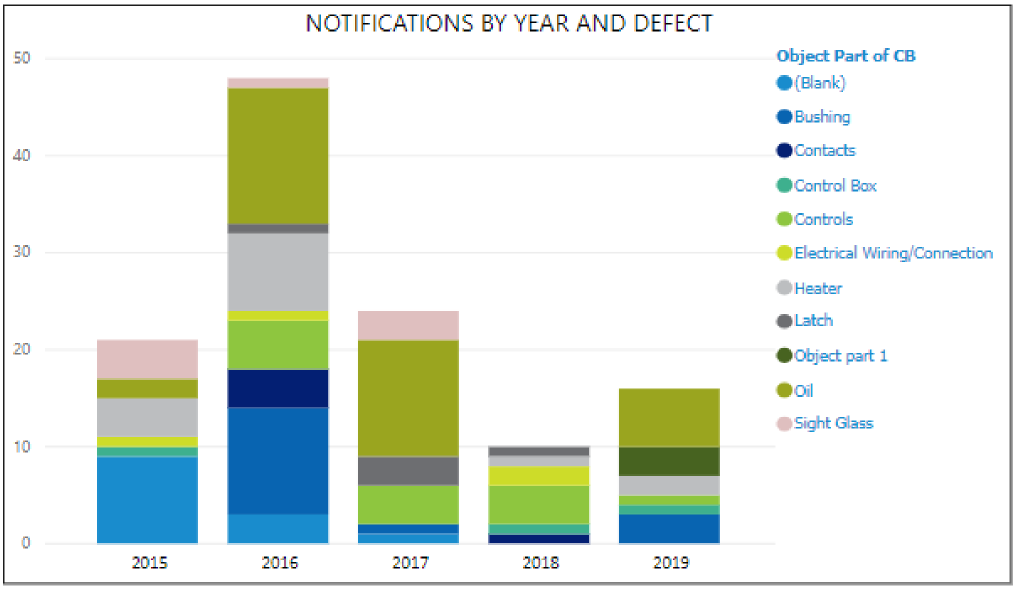

Figure 16 – Number of ZA Notifications Vs Bulk Oil CB Component (Top 10) 2015 – 2019

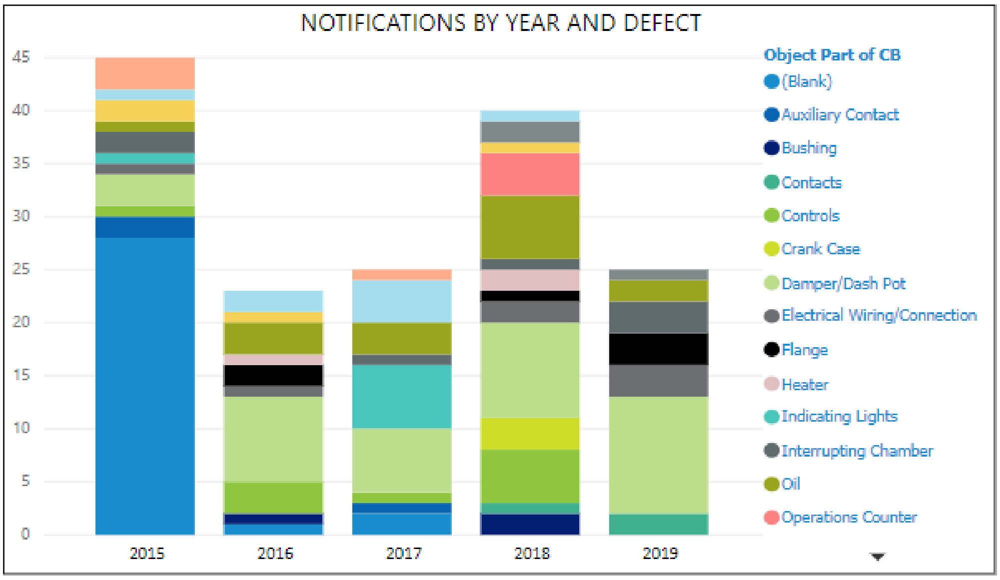

Figure 17 – Number of ZA Notifications Vs Minimum Oil CB Component (Top 10) 2015 – 2019

