Rapid Earth Fault Current Limiter (REFCL) Program

Hardening Strategy - Lines

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1	15/03/2017	First Issue	J Bernardo A Walsh
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3	02/03/2018	Inclusion of 22kV distribution network and updated for latest testing models and strategy	A Ziusudras M Wiener
4	30/05/2019	Fourth issue to incorporate updated cable testing approach	Y. Ali

Contents

1 PURPOSE AND BACKGOUND

1.1 Purpose

The purpose of this supporting document is to explain AusNet Services' line hardening strategy, which addresses the voltage stress that occurs on line equipment when a Rapid Earth Fault Current Limiter (REFCL) responds to an earth fault.

REFCLs are to be installed on AusNet Services' network in response to new bushfire mitigation regulations. Line hardening work is one of 5 work streams that comprise the REFCL installation program.

1.2 Background

AusNet Services' network operates in a geographical location which is exposed to extreme bushfire risk. These conditions warrant significant investment to mitigate the bushfire risk.

The 2009 Victorian Bushfire Royal Commission made several recommendations with respect to fires initiated from distribution electricity networks. Subsequently, the Victorian Government established the Powerline Bushfire Safety Program to research the optimal way to deploy REFCLs for bushfire prevention. This research led the Government to introduce Electricity Safety (Bushfire Mitigation) Amendment Regulations 2016.

For AusNet Services, the regulations require each polyphase electric line originating from 22 selected zone substations to comply with mandated voltage reduction performance standards (required capacity) by 1 May 2023. In the timeframes specified in the regulations, the installation of REFCLs is the only feasible technological solution.

The REFCL installation program is being delivered in three Tranches. This line hardening strategy incorporates REFCL Program deployment learnings.

The 'line hardening' work stream is concerned with the replacement of 22kV surge arrestors, 22kV feeder cables and 22kV feeder exit cables that are known to be incompatible with the new REFCL technology.

Surge arrestors are used throughout our 22kV network to provide impulse protection from faults. Surge arrestors have been designed for low impedance or solidly earthed networks to provide insulation coordination with other equipment on our network such as pole top transformers, switches and cables.

Surge arrestors fitted to a REFCL protected network (high impedance) must be capable of sustaining the elevated voltages which occur on healthy phases in response to a phase to ground fault. Sustained over-voltages are experienced regularly and repeatedly during REFCL operation. As such, surge arrestors on the REFCL protected network including those installed on transfer feeders as part of the Distribution Feeder Automation (DFA) scheme will require replacement.

Similarly, 22kV cables may also fail as they will experience elevated phase to ground voltages when a REFCL operates. A proactive approach is required to identify and replace any poor condition cables or insufficiently rated cables prior to operating a REFCL protected network. This approach involves identifying critical cables and completing an assessment to determine whether or not they need to be replaced, ensuring its failure is prevented during REFCL operation.

1.3 Strategy objective

The objective of this line hardening strategy is to:

- Describe the issues associated with the operation of surge arrestors and 22kV feeder cables on a network utilising REFCLs;
- Describe the remedial works proposed to address these issues;
- Describe the testing and replacement plan for underground 22kV cables; and
- Demonstrate that a prudent and efficient approach has been taken to the proposed hardening of AusNet Services network assets.

2 Investment need

The Electricity Safety (Bushfire Mitigation) Amendment Regulations (2016) specify the installation and operation of the voltage reduction required on a polyphase line when a phase-to-ground fault occurs, and the fault current levels that must be achieved. These specifications can only be met safely where under-rated line equipment such as surge arrestors and cables exhibiting high partial discharge (PD) or a history of failure under REFCL induced voltagestress are replaced.

The need for this 'line hardening' investment was highlighted in the REFCL trials:

> *"When an earth fault occurs, the REFCL response creates voltage stress on network equipment connected to un-faulted phases, which can lead to a second fault. Outcomes can be worse than if a REFCL were not installed.[1] "*

The 'second fault' results from the exposure of equipment such as surge arrestors or 22kV cables to the high voltages that arise from REFCL operation. These 'second faults' are also known as 'cross country faults' i.e. they occur at a location on the feeder other than the site of the initial fault which caused the REFCL to operate.

