Powercor Australia Ltd

Surge Arrester replacement re REFCL installation
Review of Powercor surge arrester replacement strategy

March 2017

Executive summary

Following the 2009 Victorian Bushfire Royal Commission investigation and report of findings, the Victorian Government mandated the installation of rapid earth fault current limiters (REFCLs) in distribution substations (supplying 22 kV distribution feeders) in high bushfire prone areas, via the Electricity Safety (Bushfire Mitigation) Amendment Regulations 2016 (the REFCL Regulations).

Powercor Australia (Powercor) requested GHD to undertake an independent assessment of its strategy for replacing a proportion of Powercor's population of surge arresters on 22 kV feeder circuits within its electricity distribution network in identified high-risk bushfire areas in which Powercor has been mandated to install REFCLs. This report outlines our review of Powercor's strategy and sets out our findings.

In recognition of the higher voltage imposed on the 22 kV network during REFCL operation (up to 24.2 kV phase to earth) than is imposed (phase-to-earth) during non-faulted operation (12.7 kV ± 10%), Powercor has developed a strategy for determining, through adoption of an appropriate principle for design of networks in bushfire prone areas, those surge arrester types:

- Capable of withstanding the over-voltage imposed during REFCL operation yet having sufficiently low residual or clamping voltage during surge suppression as to be capable of protecting the network equipment a particular surge arrester is required to protect
- Unable or likely to be unable to withstand the over-voltage imposed during REFCL operation for the REFCL operating duration required to:
    - Hardness test the network on installation of REFCLs (10 minutes 24.2 kV over-voltage)
    - Enable fault identification and clearance under phase-to-earth fault events

Our review focused on the following key considerations of the replacement strategy:

- The method used by Powercor to determine those surge arrester types to be:
    - Tested on a sample basis in order to determine whether they can be retained in service or need to be replaced where the sample is large and no technical data is available
    - Retained in service without testing i.e. where available technical data indicates suitable voltage ratings
    - Replaced without testing where sample size is small and no technical data exists to determine if voltage ratings are suitable
- The testing regimes to use for the surge arrester types to be sample tested
- The overall selection criteria for determining which surge arrester types to retain or replace.

The developed testing and selection criteria to determine which surge arresters should be replaced as part of the REFCL installation rollout strategy is as follows:

- Arrester types with small populations (<500) and unverified data specifications to be replaced
- Arrester types with large populations with known specifications that are insufficient for REFCL installations to be replaced

- Arrester types with large populations with unknown specifications to be tested against defined pass or fail criteria and those surge arrestor types that fail to meet these criteria to be replaced.

The selection and testing specification and test pass/fail criteria are as set out below:

- Arresters with known operating characteristics (e.g. where data sheets are available) to be selected for replacement where the rated voltage (U_r) is less than 24.2 kV (the maximum possible long term (>10 minute) healthy phase-to-earth voltage under REFCL operation)
- Arresters with large populations (>500) but where operating characteristics are not known to be subjected to sample testing:
  - 1-hour 24 kV soak test (1 hour) to verify rated voltage (U_r) of an arrester has not degraded with in-service age.
  - Incremental voltage test from 22 kV to 30 kV to determine the voltage at which the arrester transitions from capacitive range (blocking) to ohmic range (conducting or clamping) to determine rated voltage (U_r). With a minimum acceptable threshold prior to commencement of transition from capacitive to ohmic (the knee point of the V-I characteristic) of 24 kV as a proxy for data sheet U_r.
  - Thermal monitoring during 24 kV soak test in absence of a 22 kV to 30 kV V-I test to determine if surge arrester has entered ohmic range, indicated by rise in temperature materially (>40°C) above ambient due to increased I^2R losses.

From the laboratory testing that has been conducted on the arresters with a large population, two types of arresters currently used by Powercor met the defined pass criteria and have been identified as suitable in service surge arrester types to be retained:

- Type A Bowthorpe gapped silicon carbide, which have been in-service for many years but have operating characteristics that comply with REFCL installation.
- Type W ABB POLIM 22 kV gapless metal oxide, which is one of the currently preferred surge arrester types.

The remaining surge arrester types failed to meet the selection criteria and have been identified for replacement prior to the installation of REFCLs on the distribution network.

We consider the strategy developed and adopted by Powercor to be robust, and appropriately balances expenditure and risk considerations. It sets out a well-articulated approach based on sound technical considerations that encompasses necessary principals required for design of resonant networks in bushfire prone areas. It addresses, in full and with necessary substantiation, the network requirements to accommodate the installation of REFCLs. Further, it provides a solid basis for selection of surge arresters that will withstand the higher over-voltages that occur during REFCL operation as well as identifying those arrester types that require replacement. The strategy also takes into account consideration of the necessity to minimise the potential for network-induced fires in bushfire prone areas.

This report is subject to, and must be read in conjunction with, the limitations set out in Section 1.3 and the assumptions and qualifications contained throughout the Report.

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1. Introduction

1.1 Background

Following the 2009 Victorian Bushfire Royal Commission investigation and report of findings, the Victorian Government mandated the installation of rapid earth fault current limiters (REFCLs) in distribution substations (supplying 22 kV distribution feeders) in high bushfire prone areas, via the REFCL Regulations.

Powercor has evaluated the requirements and implications of the implementation of the REFCL installation directive. Trial projects and testing of REFCL installations were undertaken at Woodend and Gisborne substations. A major aspect of the trial program was to ascertain the network hardening requirements, that is, the higher voltage withstand requirements arising from converting solidly earthed networks into REFCL (resonant) earthed networks. The sustained over-voltages experienced during REFCL operation places a long term (>10 minutes) over-voltage stress on the network of up to 24.2 kV phase-to-earth (nominal phase-to-earth voltage is 12.7 kV ± 10%). This sustained over-voltage has the potential to cause insulation breakdown and component over-voltage failure in components not designed to withstand that overvoltage for extended periods.

1.2 Purpose of this report

The purpose of this report is to provide an independent assessment of Powercor's strategy for the replacement of a proportion of Powercor's population of surge arresters on 22 kV feeder circuits within its electricity distribution network in identified high-risk bushfire areas in which Powercor has been mandated to install REFCLs.

1.3 Scope and limitations

In developing this report, we undertook the following activities:

- Development of Red Flag report on initial findings – met with key Powercor staff in Powercor offices to discuss Red Flag report and surge arrester replacement drivers/requirements
- Reviewed additional information and accommodated discussions to address red flag issues
- Reviewed Powercor documentation reports and test reports relating to REFCL installation and impact on feeder voltage and associated voltage stress on surge arresters
- Researched into REFCL operation and network voltage impact
- Researched into surge arrester failure modes by type
- Documented the findings of our assessment of the replacement strategy
- Substantiated and consolidated our findings of the arrester replacement strategy.

Limitations

This report has been prepared by GHD for Powercor Australia Ltd (Powercor) and may only be used and relied on by Powercor for the purpose agreed between GHD and Powercor as set out in Section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Powercor arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

GHD has prepared this report on the basis of information provided by Powercor and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1.4 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

1.4 Assumptions

We have assumed that all information provided to us by Powercor relating to the surge arresters currently installed in the electricity distribution network, including test data, and current strategy documentation is accurate and complete.

2. Rapid Earth Fault Current Limiter installation and operation

This section provides further background to the need to assess surge arrester replacement arising from REFCL installations.