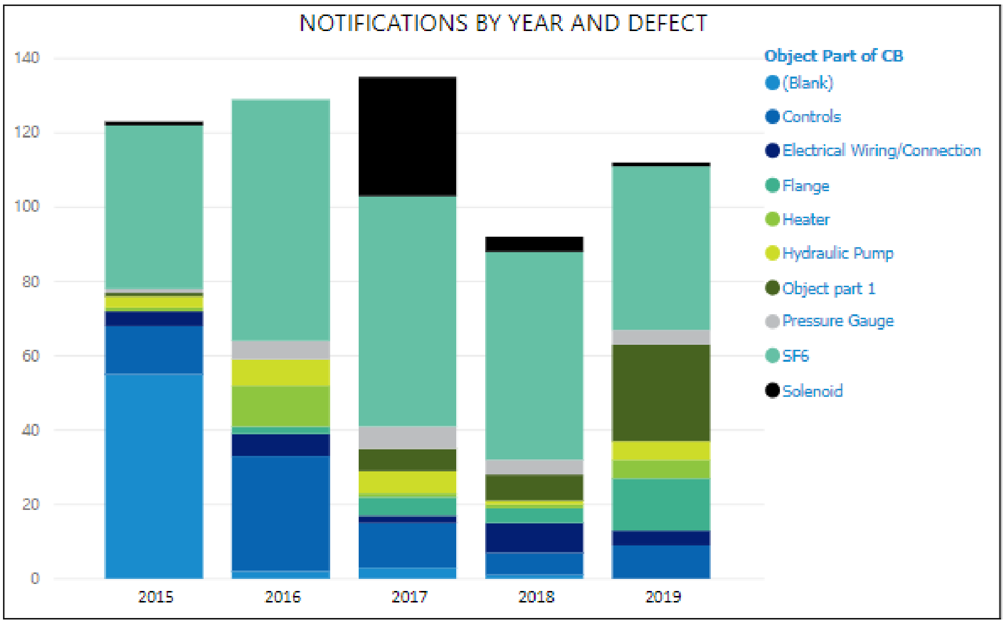

Figure 18 – Number of ZA Notifications Vs Live tank CB Component (Top 10) 2015 – 2019

Older outdoor bulk oil and minimum oil circuit breakers have porcelain housings compared to modern polymer housed SF6 insulated circuit breakers. Oil leaks in the bushings as a result of seal failure cause gradual moisture ingress and result in insulating medium failure. This results in in catastrophic failure causing safety to personnel, collateral damage and customer impact due to long restoration times.

Technical obsolescence, excessively worn out parts and non-availability of original spares parts are the key issues in maintaining the reliability of these older CBs apart from increased operating cost. Often parts are locally sourced or salvaged from retired CBs which are partly worn, deteriorated or weakened.

3.6.2 Major Asset Failures

Number of major defects and failures associated with transmission circuit breakers from 1997-2020 which require complete replacement or replacement of a major component is shown in Appendix 1. Major failures or defects can result in extended duration outages and deplete critical spares holding especially the older circuit breakers which are technically obsolete. Refer section 4.3 for details of issues.

Figure 19 below shows the average CB failure by technology and age group, excluding high operation CBs.