As noted in the above excerpt, the outcome of the second fault can be worse than if a REFCL were not installed due to the potential for both the original fault and the failing surge arrestor or 22kV cable to ignite a fire. Furthermore, the REFCL will not operate when two faults have occurred on the network and therefore no protection is provided by the REFCL following the second fault. It is therefore imperative that incompatible surge arrestors are replaced through a systematic 'line hardening' work stream as part of the REFCL installation program.

Due to the interaction between PD and REFCL operational voltages, a testing plan must be implemented to ensure the existing 22kV network is capable of safe and reliable operation during and after the exposure to REFCL voltages.

[1] Dr Anthony Marxsen, REFCL Trial: Ignition Tests, Marxsen Consulting Pty Ltd, Monday 4 August 2014, page 93.

3 Options analysis and preferred approach

The installation of REFCLs on the existing network requires the establishment of a cost effective method to replace surge arrestors and 22kV feeder cables to achieve compliance with the Regulations. As already noted, this work is essential for REFCL technology to operate safely i.e. to operate without increasing the likelihood of bushfire ignition.

AusNet Services' line surge arrestors and 22kV feeder cables are designed for phase to ground voltages up to 19.5kV. Following the installation of REFCL technology, they must now cater for elevated phase to ground voltages up to 24.2kV (i.e. 22kV plus 10%).

<u>The following activities are undertaken to evaluate options for Surge Arrestors:</u>

1. Desktop and field identification of surge arrestor types and population currently on the network; and
2. Sample testing at elevated voltages to identify surge arrestor types that cannot withstand elevated voltages.

Sample testing has assessed each surge arrestor type against its rated operating voltage and rated temporary over-voltage whilst ensuring no thermal runaway exists when subject to the new voltage requirements. This objective is to minimise the risk of failure following REFCL operation.

Tests have determined two particular types of line surge arrestors are capable of withstanding the increased voltages associated with the operation of a REFCL. AusNet Services is not proposing to upgrade these surge arrestors, which comprise approximately 60% of the surge arrestor population covered by REFCL.

The options considered to ensure that line surge arrestors are capable of operating at elevated voltages are:

1. Staged program to replace the 40% of surge arrestors that sample testing has determined will not operate satisfactorily at elevated voltages.
2. Replace all surge arrestor types that do not have a minimum designed operational limit of 22 kV. This would include replacement of some surge arrestors which performed satisfactorily in testing but were not originally manufactured to operate at 22 kV.
3. Retrofit existing three phase surge arrestor sets with an additional surge arrestor in a 'Neptune' configuration. In addition, replace single and two phase surge arrestor sets that sample testing has determined will not operate satisfactorily at elevated voltages.
4. Do not proactively replace surge arrestors allowing the existing surge arrestors to run to failure when exposed to REFCL operating voltages.

The option of removing, rather than replacing, some surge arrestors was not evaluated as AusNet Services analysis indicates that surge arrestors should be installed on distribution transformers in high bushfire risk areas (and the REFCL installations are targeted at these areas). Further, there is little cost saving resulting from the removal of surge arrestors as the largest cost component of surge arrestor replacement is labour, and labour cost will still be incurred to visit the site and remove existing surge arrestors.

A summary of our analysis in relation to each of these options is shown in Table 1.

Table 1: Options evaluated for Surge Arrestors

Option	Advantages	Disadvantages
1. Identify surge arrestors not capable of withstanding the elevated voltages (based on test results) and replace accordingly.	Ensures REFCL operating compliance on a risk-based approach. Reduces volume of work required. Ensures cost efficiency.	Risk still exists of cross country faults should surge arrestors be incorrectly identified or missed during replacement program.
2. Replace all surge arrestors.	Uniform approach. One hundred percent replacement of surge arrestors would reduce the risk associated with line surge arrestors being missed during the planning and delivery stages of the project.	Increases volume of work required. Option would not minimise direct project costs and therefore fails to maximise community benefits, assuming the risk of cross country faults can be eliminated.
3. Retrofit an additional surge arrestor in a Neptune configuration.	Reduces costs of surge arrestor replacement.	Many differing mounting brackets would need to be developed for each different transformer/ switch/ pole/ surge arrestor combination. More expensive to develop brackets than replace surge arrestors. Each installation site would require a design component. Not technically feasible in many instances due to clearance requirements.
4. Allow existing surge arrestors to fail when exposed to REFCL operating voltages.	Less up-front capex.	Likely to result in many faults during stress-testing resulting in interruptions to supply and delays to REFCL program delivery. Likely to result in additional fire starts (defeating the purpose of the REFCL program). Poor network reliability would result due to multiple outages from cross country faults affecting whole feeders (as REFCL will trip feeder CB). Significant increased risk of fire and or harm for the general public.