2.1 Victorian Bushfire Royal Commission and REFCL Mandate

In December 2011, the Powerline Bushfire Safety Taskforce (the Taskforce), established by the Victorian Government, investigated possible solutions[1] to Recommendation 32 made by the 2009 Victorian Bushfire Royal Commission (the Commission) to "*… adjust the reclose function on the automatic circuit reclosers on all 22kV feeders on all total fire ban days to permit only one reclose attempt before lockout.*"

[1] Victorian Government, *Power Line Bushfire Safety: Victorian Government Response to The Victorian Bushfires Royal Commission Recommendations 27 and 32*, December 2011

The Taskforce recognised that, whilst limiting reclose attempts will increase the risk of customers losing supply, "*… under the most dangerous fire conditions even one or two reclose attempts may be sufficient to start a fire.*" Many automatic reclosers in the Powercor distribution network will require manual adjustment to implement this recommendation, which would take an extensive amount of time, and therefore need to be undertake in advance of the bushfire season. It will also raise the potential for false or nuisance trips causing supply disruptions and long restore times due to line patrols prior to re-energisation. To avoid the possibility of false trips, the Taskforce suggested that safety devices are required which can either be adjusted remotely, or self-adjust, to quickly respond to changing risk conditions.

Acting on the Task Force's suggestion, the Victorian Government has enacted the REFCL Regulations requiring electricity distribution utilities with high voltage (HV) overhead assets in high bushfire consequence areas to meet new performance standards for the detection and limiting of arc fault energy. REFCLs were identified as a specific solution[2] to meet these performance standards and the requirements of the Commission's Recommendation 32 to provide the greatest risk mitigation against fire starts in high consequence bushfire areas.

2.2 REFCL operation and impact on network

In compliance with the requirements of the Bushfire Mitigation Regulations, Powercor is modifying its network configuration in bushfire prone areas from standard hard-earthed (either directly or through a neutral earth resistor (NER)) networks to resonant earth networks fitted with REFCLs.

An REFCL is a variation of a Peterson Coil system, where a reactor (inductor) is placed between the neutral point of an electric-power system transformer star secondary and earth. The value of the reactance is such that, when an earth fault occurs, the current through the reactor exactly balances, but in opposite phase, the now unbalanced healthy feeder phase-to-earth capacitive current.

This imposed voltage across the Peterson Coil arising from this reactive current flow during a single phase-to-earth fault on an REFCL system displaces the voltage of the neutral star point of the transformer secondary and collapses the faulted phase voltage to near earth potential. This limits the energy of the fault and hence materially reduces the likelihood of fire ignition. A consequence of this neutral displacement is the phase-to-earth voltage of the two healthy phases is displaced by a factor of $\sqrt{3}$ with respect to earth. Hence the phase-to-earth voltage of the remaining two feeders equate to the phase-to-phase voltage (22 kV ± 10%) under normal operating conditions (refer Appendix A). The phase-to-phase relationship is however unchanged. A REFCL system incorporates an inverter that adjusts the current through the Peterson coil to ensure that the faulted phase is driven close to earth potential (typically within 100 V to 200 V of earth).

The voltage set point on Powercor 22 kV bus bars is nominally 22 kV phase-to-phase but can vary due to the magnitude and type of customer load connected. Heavy loads lead to voltage drop along the feeder, and control systems at the substation are designed to boost the bus bar voltage to compensate for this voltage drop. Within normal operations, it is usual for bus bar voltages to be 5% above nominal on a continuous basis. The maximum allowable excursion is +10% above nominal on a continuous basis (i.e. 24.2 kV).

The REFCL system also contains a proprietary method for fault confirmation that uses the REFCL inverter technology to displace angularly the system neutral voltage. This angular displacement further increases the voltage on healthy phases to up to 24 kV for a nominal 22 kV phase-to-phase operating voltage period of 10-15 seconds each time the REFCL

[2] Ibid., p. 4

searches for a sustained fault. Phase-to-phase voltages are not affected by REFCL operation (refer Appendix A).

Powercor has determined that 'hardness' testing of a distribution network with REFCLs installed is necessary to identify those network components likely to fail under REFCL operation from the increase in imposed voltage. This hardness testing requires increasing the network voltage to 24.2 kV (representing maximum phase-to-earth voltage imposed on healthy feeders if, prior to fault conditions, the feeder was running at 22 kV + 10%) for a period of 10 minutes. Powercor considers this 10-minute duration to be a balance between being sufficient stress network components to identify weaknesses but of insufficient duration to create failures due to thermal stress and or insulation breakdown creep. We consider this hardness testing regime to be appropriate for the reasons set out above. That is, on consideration of the merits and demerits of longer and shorter durations, we concur with Powercor's selection of a ten minute duration +24.2 kV test as being appropriate for 'hardness testing' of networks fitted with REFCLs. We consider such a regime is adequate to identify components likely to fail and hence potentially cause a bushfire risk and or impact network reliability under REFCL operation, without unduly stressing components leading to degradation in voltage withstand capability and hence premature failure under normal, non-faulted, network conditions.

2.3 Powercor experience of REFCL at test locations

Powercor has conducted REFCL installation trials on the Woodend and Gisborne 22 kV distribution networks to assess the migration of the networks to a resonant earth network. The objective of the trial was to identify system component upgrade or amendment to network management strategy and policy that may be required to support the installation of REFCLs.

The key discussion points for surge arresters highlighted in the report discussing the trial were:

- Compliance with Class A[3] and the test procedure to be applied.
- Pressure relief test.
- Applicable AS and IEC standard requirements for spark testing.

The surge arrester options available to meet the over-voltage requirements for an REFCL installation were reviewed, and the ABB POLIM K22-80 was considered by Powercor an option that satisfied the pressure testing requirements as per the standards.

The report recommended that Powercor should adopt the Australian Standard as the requisite testing for pressure testing of surge arresters to meet the Class A requirements. We concur with Powercor's adoption of the Australian Standard over the IEC standard as the Australian Standard includes specific requirements for bushfire ratings of surge arresters. We set out our analysis of the report's recommendations as to the test procedure to be applied to networks on installation of REFCLs and the selection of approved surge arresters for various duties in later sections of this report.

3. Surge arrester characteristics

This section describes the operating characteristics of surge arresters by type (gapped silicon carbide resistive blocks and gapless metal oxide blocks), typical rating parameters and failure mechanisms.

[3] Class A surge arresters have the lowest fire start risk, typically due to additional design features such as arc control devices to minimise the expulsion of molten particles should they fail internally.

3.1 Operation

The main task of a surge arrester is to protect equipment from the effects of over-voltages. During a normal discharge operation, an arrester should have no negative effect on the power system, and must be capable of withstanding and clamping typical surges, maintaining a specified maximum residual or clamping voltage for a given transient over voltage magnitude and duration, without incurring damage.

Surge arresters satisfy these operating requirements due to the following properties:

- High resistance during normal operation to avoid negative effects on the network arising from phase to ground currents
- Low resistance during surges, so that over-voltages on the network close to critical components are limited i.e. 'clamped' at an acceptable level
- Sufficient energy absorption capability for thermally stable operation during transient over voltages (TOVs) of relatively low duration.

There is only small leakage current, predominantly capacitive, flowing through the arrester when continuous operating voltage is applied. However, during TOV conditions, excess energy due to surges can quickly be dissipated and the voltage clamped by an arrester passing a high discharge current to earth as the surge arrester transitions from high impedance to low impedance.

There are two main surge arrester types:

- Gapped silicon carbide (SiC) resistive blocks.
- Gapless metal oxide varistor (MOV) blocks.