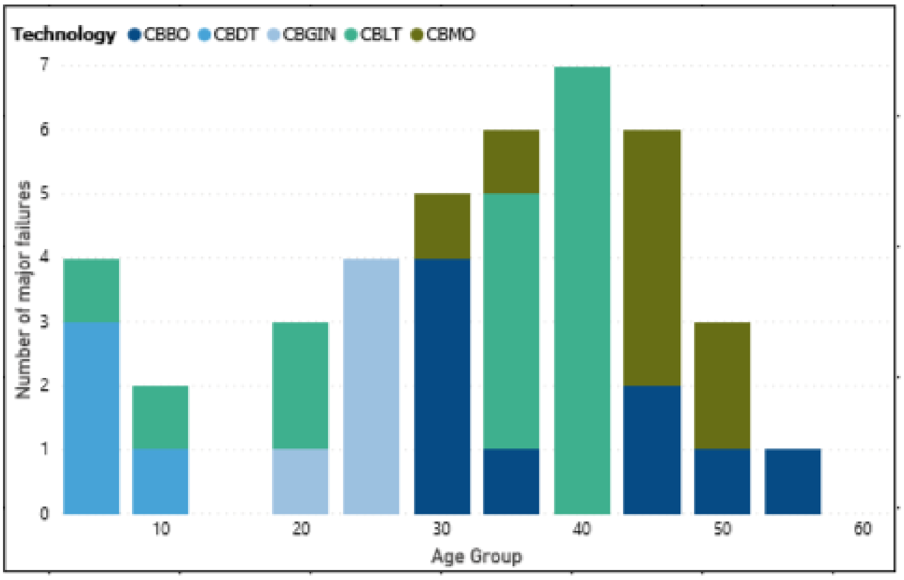

Figure 19 –CB major failures by technology and service age (low operating CBs)

3.6.3 High Operation Circuit Breakers

Most circuit breakers operate at a low annual frequency rate, less than 10 operations per year. Many capacitor bank and shunt reactor circuit breakers operate at a significantly higher rate than feeder, bus or transformer circuit breakers due to their use for voltage support.

Due to the high operations, some capacitor bank and shunt reactor circuit breakers economic life is dependent on their duty and require major component or complete replacement at a relatively young age. There is only a total population of 59 regulated asset base capacitor bank circuit breakers and it is evident from the Major failure list in appendix A, that capacitor bank CB have a much higher relative major failure rate than other applications, predominantly due to high operations related electrical and mechanical wear out. This is shown in Figure 20 below. In most cases these failures occur on the very high operated CB or those approaching their design limits.

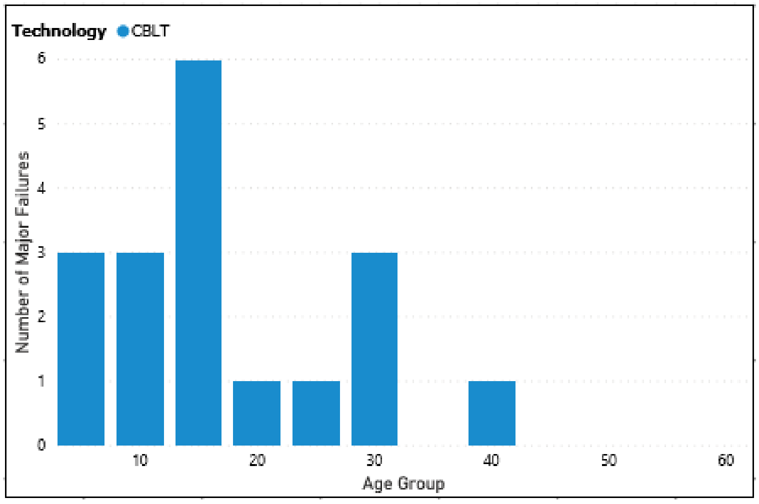

Figure 20 –CB failures by technology and service age (High operating CBs)

The original 1980's and 1990's vintage capacitor bank CB are now obsolete designs and refurbishment for life extension is no longer a viable option. All the early 2000's designs are also now obsolete, and refurbishment is no longer a longer economic for the highest operated CB. During the current TRR period the original highest operation 66kV capacitor banks circuit breakers have been targeted for replacement. There continues to be recent major failures as others approach their endurance limits. Number of capacitor bank circuit breakers failed in the past and recently is shown in Appendix 1.

Figure 21 below shows the average operation frequency of capacitor bank circuit breakers. It is observed that approximately 25% of the Cap bank CB population undergoes more than 100 operations per year due to the heavy usage.