Option 1 is the preferred option as it is evident from the above table it is:

- It is the lowest cost option, providing that the risk of cross country faults can be mitigated;
- It is strongly preferred to Option 3, which is not feasible;
- It is strongly preferred to Option 4, which exposes the community to unacceptable safety risks and reliability outcomes; and
- Meets the objective of safe compatible operation with REFCL technology.

<u>The following activities are undertaken to evaluate options for 22kV feeder Cables:</u>

1. Desktop and field identification of critical cable types and population currently on the network; and
2. Targeted on-line and off-line testing to confirm if the cables cannot withstand elevated voltages:
    - On-line tests ranging from visual inspection, spot Partial Discharge (PD) measurements using on-line PD measurement devices (such as Prycam) and non-invasive inspection methods (RF scanners, Ultrasonic and Corona cameras)
    - Off-line tests ranging from sheath integrity, Dielectric Spectroscopy (DS), Dielectric Dissipation Factor (DDF) and Capacitance, Partial Discharge (PD) and High Voltage (HV) withstand.

Targeted testing ensures each critical feeder cable in a REFCL protected network are appropriately rated and with a sound condition score minimising the risk of failure during REFCL operation.

Currently the highest voltage (phase to ground) subjected to the 22kV feeder network has been 19.5kV. Testing has shown that many of the joints and terminations for the network will not withstand REFCL operations over a prolonged period of time. These joints and terminations prior to the installation of a REFCL proved sufficient when operating up to 19.5kV however any presence of PD within these joints/terminations will significantly reduce the lifespan of the cable once subjected to REFCL operational voltages.

Learnings from Tranche 1 commissioning and testing activities has shown steam cured XLPE cables manufactured prior 1986 to have an accelerated rate of failure during stress testing and commissioning.

The options considered to ensure that the 22kV feeder cables are capable of operating at elevated voltages are:

1. Staged program to replace critical cables that targeted testing or desktop identification has determined will not operate satisfactorily at elevated voltages.
2. Replace all critical cables that do not have a minimum designed operational limit of 24.2 kV (i.e. 22kV +10%). This will involve replacement of some cables which performed satisfactorily in testing but were not originally manufactured to operate up to 24.2kV.
3. Do not proactively replace cables allowing the existing cables to run to failure when exposed to REFCL operating voltages.

A summary of our analysis in relation to each of these options is shown in Table 2.

Table 2: Options evaluated for 22kV Cables

Option	Advantages	Disadvantages
1. Identify critical cables in REFCL protected network not capable of withstanding the elevated voltages (based on test results and desktop assessment) and replace accordingly.	Ensures REFCL operating compliance on a risk-based approach. Reduces volume of work required. Ensures cost efficiency.	Risk still exists of cross country faults should critical cables be incorrectly identified or missed during replacement program.
2. Replace all critical cables.	Uniform approach. One hundred percent replacement of feeder cables would reduce the risk associated with feeder cables being missed during the planning and delivery stages of the project.	Increases volume of work required. Option would not minimise direct project costs and therefore fails to maximise community benefits, assuming the risk of cross country faults can be eliminated.
3. Allow critical cables to fail when exposed to REFCL operating voltages.	Less up-front capex.	Likely to result in many faults during stress-testing resulting in interruptions to supply and delays to REFCL program delivery. Likely to result in additional fire starts (defeating the purpose of the REFCL program). Poor network reliability would result due to multiple outages from cross country faults affecting whole feeders (as REFCL will trip feeder CB). Significant increased risk of fire and or harm for the general public. Outage durations will be higher due to cable repair times.

Option 1 is the preferred option as it is evident from the above table it is:

- It is the lowest cost option, providing that the risk of cross country faults can be mitigated;
- It is strongly preferred to Option 3, which exposes the community to unacceptable safety risks and reliability outcomes; and
- Meets the objective of safe compatible operation with REFCL technology.