3.1.1 SiC surge arresters

This type of surge arrester comprises hermetically sealed fully vitrified glazed porcelain housings enclosing ceramic bonded silicon carbide non-linear resistors and a series spark gap. The arresters have rubber compression seals between the surface ground porcelain and the copper based metal end caps, and filled with an inert gas and sealed at atmospheric pressure.

During normal system operating voltage conditions, the spark gap is non-conducting and the arrester acts as an insulator. However, when a surge occurs, the spark gap in series with the silicon carbide blocks breaks down and allows surge current to flow to earth via the silicon carbide resister elements that help to dissipate the energy in the TOV surge. The arrester returns to its normal stable state once the voltage returns to normal operating conditions.

Surge arresters that use spark gaps can be unreliable, either failing to strike an arc when required and hence maintaining a high impedance and not clamping a TOV or failing to extinguish after the voltage surge has passed. Such unreliability is typically due to material failure, contamination or moisture within the housing or after repeated operation that can compromise the spark gaps due to pitting.

Arresters that use columns of metal oxide blocks (alternatively known as metal oxide varistor (MOV) blocks) have replaced the gapped SiC type of surge arrester as preferred arrester of choice for DNSPs.

3.1.2 MOV surge arresters

This type of arrester is based on nonlinear, voltage dependent, resistors (called interchangeably varistors, voltage dependent resisters (VDRs) or MOVs). It is the current preferred design of surge arresters by DNSPs. These surge arresters utilise a number of MOV blocks, which are typically zinc oxide semiconductor, that are sensitive to voltage. These discs are arranged to form a cylindrical stack enclosed in a housing of polymer or porcelain.

During steady state conditions, line-to-ground voltage is applied continuously across the arrester terminals. When over-voltages occur that exceed the voltage blocking capability of the MOV blocks, the MOV blocks transition from high resistance to low resistance. The surge arrester therefore immediately limits the over-voltage to the required protective level (the arresters residual or clamping voltage for a given surge current) by conducting the surge current to earth. As metal oxide has a negative temperature co-efficient of resistivity, the resistance of the MOV block decreases as its temperature increases and hence the leakage discharge current increases for a given clamping voltage due to energy in the voltage surge being converted to heat energy. The heat generated by this discharge current flowing through the MOV blocks is dissipated through the arrester housing.

Following removal of the TOV when the surge voltage has returned to within the rated operating voltage limits and when the heat generated by the discharge event has been dissipated, the arrester returns to its stable operating state under nominal system operating conditions. Surge arresters exhibit a different TOV clamping regime immediately post a prior operation (due to heat generated by the prior operation in the MOV stack when clamping the over-voltage) than when at ambient temperature. This TOV characteristic is known as the prior duty TOV characteristic. The voltage-duration curve for different transient voltages and their duration is lower for the prior duty curve than for the 'cold' duty curve. As such, surge arresters that have recently operated have a lower voltage-duration clamping capability than those that have not recently operated.

Figure 1 TOV capability with and without prior duty[4]

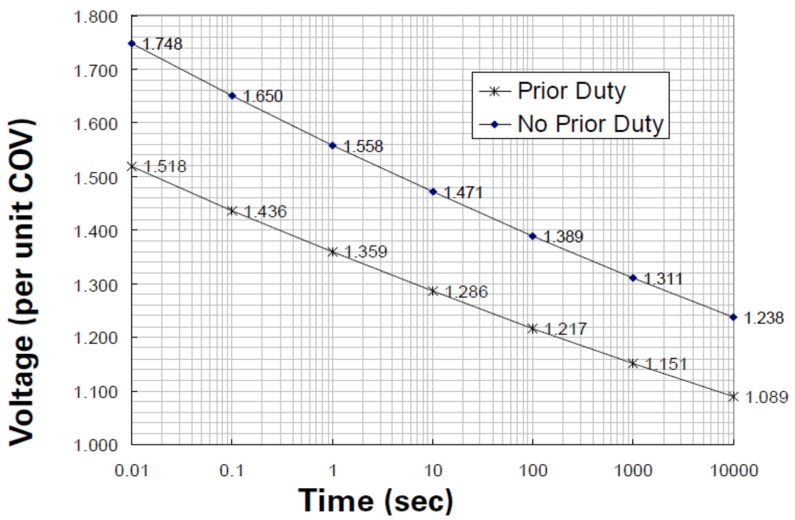


Figure shows the TOV capability (followed by U_c), for ambient temperature of $60^{o}C$. The 24-hour TOV without prior duty is 1.173 per unit of U_c and the 24-hour TOV with prior duty is 1.035 per unit of U_c.

3.1.3 Temporary over-voltage

A surge is a transient over-voltage caused by short-term phenomena, typically with voltage levels between 2 p.u. and 3 p.u. [5] (as clamped by the surge arrester) and lasting milliseconds to seconds. When a surge arrestor clamps a voltage surge to its residual or clamping voltage, for durations that exceed its TOV curve rating, heat energy in the surge arrester (due to I^2R losses) is greater than that which the surge arrester can dissipate through conductive, convective and or radiant heat dissipation without the surge arrester temperature exceeding the MOV

[4] Figure reproduced from Cooper Power Systems *UltraSILTM polymer-housed VariStarTM surge arrester data sheet – 235-5*, August 2014

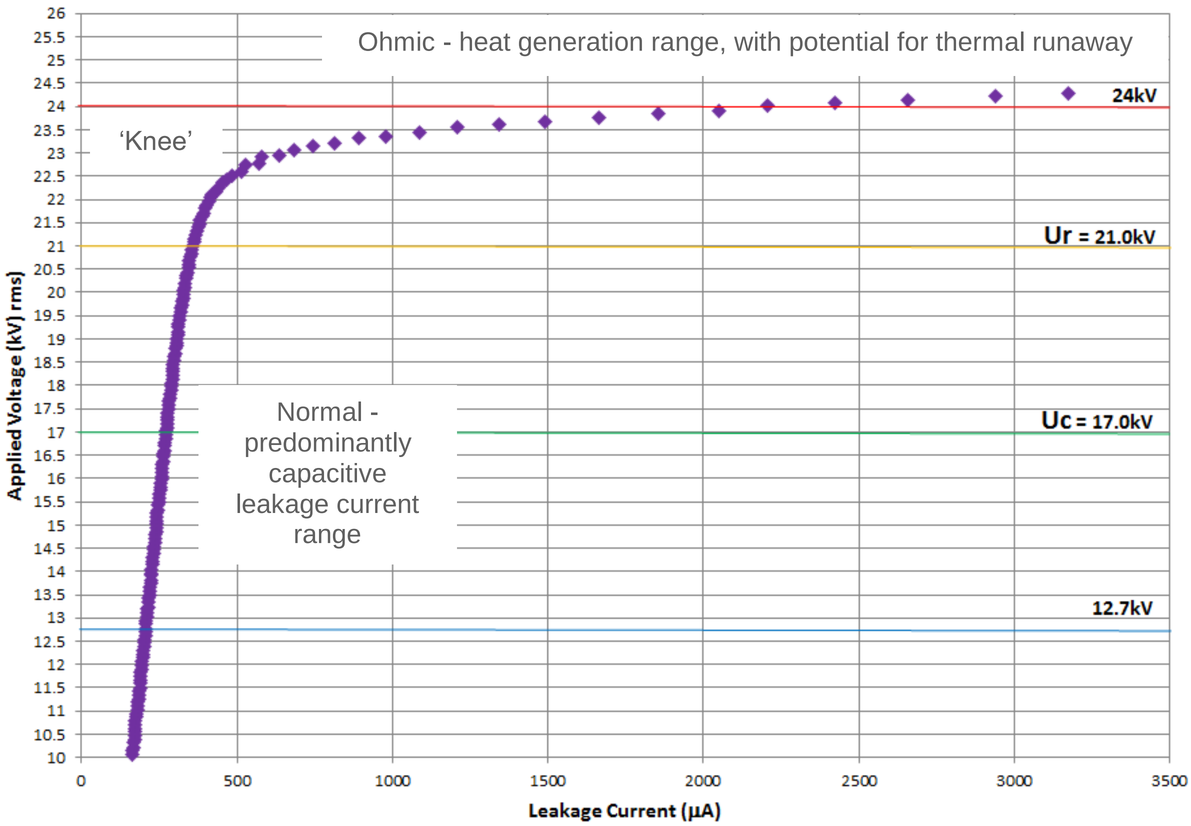
[5] Two to three per unit (p.u.) i.e. in this case, two to three times normal operating voltage.

temperature rating. TOV withstand duration, for a given over-voltage, is therefore a function of the heat generated by the metal oxide elements and the heat dissipation capability of the arrester housing.