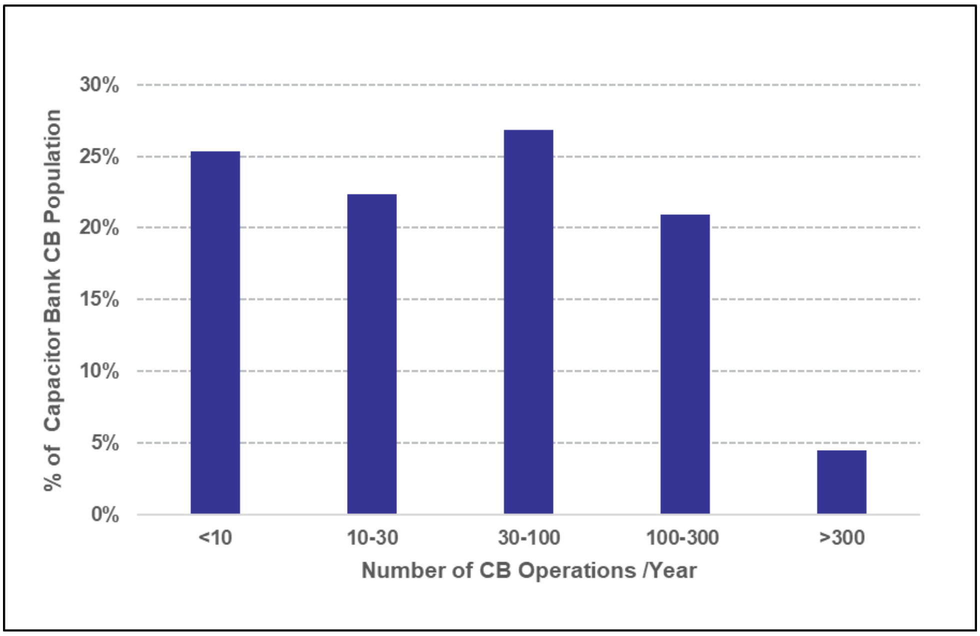

Figure 21 – Annual Capacitor Bank CB Operations

4 Other Issues

4.1 PCB in Bulk Oil and Minimum Oil Circuit Breakers

Older minimum oil circuit breakers have been found to contain Polychlorinated Biphenyls (PCBs) in oil which requires special handling procedures to be followed during their life cycle management due to health and safety and environment concerns if contaminated with environment.
Circuit breakers which have been found to contain more than 2 mg/kg stipulated by the HSEQ guidelines (HSP 05-32) are treated as PCB contaminated and needs to be handled with care.

4.2 Asbestos in Older Oil Circuit Breakers

Asbestos containing material are found in older bulk oil circuit breakers such as [C-I-C] circuit breakers in arc chutes, covers and panels used in control cubicles. Asbestos material has the potential to cause harm to the safety and health of people, equipment, or the environment. Certain control measures have to be adopted when it is required to modify or removing asbestos as per HSP-05-05-1 guideline.

4.3 Technical Obsolescence / Spares Management

Manufacturers generally cease to formally support when CB's are older and could not normally obtain OEM spares parts beyond 30 years. Similarly, the specialist knowledge and ability of the manufacturer to overhaul / refurbish their circuit breakers will also diminish over time.

Although serviceability can be improved midway through asset operational life, by increasing the level of spares held in stores just before the OEM ceases manufacture stores holding will deplete to the point that salvaging components and reverse engineering become the only means of supporting a fleet of circuit breakers. Ultimately, even reused components cannot economically extend asset lives further and at this point a circuit breaker will become obsolete.

In regard to bulk oil and minimum oil circuit breakers, are now technically obsolete and no manufacturer support is available, and the availability of spares is very limited to maintain a reliability of older circuit breakers.