This option preference has led to the development of a cable testing spreadsheet model. The options considered to ensure that the 22kV feeder cables are capable of operating at elevated voltages include variations on:

- Which cables have potential manufacture dates prior to 1986
- Which cables to PryCAM test
- Which cables should be deemed critical to test by varying thresholds for
    a. Qty Customers serviced
    b. Qty of joints in a cable section
- Method of testing Critical cables
    a. Test if it fails PryCAM
    b. Test it without PryCAM first
- How to offline test non-critical cables
    a. Don’t PryCAM test
    b. PryCAM then offline test if fails
    c. PryCAM and don’t offline test even if it fails

The developed models for testing can be categorised as 4 options shown in Table 3.

Note: Each option is a base on which there are multiple alterable variables.

Table 3: Options evaluated for cable testing

Option	Notable Advantages	Notable Disadvantages
1. PryCAM: All cables Offline test: Critical cables that fail PryCAM Run non-critical to failure	Lower upfront cost	Conservative testing High run-to-failure rates
2. PryCAM: all cables Offline Test: All Cables that fail PryCAM	Very thorough testing regime ensures all potentially problematic cables are offline tested. No future potential STIPIS impact on the company or cable replacement cost assuming current test find all faults	Most number of tests and find rates, most expensive option.
3. PryCAM: Selective based on variables Offline Test: only critical cables that fail PryCAM	More inclusive offline testing regime than Option 2	High run-to-failure rates due to lack of testing
4. PryCAM: Critical cables and cables where the manufacture date cannot be determined Offline Test: Critical cables that fail PryCAM Run everything else to failure	Relatively balanced potential future impact & upfront costs Preferred option	

Option 4 is the preferred option as it is evident from the above table it is:

- It is the best balanced option for testing, balancing both potential impact with upfront costs
- It is strongly preferred to Option 2, which is not feasible and has already been discussed as a non-viable solution; and
- Meets the objective of safe compatible operation with REFCL technology.

The following activities are undertaken to evaluate options for 22kV feeder exit cables:

1. Staged program to offline test and replace feeder exit cables that testing has determined will not operate satisfactorily at elevated voltages.
2. Replace all feeder exit cables. This will involve replacement of some feeder exit cables which performed satisfactorily in testing but were not originally manufactured to operate at 22kV.
3. Do not proactively replace feeder exit cables allowing the existing feeder exit cables to run to failure when exposed to REFCL operating voltages.

Experience from Tranche 1 and PD testing of Tranche 2 feeder exit cables has shown a much higher level of PD in feeder exit cables then could be expected from historical data.

A summary of our analysis in relation to each of these options is shown in Table 4.

Table 4: Options evaluated for 22kV Feeder exit Cables

Option	Advantages	Disadvantages
1. Offline test feeder exit cables in REFCL protected network to determine those not capable of withstanding the elevated voltages and replace accordingly.	Ensures REFCL operating compliance on a risk-based approach. Reduces volume of work required. Ensures cost efficiency.	Risk still exists of cross country faults should feeder exit cables be incorrectly identified or missed during replacement program.
2. Replace all critical cables.	Uniform approach. One hundred percent replacement of feeder exit cables would reduce the risk associated with feeder cables being missed during the planning and delivery stages of the project.	Increases volume of work required. Option would not minimise direct project costs and therefore fails to maximise community benefits, assuming the risk of cross country faults can be minimised.
3. Allow critical cables to fail when exposed to REFCL operating voltages.	Less up-front capex.	Likely to result in additional fire starts (defeating the purpose of the REFCL program). Poor network reliability would result due to multiple outages from cross-country faults affecting whole feeders (as REFCL will trip feeder CB). Significant increased risk of fire and or harm for the general

Option	Advantages	Disadvantages
		public. Outage durations will be higher due to cable repair times.

Option 1 is the preferred option as it is evident from the above table it is:

- It is the lowest cost option, providing that the risk of cross country faults can be mitigated;
- It is strongly preferred to Option 3, which exposes the community to unacceptable safety risks and reliability outcomes; and meets the objective of safe compatible operation with REFCL technology.