The heat generated is a function of the voltage across the MOV stack when operating in the ohmic range multiplied by the resistive current flowing through it (V x I, also known as I^2R losses). The magnitude of the resistive current is dependent on the voltage applied to the surge arrester and the resistance of the MOV blocks when conducting. In normal operating mode, the resistive component of the leakage current flowing through the MOV is minimal as the MOV stack is in high resistive mode. In clamping mode, the resistive current flowing through the surge arrester is high following its transition from high resistance to low impedance, thereby clamping an over-voltage. The surge arrester enters clamping mode when the applied voltage is above the 'knee' or transition point of the MOV where the MOV transitions from high resistance to low resistance. At this point the surge arrester is operating in its clamping or ohmic range of the MOV stack V-I curve (refer Figure 2).

Whilst below the 'knee' point, the majority of the leakage current will be reactive (capacitive), there is also a small resistive element to this current as the MOVs do not present infinite resistance when operating below the 'knee' point. This resistive current in blocking mode increases as the MOV stacks degrade due to repeated operation resulting in degraded gapless surge arresters exhibiting higher temperatures than non-degraded gapless surge arresters under normal operating conditions.

Figure 2 Surge arrester V-I characteristic example



3.2 Ratings

Typical rating nomenclature for the primary arrester electrical parameters is set out in Table 1.

Table 1 Surge arrester rating terms

Rating	Symbol	Description
Continuous operating voltage	U_c	Maximum continuous operating voltage that can be applied without restriction Equals or exceeds the normal system maximum line-to-earth operating voltage (refer IEC 60099-5) - for a 22 kV system: U_c = 12.7 kV + [allowed continuous over-voltage at furthest feeder customer connection point] + [maximum potential volt drop at rated feeder current] For rural circuits, the maximum continuous over-voltage is 1.1 p.u.[6]
Rated arrester voltage[7]	U_r	Rating should exceed the maximum voltage that may be applied to a surge arrester during normal operation e.g. by a healthy feeder during a phase-to-earth fault condition prior to the fault being cleared. For resonant earth networks, such as those with REFCLs installed, the rated surge arrester voltage for a 22 kV circuit is typically recommended to be between 24 kV and 27 kV[8].
Residual or clamping voltage	U_{res}	Peak value of voltage that appears across the terminals of an arrester during the passage of discharge current under TOV conditions. Also often referred to as discharge or clamping voltage.
Temporary over-voltage	TOV	Temporary over-voltage capability of a surge arrester. This is graphically represented as a power frequency withstand voltage versus time characteristic (refer Figure 2).

3.3 Failure modes and mechanisms

The principal cause of failure of a surge arrester under TOV conditions is a function of the duration of the TOV, the voltage imposed across the surge arrester and the resulting resistive current flowing through the surge arrester. The surge arrester will fail under TOV conditions when the rate of energy dissipated in the surge arrester exceeds the ability of the surge arrester to dissipate the generated heat sufficiently during the duration of the TOV to maintain the MOV stack at or below maximum rated temperature.

The principal failure mode of a surge arrester predominately results in a short circuit inside its housing, due to dielectric breakdown where the internal blocks are unable to withstand the voltage applied; be that normal system voltage, temporary over-voltage, lightning or switching surge voltage. A short circuit failure is considered fail-safe, as the surge arrester, having operated, does not represent an ongoing and unknown risk to network assets. An open circuit failure, although not the dominant failure mode, will allow damage to other equipment to occur in the event of a TOV subsequent to open circuit failure of the surge arrester without the risk being evident.

Therefore, industry standards associated with the design, construction and operation of surge arresters all require the device to fail, predominantly, in a safe manner i.e. short circuit.

The common failure mechanisms for surge arresters are[9]:

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6 p.u. is per-unit of the peak value of the highest continuous phase-to-earth voltage

7 U_r is defined by the transition from capacitive operation to ohmic. That is it is the operating voltage of the surge arrester just below the knee point – see Figure 2

8 Cooper Power Systems data sheet – 1235-35, August 2014

9 These are general failure mechanisms and are not unique to networks with REFCLs installed

- Moisture ingress
- Temporary over-voltage exceeding V-t ratings
- Thermal runaway
- Ageing of MOV blocks
- Damage from surge duty.

In addition to these common failure mechanisms, surge arresters may fail due to having ratings that are insufficient for use under REFCL operating conditions.

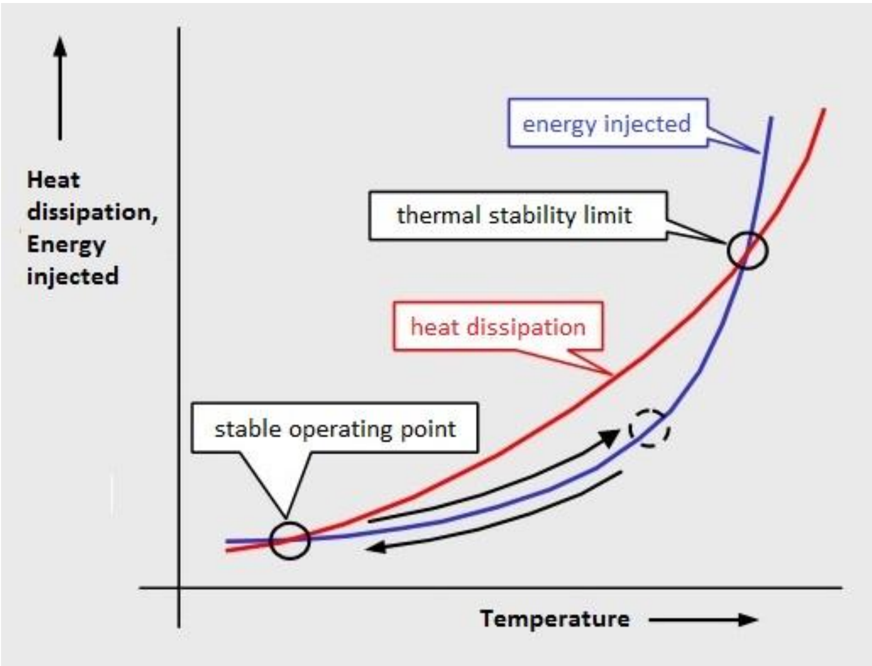
A visual inspection of a surge arrester will only identify a failed device in instances where the failure in the MOV blocks has caused an explosion, resulting in the cracking or rupture of the arrester housing. A surge arrester degraded by repeated TOV clamping operation exhibits higher resistive leakage current, under normal operation, without necessarily showing external signs of degradation. This higher resistive leakage current results in heating of the surge arrester above ambient detectable by thermal imaging.