4.4 New Technology and Increased Customer Expectations

With the increased use of new technology by customers and their expectation of higher reliability of power supply require faster and reliable circuit breakers for fault clearing. Oil Circuit breakers built in 1960s are generally maintenance intensive and lower operating duty compared to modern SF6 CBs. Also, modern circuit breakers are provided with polymer housing /enclosures and fail safe compared to older circuit breakers provided with porcelain housing / enclosure.

5 Risk and Option Analysis

A risk assessment considering the calibrated condition and economic consequences of failure, namely safety risk, supply risk and collateral damage risk, has been derived as shown in Table 8. The condition of the assets (C1- C5) and the monetised consequence of failure (criticality bands 1 – 5) is as explained in section 3.4 and 3.5.

Table 8: Circuit Breaker Risk Assessment

Criticality Band	C1	C2	C3	C4	C5
5	66	47	64	21	30
4	26	18	52	18	24
3	9	12	5	2	16
2	13	20	16	5	14
1	207	154	92	86	46

The CB Replacements and major refurbishment asset works in progress during the current TRR period (2017-2022) have been excluded from the risk matrix.

There are 123 circuit breakers in the high-risk area (Red zone) of the matrix. These mainly correspond to very poor condition (C5) 66kV [C-I-C], 220kV [C-I-C], [C-I-C] and 500kV [C-I-C] circuit breakers. The poor condition (C4) are mainly 66kV [C-I-C], and [C-I-C] circuit breakers.

Risk matrix shows that large number of circuit breakers fall into criticality band 1 or 2 due to replacement of bulk oil and minimum oil CBs with inherently safer dead tank type circuit breakers with polymeric bushings during terminal station rebuilds and with improved network design topology in the last 10 -15 years.

Replacement 15 off identified high risk C5 condition 66kV [C-I-C] bulk oil circuit Breakers at GNTS, HOTS and FTS Terminal Stations have been proposed under station rebuilds during the 2022-2027 TRR period.

Excluding the replacement identified to be replaced under station major rebuild projects during 2022-2027, following asset replacements are identified to be carried out under TRR 2022-27 period:

- Replace 2 off [C-I-C] and 4 off [C-I-C] (associated with very poor condition CT's)
- Replace 8 off identified high operation capacitor bank CB reaching their duty limits / C5 condition 2 off 220kV [C-I-C], 1 off [C-I-C] and 4 off 66kV [C-I-C] and 1 off [C-I-C]

6 Asset Strategies

6.1 New Installations

- Specify outdoor SF_6 insulated dead tank/ polymer insulator circuit breakers up to 220kV and Live tank / polymer insulator circuit breakers for 275kV and above for replacement in outdoor terminal stations.
- Specify SF6 insulated circuit breaker for 66kV and above voltages in Gas insulated switchgear (GIS)
- Specify indoor metal clad /arc fault rated vacuum interrupter or SF6 insulated circuit breaker in indoor modular AIS or GIS for 22 kV indoor installations.

6.2 Condition Monitoring

- Continue visual checks of circuit breakers as part of the regular terminal station inspections.
- Continue annual non-invasive condition monitoring scans including the use of radio frequency interference, ultrasonic, infra-red thermal and UV corona camera testing to evaluate the integrity of circuit breaker insulation and external and internal connections.
- Continue to establish the bulk oil CB's SRBP bushing condition through electrical testing program

6.3 Maintenance

- Continue scheduled preventative maintenance as per specific Standard Maintenance Instructions for each circuit breaker type.