3.3.1 Thermal runaway from surge duty

With reference to Figure 2, surge arresters operating in the ohmic range under TOV conditions are subject to heat generated in the MOV stack. The thermal energy handling capability of a surge arrester is defined as the maximum quantity of energy that can be injected into a surge arrester following which the device can still cool back to its normal operating temperature after removal of the overvoltage.

Figure 3 shows the relationship between the thermal energy handling capability (heat dissipation ability), the energy injected due to a TOV and MOV stack temperature of a surge arrester. The design of the surge arrester determines its ability to dissipate heat into the surroundings.

Figure 3 Thermal stability[10]



[10] Siemens, *Metal-Oxide Surge Arresters in High-Voltage Power Systems: Fundamentals*, 3rd edition, September 2011, Figure 7, p. 15

In Figure 3, the two thermal curves have two common points. The intersection at the lower temperature is considered the stable operating point where the heat generated in the metal oxide resistor block is thermally balanced by the amount of heat irradiated from the surge arrester housing.

In the event of a discharge operation, the energy generated by surge arrester operation produces a rapid temperature rise in the surge arrester, as shown in Figure 3 (refer: the arrow moving to the right along the blue line). Provided the point of intersection at the higher temperature is not reached (thermal stability limit), the surge arrester can dissipate the heat generated by the energy loss, and will return to the stable operating point on removal of the TOV.

If the thermal stability limit is exceeded the surge arrester will become thermally unstable with the temperature of the MOV stack continuing to rise for a given clamping voltage. The temperature limit is a function of the heat generated by the MO elements and heat dissipation capability of the arrester housing. For some MOV types, such as ZnO, the heat generated by a constant voltage will increase to a higher degree than would otherwise be the case for resistors with a positive temperature co-efficient of resistivity due to the negative temperature coefficient of resistivity of the MOV material. That is, as temperature increases, the resistance of the MOVs decreases resulting in increasing current flow and hence I^2R losses for a given overvoltage, leading ultimately to thermal runaway. This negative temperature coefficient of resistance results in the device, when operating in the ohmic range, rapidly increasing in internal temperature because of the continually increasing discharge current until destruction of the device. The negative temperature coefficient of resistivity of the MOV blocks is the mechanism that drives the thermal runaway, not the limitation of the housing to dissipate heat per se.

3.3.2 Consequence of surge arrester failure/degradation

If a surge arrester fails, it normally fails short circuit with the failure detected by protection circuitry, and the surge arrester is replaced. However, if the surge arrester fails open circuit and or its performance is compromised through repeated operations, these failure modes are not readily detectable. Surge arresters exhibiting these failure modes are no longer able to protect the components they are intended to protect, resulting in increased network outages following TOVs arising from e.g. lightning strikes.

3.3.3 Insufficient ratings under REFCL operating conditions

Adapting the network configuration to a resonant earth network employing REFCLs requires a review of all system components to ensure they can withstand the higher continuous and transient voltages generated during a phase-to-earth fault and REFCL operation.

Each type of surge arrester installed on the network needs to be assessed to ensure it can safely operate for temporary over-voltages of 24 kV without high leakage currents and from heating effects at 24 kV posing a potential risk of thermal runaway. This can only be assessed from the characteristics of a particular surge arrester as set out in the manufacturers data sheet (assuming that the surge arrester performance has not degraded from repeated operations), or by testing the units.

3.3.4 Findings from failure mode evaluation

Our findings from analysis of the failure mode of surge arresters are:

- The second most common cause of failure is over-temperature due to operation beyond its TOV capabilities as defined by its V-t curves, or temperature induced degradation of the MOV stack through repeated operation.

- Surge arresters should be operated in the capacitive region (i.e.at a voltage below U_r) under normal long-term operating conditions.
- Healthy feeder operation at up to 24.2 kV phase-earth voltage under REFCL operation conditions should be considered normal operation of the network, given the design of REFCLs maintains operability of the non-faulted or healthy feeders for a controllable period. Therefore, surge arresters selected for resonant operation should have an U_r (either as specified in its data sheet or as demonstrated by means of V-I tests) of greater than 24.2 kV. They should also have a maximum clamping or residual voltage for a given over voltage-time duration appropriate for its location on the network and for the components it is intended to protect.

4. Powercor surge arrester replacement strategy

4.1 Review of documentation

The documents reviewed during our review were:

- Powercor Replacement criteria email to GHD 10/02/2017.
- Surge Arresters of Woodend & Gisborne, 30/09/2015.
- Powercor Electricity Networks Scope of Works for an External Party (for REFCL testing of distribution surge arresters (additional testing)), 16/06/2016.
- Powercor Transformer Failure Rate Due to Lightning, 31/05/2016.
- Central Test Result, 26/05/2016.
- Select Solutions Test Result, 11/07/2016.
- Powercor 22 kV Surge Arrester Review, 02/11/2016

4.2 Options assessment

Powercor considered a range of options in terms of operating regime for the REFCL and in terms of requirements to ‘hardness’ test each 22 kV system to which REFCLs are to be fitted.

In this respect, we consider the options considered robust.

4.2.1 Do nothing

Powercor has adopted a network hardening strategy for circuits fitted with REFCLs, in which network components are voltage stress tested. During stress testing following REFCL installation as part of the commissioning programme, all connected line assets experience, as a minimum, REFCL induced phase-earth voltages (up to 24 kV RMS) for 10 minutes duration. This hardness testing, in itself, implicitly contemplates a do-nothing option in that it identifies those components likely to fail if no change in network components (e.g. surge arresters) is made to accommodate REFCL installation.

Thus, the testing demonstrates the implications of adopting a “do nothing” option in terms of identifying component failure under these conditions. With respect to surge arresters, the limitations of stress testing are that any arresters that fail open-circuit or in which the MOV stack V-t characteristics degrade do not necessarily have any external signs of failure, and the need for replacement may not be obvious.

4.2.2 Replace based on technical criteria

The key elements of the replacement strategy are:

1. The U_r of the surge arrester type, specified in datasheets, must be greater than the healthy phase-to-earth voltage when the REFCL operates under maximum allowable 22 kV feeder operating conditions; that is, maximum allowed continuous phase-to-phase operating voltage of 22 kV x 1.1 = 24.2 kV.

2. Hardness testing of 22 kV circuits following installation of REFCLs, where the REFCL inverter is used to drive the phase-to-earth voltage to 24.2 kV for ten minutes, to identify those components that are likely to fail under REFCL operation. The substantiation of 10 minutes (being the median value of a range between 5 and 15 minutes) as the determined required over-voltage withstand duration arising from REFCL operation for hardness testing of 22 kV circuits to which REFCLs are installed. A test duration of 5 minutes is considered too short to sufficiently voltage stress network components to identify devices that are outside their normal rating or, for example, deteriorated to a point where they no longer meet their voltage withstand specification. An over-voltage duration materially beyond ten minutes (e.g. 15 to 20 minutes) is likely to overstress components leading to failure either during the test or subsequent to the test from, for example, thermal stress or insulation degradation arising from the prolonged overvoltage.

3. Out of circuit surge arrester test parameters defined as:

   a. A 24 kV soak test at 1 hour

   b. A V-I ramp test to 30 kV or until the surge arrester is driven into its ohmic range, thereby clamping the applied voltage, within the limits of the test equipment source current and

   c. A temperature test in absence of a V-I ramp test and as a proxy for a V-I test. Surge arresters exhibiting a material temperature rise of 40°C above ambient at the 24 kV test voltage are considered to have operated in their ohmic range as it is the resistive current losses during ohmic range operation that causes temperature rise above ambient.

4. Pass/fail criteria defined as follows:

   a. Withstand 24 kV soak test without a material temperature rise or surge arrester failure; and:

      i) Demonstrate that the surge arrester ‘knee point’ i.e. transition from capacitive range to ohmic range from the V-I ramp test is above 24 kV indicating that the U_r of that surge arrester is above 24 kV; or

      ii) In absence of a satisfactory V-I ramp test, that the temperature of the surge arrester during the 24 kV soak test does not exceed 40°C above ambient.

5. The specification of the minimum population size for a surge arrester type where datasheet information is not available, warranting sample testing in lieu of routine replacement. This minimum population size has been set at 500, based on the marginal cost of testing to assess surge arrester type replacement for a batch of 30 over the cost or simply replacing units taking into account management costs.

   Where there is no manufacturer’s data available for existing surge arresters, and the population size is over 500, a statistically significant sample (previously determined by Powercor as being 30 to give a 90% confidence factor that the sample is representative) is tested.

6. Surge arrester types are selected for retention or replacement on the following basis:

a. Surge arrester types with datasheet information contemporary with their installed date where the data sheet specifies a U_r>24.2 kV and where there are no concerns as to performance degradation are retained

b. Surge arrester types with datasheet information contemporary with their installed date where the data sheet specifies a U_r<24.2 kV are replaced

c. Surge arrester types without contemporary data sheet information or where there are and where the population size is < 500 are replaced

d. Surge arrester types without contemporary data sheet information or where there are legitimate concerns as to performance degradation and where the population size is > 500 are tested on a sample basis of 30 units:

i) Those surge arrester types that are tested on a sample basis and where all of the sample pass the testing criteria are retained

ii) Those surge arrester types that are tested on a sample basis and where one or more of the sample fail to meet the testing criteria are replaced.

The above testing specifications and replacement criteria and pass/fail criteria are summarised in Table 3, Table 2 and Table 4 respectively.

4.3 Findings regarding current strategy

Overall, we consider the Powercor strategy for selection of surge arresters to be replaced or retained robust. We are of the opinion that it appropriately balances expenditure and risk. The strategy addresses the key requirements for bushfire risk mitigation as detailed by the Victorian Bushfire Royal Commission, and recognises the importance that surge arresters need to have the capability to withstand the phase-earth voltages that can be generated by REFCL operation.

Powercor sets out a well-articulated approach based on sound technical considerations that encompasses the necessary principles required for design of resonant networks in bushfire prone areas. Powercor's surge arrester replacement strategy addresses, in full and with necessary substantiation, the network requirements to accommodate the installation of REFCLs. Further, it provides a solid basis for selection of surge arresters that will withstand the higher phase-earth voltages that occur due to REFCL operation as well as identifying those arrester types that require replacement. The strategy also takes into account consideration of the necessity to minimise the potential for network-induced fires in bushfire prone areas.

In short, we consider the replacement strategy addresses the issue of in-situ surge arresters with insufficient rating for resonant earth networks potentially compromising the benefits of installing REFCLs through network components being inadequately protected and therefore contributing to poor network reliability, or causing high energy phase-to-phase faults.

5. Replacement selection criteria

Table 2 shows the replacement criteria for surge arresters to meet the requirements of REFCL installations.

Table 2 Surge arrester replacement criteria

Criteria for Replacement	Reason
Small arrester type population (<500) and unknown arrester type with no data available	Cost of testing and assessing a representative sample exceeds or is comparable to cost of replacing population

Criteria for Replacement	Reason
Data sheet available demonstrating surge arrester ratings not compatible for REFCL application	One of more of ratings specified in data sheet is below required rating for REFCL operation For example, U_r below possible healthy phase-to-earth voltage under REFCL operation when feeder operating within acceptable voltage limits (22 kV ±10% i.e. 24.2 kV)
Large arrester type population (>500) with no data available, one or more samples failed testing	Population large enough to warrant test but one of more of sample failed test
Assessed surge arrester age/condition – replacement of assets with in-service age exceeding economic life[11]	Current Powercor asset management practice to replace surge arresters based on in-service age and/or condition assessment

5.1 Findings

A surge arrester with U_r less than 24 kV will operate in the ohmic range of its V-I characteristic during operation of an REFCL (refer Figure 2). Such operation is not consistent with surge arrester manufacturer's recommendations or, in keeping with the design approach adopted by Powercor for 22 kV networks in bushfire prone areas. A further requirement in bushfire areas is that the surge arrester be Class A rated (i.e. the housing is designed to contain any explosive failure of the MOV blocks).

Powercor advised that the rating of the surge arrester in terms of U_c and residual voltage was selected according to the location of the surge arrester on the network and the equipment to be protected by the surge arrester.[12]

For nominal 22 kV electricity distribution networks with acceptable ±10% voltage limits utilising REFCLs, surge arresters are selected with the U_r value of at least 24 kV and with a residual clamping voltage below that required to protect the network component that a particular surge arrester is protecting for a give TOV voltage-time condition.

6. Testing and assessment

This section describes Powercor's testing specification and regime for surge arresters employed in bushfire prone areas, and the pass/fail assessment criteria used to assess the serviceability of the different types of surge arresters currently installed in the Powercor electricity distribution network.

6.1 Network testing

An integral part of commissioning an REFCL network is voltage stress testing. Voltage stress testing uses the REFCL inverter to displace fully the voltage on each phase to the nominal set point on a phase-to-ground basis. The purpose of this test is to identify aged, unreliable and incompatible assets on the network in order to provide assurance the system will withstand the operation of an REFCL. Each phase is tested for a period of ten minutes at the time of commissioning (refer Section 2.2).

11 The cost of replacing surge arresters under these conditions in the current regulatory period has been recognised in the AER's final determination and, as such, does not form part of the contingent project cost for replacement of surge arresters arising from REFCL installation.

12 Powercor, *22 kV Surge Arrester Review*, 2 November 2016

6.2 Surge arrester type testing

Given the modes of failure for surge arresters outlined in Section 3.3, the test parameters considered necessary to assess the suitability of a specific surge arrester type to remain in-service in a 22 kV network employing REFCLs are set out in Table 3.

The environment for the surge arrester tests is a controlled ambient temperature of 22°C and less than 60% relative humidity.

A summary of the tests by surge arrester type are:

- Silicon carbide - due to operating characteristic with spark gap that operates above 90 kV, a 1-hour 24 kV test is sufficient on a sample of 30 basis to determine which percentage, if any, of SiC type surge arresters have been compromised due to pitting of spark gap and/or insulation breakdown.
- Metal oxide varistor – 24 kV soak test and incremental V-I test to determine if device is operating in the ohmic range at 24 kV.
    - Where a V-I test is not practicable e.g. due to limitations of the test equipment, an eight hour 24 kV test result showing arrester temperature rising significantly above ambient is considered a reasonable proxy for determining if device is operating in ohmic range at an imposed 24 kV in absence of incremental V-I test.