6.4 Spares Holding

- Maintain strategic spares holding of CB as per spare holding policies
- Continue to salvage best parts and complete assemblies of obsolete CB to achieve per spare holding policies

6.5 Refurbishment

- Use bushing replacements to manage shorter term risk for from the very poor condition bushings of bulk oil CBs, identified during the electrical testing condition monitoring program
- Complete refurbish [C-I-C] CB mechanisms and [C-I-C] during TRR 2022 -2027 period
- Continue to refurbish/ repair SF6 leaks in live tank circuit breakers and GIS, where economical

6.6 Replacement

- Replace 2 off [C-I-C] and 4 off [C-I-C] (associated with very poor condition CT's)

Replace 8 off identified high operation capacitor bank CB reaching their duty limits / C5 condition 2 off 220kV [C-I-C], 1 off [C-I-C] and 4 off 66kV [C-I-C] and 1 off [C-I-C]

7 Appendix 1 – Circuit breaker Significant Failure History 1997-2020

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
13/12/1997	HWPS	220	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	26	Bushing explosion with collateral damage. Insulation deterioration accelerated due to low oil level.	Replaced failed and damaged bushings.
7/02/2001	ROTS	220	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	28	High Resistance joint developed internal to bushing head causing significant overheating.	Replaced bushing.
1/03/2001	HWPS	220	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	30	High Resistance joint developed internal to bushing head causing significant overheating.	Replaced bushing.
29/07/2001	TTS	220	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	27	Electrical testing indicated unacceptable internal insulation integrity and could not be returned to service.	Replaced bushing.
3/09/2001	TTS	220	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	27	Bushing explosion with collateral damage.	Replaced failed and damaged bushings. Established bushing oil sampling regime as part of Class 2 maintenance for fleet.
10/10/2002	SYTS	500	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	19	Partial closure due to loose drive rod nut causing half interrupters not to engage.	Replace Interrupter assembly
4/02/2003	SYTS	500	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	20	During operation, a flashover to tank occurred due to loose contact fingers falling out.	Replace Interrupter assembly.

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
14/03/2003	SHTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Transf./Line/Bus Tie	3	Catastrophic failure while attempting to clear a downstream fault. Investigations revealed TRV exceeded CB capability.	Complete CB replaced with same type. All similar CB on transformer bays fitted with 26nF surge capacitors to reduce TRV.
11/06/2003	SMTS	500	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	22	Partial closure due to interrupter nozzle fracture blocking the operation.	Replace Interrupter assembly.
23/07/2004	SMTS	500	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	23	During X ray inspections to check for nozzle problems found a broken drive rod at the 4th interrupter stage. The interrupter was wedged close. This CB was only operating 3 out of 4 interrupters.	Replace Interrupter assembly.
4/10/2004	SYTS	500	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	21	During open operation a flashover to the tank occurred. Possibly particles contamination. Only 18 months since refurbishment by OEM.	Replace Interrupter assembly.
12/05/2005	EPSY	220	[C-I-C]	[C-I-C]	SF_6 – Live tank	Generator	1	Catastrophic failure during opening operation to offload Generator.	Complete CB replaced. Investigations could find no obvious cause.
14/08/2005	RWTS	66	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	45	Catastrophic failure during trip operation. Investigations suspected a wear out failure.	Complete CB replaced with same type. Remaining OS10 on network programmed for replacement.
28/08/2006	DDTS	220	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	4	Mechanism failure with broken component parts during close operation. CB switches a Cap Bank.	Complete mechanism replaced.
10/10/2006	ERTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	11	Catastrophic failure during opening operation. Investigations revealed an early wear out failure at 2400 operations.	Complete CB replaced. Policy change and Operation limit for type reduced to 1800 operations.

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
22/08/2007	BETS	66	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	1	Flashover to tank during close operation to energise line. Flashover on line side of CB. Most likely particle contamination.	Complete CB replaced.
29/12/2007	MLTS	220	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	6	Mechanism failure with broken component parts on No. 2 cap bank CB during close operation. CB was a high operation Some suspected interrupter damage due to internal arcing. CB switches a Cap Bank.	Complete CB replaced with same type. Integrity of the fleet of same type checked by ABB.
10/04/2008	TGTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	1	Catastrophic failure during opening operation to de-energise Cap Bank. Investigations revealed incorrect factory mechanical setup.	Complete CB replaced. All CB manufactured by Indian factory (approx half the fleet) recalled and interrupters replaced. Revised earth fault protection settings applied to all Cap Banks to detect this failure mode.
14/08/2008	TBTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	6	Mechanism seized and failed to close. 1600 operations.	Complete CB replaced. SMI updated to incorporate further mechanism instructions and warnings.
10/10/2008	BATS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	4	During maintenance, mechanism seized, and could not operate. Investigations suspected accidental overcharging during maintenance.	Complete CB replaced. SMI updated to incorporate further mechanism instructions and warnings.
11/12/2008	MWTS	66	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	25	Mechanism components broken and frame damaged. Due to loss of damping and wear out adjustment.	Complete mechanism replaced.
5/04/2009	MWTS	66	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	41	Burn out of solenoid mechanism.	Complete mechanism replaced.