Table 3 Testing specifications

Test parameter	Value	Duration	Test measurements to perform/record	Purpose
Applied voltage – rated voltage	U_r (defined as rated operating voltage) For a resonant impedance grounded star configuration, recommended U_r for 22 kV circuit surge arresters is 24 kV to accommodate maximum system voltage conditions of un-faulted phases	1 hour at 24 kV Note: Maximum intended duration of operation of REFCL (network stress test is 10 minutes (refer Section 2.2))	• Voltage • Leakage current - resistive component • Surface temperature	Determine rating of surge arrester has not deteriorated with age and/or condition. Check U_r rating of surge arrester is sufficient to accommodate installation of REFCL (where U_r is not known) or, where U_r is known, there has been no deterioration with age and/or condition
Voltage ramp from nominal operating system voltage	22 kV to 30 kV ramp in 0.5 kV increments, holding at each increment for 10 seconds	10 seconds at each voltage increment Note: if a datasheet is available, adjust to ensure that TOV duty rating is not exceeded i.e. total duration should not exceed max duration at highest voltage according to TOV duty curve.	• Voltage • Leakage current - resistive component • Surface temperature	Determine 'knee' point of surge arrester operation

Test parameter	Value	Duration	Test measurements to perform/record	Purpose
		In absence of data sheet, select most likely comparable, conservative rating.		

6.3 Assessment criteria

Table 4 shows the pass/fail criteria for the defined tests for assessing the suitability of the various types of surge arresters currently utilised in the electricity distribution network.

Table 4 Pass/fail criteria

Assessment metric/method	Applicable to	Assessment criteria	Replace/Retain criteria	Reason
Data Sheet Review	All surge arresters types with relevant datasheet	Datasheet or asset operating specifications suitable for REFCL operation. I.e. U_r specified as being > 24 kV	Replace if U_r < 24 kV Retain if U_r > 24 kV	Compliance of surge arrester with REFCL operation requirements verification Manufacturer recommendation for resonant earth circuits is U_r rating must exceed maximum phase-to-earth voltage resulting from REFCL operation
Population size of surge arrester with no data sheet available	All surge arresters types with no contemporary datasheet or where repeated operation may have degraded surge arresters	Population size < 500 or population size ≥ 500	Replace if population < 500 without testing. Sample test if population ≥ 500	Compliance of surge arrester with REFCL operation requirements cannot be verified as diagnostic testing of sample is uneconomic for sample sizes < 500
Rated voltage compliant with REFCL operation	All surge arrester types sample tested	U_r ≥ 24 kV as determined by testing	Replace if U_r < 24 kV as determined by sample testing Retain if U_r > 24 kV	Compliance of surge arrester with REFCL operation requirements verification Manufacturer recommendation for resonant earth circuits is U_r rating must exceed maximum phase-to-earth voltage resulting from REFCL operation

Assessment metric/method	Applicable to	Assessment criteria	Replace/Retain criteria	Reason
V-I Characteristic Confirmation Test	All surge arrester types sample tested	Surge arrester knee point occurs > 24 kV or < 24 kV	Replace arrester type if V-I plot shows knee point to occur < 24 kV Retain arrester type if V-I plot shows knee point to occur > 24 kV	V-I characteristic plot knee point used as a proxy for U_r in absence of data sheet or to verify if surge arresters have degraded through operation by comparison with data sheet specified U_r
Long duration healthy phase-to-earth voltage under REFCL operation Confirmation Test (24 kV for > 1 hr)	All surge arrester types sample tested	Arrester does or does not exhibit signs of thermal runaway. Case temperature of surge arrester exceeds or does not exceed 40ºC above ambient temperature as a proxy for identification of a surge arrester operating in its ohmic range or in its capacitive range at 24 kV in absence of a reliable V-I test.	Replace if case temperature exceeds 40ºC above ambient Retain if case temperature does not exceeds 40ºC above ambient	Assess if thermal runaway is likely when V-I test not possible. Assesses if ageing affect is evident Materially higher than ambient case temperature under 24 kV long duration test indicates surge arrester is operating in its ohmic range and hence U_r < 24 kV.

It is industry practice to specify TOV surge arrester performance using prior duty TOV V-t plots for non-directly earthed neutral point networks such as those with NERs or REFCLs installed. This is to ensure the likelihood of arrester failure is minimised in high bushfire risk areas, and therefore minimise the risk of fire ignition due to arrester failure. Surge arrester TOV ratings with prior duty are specified to ensure the arresters are capable of withstanding the duty imposed by the network. The following is a common scenario demonstrating the requirement for a TOV rating with prior duty:

- A lightning storm inducing over-voltages on the overhead system causing a number of surge arresters to operate, resulting in a temperature rise for those arresters (i.e. prior duty)
- Coincidently the storm causes a phase-to-ground fault, initiating an REFCL operation resulting in the healthy phase voltages increasing to 24.2 kV until the fault is detected and cleared.

7. Powercor surge arrester population

Table 5 shows the age profile of the Powercor surge arrester population.

Table 5 Surge arrester age profile

Surge Arrester Type	Population			Period of Usage	Avge Age (as at 2016)
	HBRA	LBRA	% Total		
A - Bowthorpe 1982-1995	25,172	11,079	23.6%	1982 - 1995	27.5
B - Bowthorpe 1980-1981	545	465	0.7%	1980 - 1981	35.5
C - Bowthorpe 1973-1978 (22 kV)	1,897	1,306	2.1%	1973 - 1978	40.5
D - ASEA 1978-1982	1,215	900	1.4%	1978 - 1982	36.0
E - Bowthorpe 1986-89	18	55	0.0%	1986 - 1989	28.5
F - Bowthorpe 1990-1992	333	810	0.7%	1990 - 1992	25.0
G - Bowthorpe 1980-1983	1,293	124	0.9%	1980 - 1983	34.5
H - Bowthorpe 1973-1978 (SWER)	1,180	59	0.8%	1973 - 1978	40.5
I - Stanger 1961-1962*	88	-	0.1%	1961 - 1962	54.5
J - All Brown Bodied*	395	86	0.3%	Pre 1973	43.0
K - Bowthorpe 1972*	71	54	0.1%	1972	44.0
L - ASEA XBE 1986-1987*	32	22	0.04%	1986 - 1987	29.5
M - Bowthorpe 1985	41	48	0.1%	1985	31.0
N - ABB MVK 1995 Polymer	11,395	9,829	13.8%	1995 - 2000	18.5
O - ABB MWK 1995 Polymer	516	1,831	1.5%	1995 - 2000	18.5
Q - Bowthorpe EGB 1995 Polymer*	1,369	914	1.5%	1995 - 1996	20.5
R - Bowthorpe HEB 1995 Polymer*	28	170	0.1%	1995 - 1997	20.0
S - Cooper Class A	26,302	15,415	27.2%	2001 - 2010	10.5
T - Cooper Class C	2,053	5,993	5.2%	2001 - 2010	10.5
V - ABB Polim Class C	76	18	0.1%	2010 - to date	3.0
W - ABB Polim Class A	1,047	135	0.8%	2010 - to date	3.0
U – Unknown	19,070	9,894	18.9%	-	-
Total	94,136	59,207	100%		

* Arrester types shown in Red are do not have pressure relief or have unacceptable pressure relief performance, and therefore fail catastrophically with a high likelihood of hot internal components being expelled. These arrester types represent a total of 2.1% of the surge arrester population.

8. Surge arrester test results analysis

Powercor arranged for testing of selected surge arrester types, focusing on those types that represented a significant proportion of the total network population.

For these tests, Powercor used the services of two accredited testing companies - Select Solutions and Central Test. The tests conducted by each company were as shown in Table 6.

Table 6 Test specifications

Company	Test Specifications
Select Solutions	Temperature 23 ± 2°C Relative Humidity 48 ± 5% • Tested individually on earth bracket provided • HV test at 24 kV for 1 hour or until arrester failure, recording leakage current and applied voltage for duration of test at 3 second intervals

Company	Test Specifications
	• Determination of V-I characteristic at 0.25 kV increments from 10 kV to 30 kV or arrester failure or to test equipment limitations • Visual inspection and photographed before and after to identify any blemishes, tracking or cracking
Central Test	Ambient temperature Relative Humidity not specified • HV test at 24 kV for 8 hours or until arrester failure, recording leakage current at 1 minute intervals and arrester temperature on 30 minute intervals for duration of test • Visual inspection and photographed before and after to identify any blemishes, tracking or cracking

From our detailed review of the test results, we consider that the V-I characteristic tests conducted by Select Solutions identified Type A and Type W (ABB POLIM class) arresters only as having sufficient U_r rating for use in a resonant earth network. The remainder failed to meet this selection criteria as described in Section 6.3.

We considered the results of the 8-hour test conducted by Central Test as a proxy for surge arresters that were likely operating in the ohmic range due to marked temperature increase above ambient temperature. Types N, O and S (21 kV) are regarded as likely to have been operating in the ohmic range during the test, and therefore failed the selection criteria requiring $U_r \geq 24$ kV.

From this analysis, the assessed actions are shown in Table 7. We consider the assessed actions accurately reflect the pass/fail criteria outlined in Section 4 and are in keeping with Powercor's overall surge arrester replacement identification strategy for 22 kV networks in bushfire prone areas.

Table 7 Surge arrester type assessment

Type	Details	Tested	Assessed Action	Comment
A	Bowthorpe porcelain SiC (1982-1991/92); 22 kV rated	Yes	Retain	V-I characteristic from testing showed linear leakage current response to voltages up to 30 kV without signs of being in ohmic range, remained close to ambient during 24 kV soak test, high TOV rating
A	Bowthorpe porcelain SiC (1991/92-1995); 24 kV rated	Yes	Retain	
A	Bowthorpe porcelain SiC (1987-1989); 24 kV rated	Yes	Retain	
B	Bowthorpe porcelain SiC (1980-1981)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic
C	Bowthorpe porcelain SiC (1973-1978)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic
D	ASEA porcelain SiC (1978-1982)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic
E	Bowthorpe porcelain ZnO (1986-1989)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic
F	Bowthorpe porcelain ZnO (1990-1992)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic

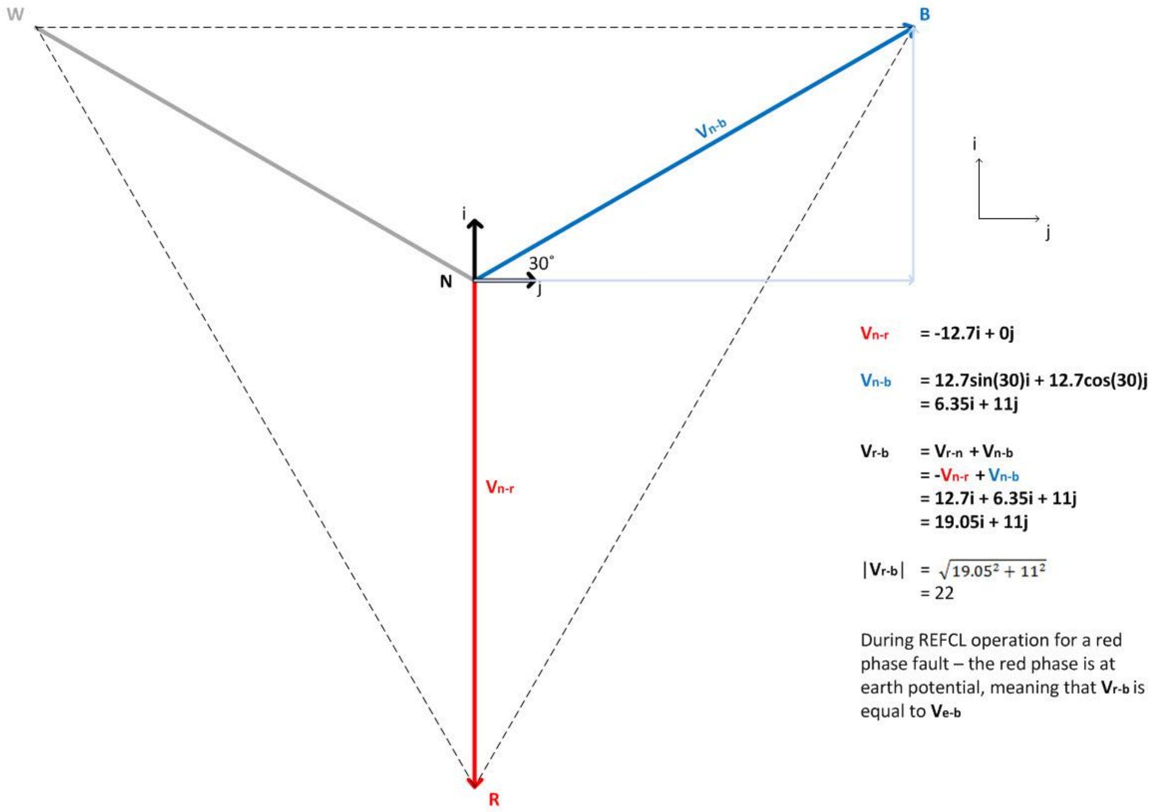
Type	Details	Tested	Assessed Action	Comment
G	Bowthorpe porcelain SiC (1980-1983)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic. Retain on SWER
H	Bowthorpe porcelain SiC (1973-1978)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic, Retain on SWER
I	Stanger porcelain SiC (1961-1962)	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
J	All Brown Bodied porcelain SiC	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
K	Bowthorpe porcelain SiC (1972)	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
L	ASEA XBE porcelain SiC (1986-1987)	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
M	Bowthorpe porcelain SiC (1985)	No	Replace	Small population and unverified data specifications, diagnostic testing uneconomic
N	ABB MVK20-H30 Polymeric ZnO (1995-2000)	Yes	Replace	24 kV soak test indicated operating in the ohmic range, and therefore has knee point below 24 kV
O	ABB MWK19-H30 Polymeric ZnO (1995-2000)	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria, experienced rise of 30°C above ambient during 24 kV soak test
Q	Bowthorpe EGB porcelain ZnO (1995)	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
R	Bowthorpe HEB porcelain ZnO (1995)	No	Replace	Diagnostic testing uneconomic, priority replace due to known issue
S	Cooper UltraSil ZnO, (2001-2005); Class A, 21 kV U_r	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria, experienced rise of 40°C during 24 kV soak test
S	Cooper UltraSil ZnO, (2005-2010); Class A, 24 kV U_r (9 shed version)	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria
T	Cooper UltraSil ZnO, (2001-2005); Class C, 21 kV U_r	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria
T	Cooper UltraSil ZnO, (2005-2010); Class C, 24 kV U_r (9 shed version)	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria
U	Unidentified type	No	Replace	Compliance with REFCL operation requirements cannot be verified
W	ABB Polim D Polymeric ZnO (2010-); Class A 20 kV	No	Replace	Current preferred type, compliance with REFCL operation requirements not verified

Type	Details	Tested	Assessed Action	Comment
W	ABB Polim D Polymeric ZnO (2010-); Class A 22 kV	Yes	Retain	Current preferred type, testing showed ‘knee’ point above 25 kV, remained thermally stable during 24 kV soak test
W	ABB MWK20 Polymeric ZnO (2010-)	Yes	Replace	Testing showed ‘knee’ point below 24 kV which is outside pass criteria

Appendices

Appendix A – Phase voltage calculation

The following diagram shows the calculation of phase voltages for a 22 kV network, and the impact of REFCL operation.



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