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
7/04/2009	MWTS	66	[C-I-C]	[C-I-C]	Bulk oil	Transf./Line/Bus Tie	41	Internal Flashover on Wph (MFA feeder) during clearing a downstream fault. Suspected interrupter wear out failure.	Complete CB replaced.
29/10/2009	RTS	66	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	40	Catastrophic failure during trip operation. Investigations suspected a combination of wear out and evolving fault conditions.	Complete CB replaced with same type. Remaining HKEY at RTS programmed for replacement.
12/12/2009	SMTS	220	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Transf./Line/Bus Tie	1	Flashover to tank at mechanism support insulator end while CB open. Possible particles contamination.	Complete CB replaced.
9/06/2010	GTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	10	Failure to clear current during opening operation to de-energise Cap Bank. Bus Protection operated preventing catastrophic failure of CB. Investigations revealed an early wear out failure at 1830 operations (compared to internal revised limit of 1800 operations).	Complete CB replaced. Policy change and Operation limit for type reduced to 1000 operations.
9/11/2010	TSTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	8	Failure to clear current during opening operation to de-energise Cap Bank. Bus protection operated. Later investigations could find no root cause. Approx 1600 operations	Complete CB replaced.
14/12/2010	SVTS	220	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	44	Partial close operation. Drive insulators flange mortar crumbled.	Replaced broken drive insulators.

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
20/12/2010	KTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	10	Maintenance check discovered unacceptable SO2 levels, indicating excessive arcing. Later investigations found wear out and slack internal drive rod. CB had performed 1500ops.	Complete CB replaced.
28/12/2010	HWPS	220	[C-I-C]	[C-I-C]	SF_6 – DT or GIS	Generator	6	Flashed over to earth following an unsynchronised close and immediate trip signal from Generator. Investigations suspect extreme TRV and DC offsets have exceeded CB capability.	Complete CB replaced.
25/03/2011	WMTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	16	Extreme SF_6 leak developed quickly requiring weekly top ups. Leak from drive crankcase and could not be repaired in situ.	Complete CB replaced.
1/04/2011	HTS	66	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	14	Mechanism components broke, resulting in failure of mechanism to open or close CB. CB duty is on a high operation cap bank. Mechanism > 2000 operations.	Complete mechanism replaced.
29/07/2011	TTS	220	[C-I-C]	[C-I-C]	SF_6 – Live tank	Cap Bank	10	High SO2, a by-product of excessive arcing. Loose interphase linkages due to lack of locking washers. Later internal investigation found damaged nozzle. CB switches a high operation Cap Bank.	Complete CB replaced.
30/09/2011	YPS	220	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	32	Partial close operation. Mechanism failed and broken parts due to sticking mechanism.	Complete mechanism and pole (with interrupters) replaced.

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
17/06/2015	MLTS	220	[C-I-C]	[C-I-C]	LT	Transf./Line/Bus Tie	32	Replace Red Phase hydraulic ram	Hydraulic Ram replaced
24/10/2016	RWTS	66	[C-I-C]	[C-I-C]	Bulk Oil	Transf./Line/Bus Tie	48	Replace broken trip latch	Replaced trip latch
24/02/2017	SVTS	220	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	48	Replace cracked rotating drive insulator	Replaced drive rid insulator
3/05/2017	TTSX	66	[C-I-C]	[C-I-C]	SF6 – Live tank	Cap Bank	27	Replace CB Mech	Replaced the mechanism
31/05/2017	LYPS	500	[C-I-C]	[C-I-C]	CBLT	Transf./Line/Bus Tie	31.6	Multiple hydraulic issues across the phases in short succession	Whole 3 phase CB replaced
6/06/2017	MLTS	220	[C-I-C]	[C-I-C]	SF6 – DT or GIS	Generator	1	MLTS-Replace Wph Ram ELTS Ln 2 Bus CB	Hydraulic Ram replaced
17/06/2017	SVTS	66	[C-I-C]	[C-I-C]	CBLT	Cap Bank	26.6	Explosive failure of red phase interrupter expelling oil and causing CB fire.	CB Replaced
23/06/2017	SVTS	66	[C-I-C]	[C-I-C]	SF6 – Live tank	Cap Bank	27	Replace faulty CB	Replaced CB
9/07/2017	SVTS	66	[C-I-C]	[C-I-C]	CBLT	Cap Bank	38	CB Failure due to possible contact restrike and contact erosion	CB replaced
8/09/2017	KTS	500	[C-I-C]	[C-I-C]	CBLT	Transf./Line/Bus Tie	15.7	Loose pre-insertion contact crown became jammed in interrupter	Complete CB Pole replacement
9/11/2017	KTS	500	[C-I-C]	[C-I-C]	CBLT	Transf./Line/Bus Tie	7.3	Rupture disc operated.	CB head replaced
29/12/2017	EPSY	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Generator	4	EPSY- replace 1 GEN TR 220KV CB Rph	CB replaced
2/03/2018	GTSX	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	35	Replace hydraulic ram on W phase	Hydraulic Ram replaced
3/04/2018	BLTS	220	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	43	Replace Interrupter Head	Interrupter Head replaced
4/04/2018	ERTS	220	[C-I-C]	[C-I-C]	Minimum Oil	Transf./Line/Bus Tie	42	Replace Interrupter Head	Interrupter Head replaced
16/07/2018	HOTS	66	[C-I-C]	[C-I-C]	CBLT	Cap Bank	13	Internal flashover	CB replaced

Incident Date	Station	kV	CB Manuf.	CB Designation	Technology	Duty	Age (years) at time of failure	Nature of Failure	Remedial Action
3/08/2018	ROTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Cap Bank	24	No3 CAP BANK HEAD REPLACE RPH	defective CB pole replaced
5/09/2018	WMTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	33	replace defective high resist heads S/C	defective CB pole replaced
18/10/2018	SVTS	66	[C-I-C]	[C-I-C]	Bulk Oil	Transf./Line/Bus Tie	51	Replacement of the SVTS 1-2 B/T CB	CB replaced
26/10/2018	MLTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	35	MLTS-A2 TRAN 1B CB Replace Hyd Ram	Hydraulic Ram replaced
17/12/2018	GTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	35	Replace Hydraulic Ram - B3 Trans 2 B CB	Hydraulic Ram replaced
18/12/2018	GTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	37	Replace Hydraulic Ram - MLTS 2 Line CB	Hydraulic Ram replaced
2/08/2019	LYPS	500	[C-I-C]	[C-I-C]	CBLT	Line	17	Guide for pre-insertion resistor broken, near miss	CB pole replaced
14/10/2019	MLTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	36	MLTS - GTS2 L2 B CB Replace hyd Ram	Hydraulic Ram replaced
7/02/2020	WOTS	330	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	34	WOTS-Replace Jind Line 1B CB Mechanism	Replaced the mechanism
22/04/2020	GTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	37	GTS-Replace Hydraulic Ram B1 Trans 220K	Hydraulic Ram replaced
30/04/2020	MLTS	220	[C-I-C]	[C-I-C]	SF6 – Live tank	Transf./Line/Bus Tie	37	MLTS- Replace Hydraulic Ram GTS 1L 2B CB	Hydraulic Ram replaced