3.1 Preferred Option Risks

Surge Arrestors

The key risk associated with replacing only tested surge arrestor types is that the risk of a cross-country fault still exists. Although a pragmatic approach, surge arrestors may be missed in the replacement works, as it will be heavily reliant on the validation of internal database information against field inspections. This risk is mitigated by testing during the commissioning phase of the REFCL and annual insulation tests which aim to identify and rectify any failing or missed assets.

A further risk arises from selecting surge arrestors to be replaced utilising sample testing. It is possible that some surge arrestor types that passed the sample testing will experience some failures in operation. This risk has been mitigated by selection of a statistically significant test sample size.

22kV feeder cables

The key risk common among most of the options presented is the balancing of unbudgeted potential future financial impact due to the shortened lifespan of cables as a result of exposure to REFCL voltages and project delays due to cable failures during commissioning activities. Balancing this with the upfront cost of proactive replacement, testing and replacing cables exhibiting poor PD results leads to the selection of option 4. The only option with minimal risk is option 2, which elects to perform tests to the point of excess at great cost.

While not presenting the lowest upfront cost for a cable hardening strategy, which will always be the ‘do nothing’ approach, or taking a high cost low risk approach. Option 4 presents a reasonable upfront cost while maintaining a justifiable potential future costing.

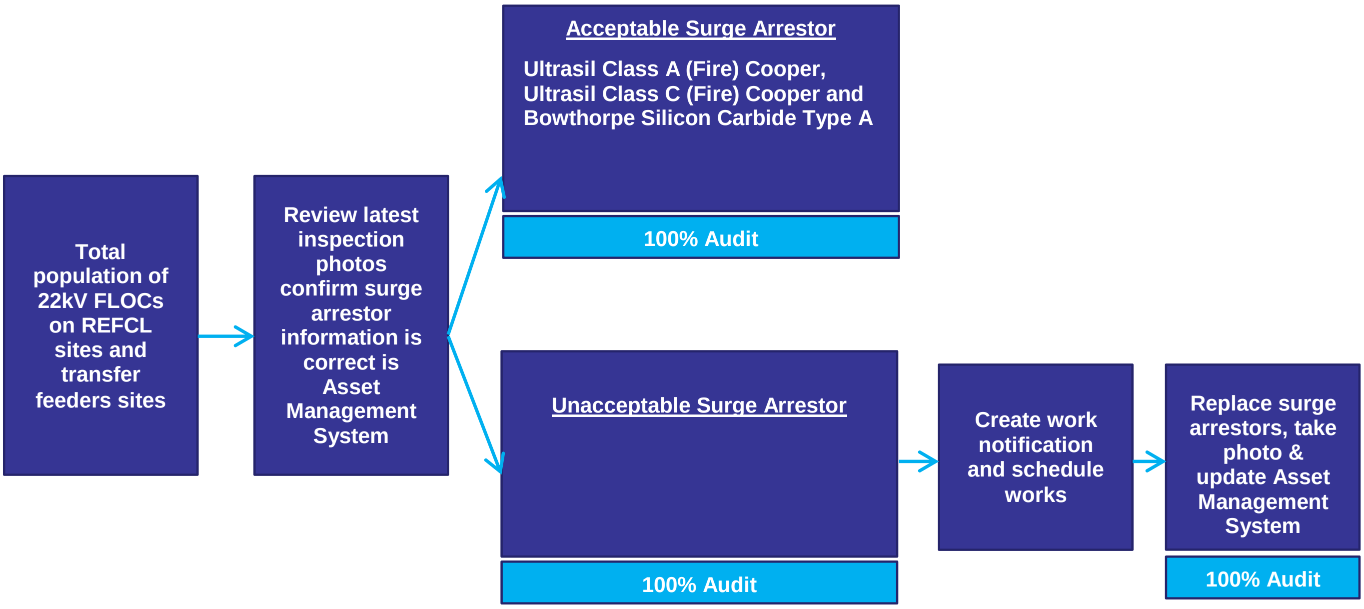
4 Efficient and prudent program delivery

Surge Arrestors

Approximately 60% of line surge arrestors do not need to be replaced due to the outcomes of testing.

Surge arrestor replacement activities will be completed on a staged feeder by feeder basis and where possible, surge arrestor work will be integrated with other REFCL, maintenance, bushfire mitigation or safety program works.

The number of line surge arrestors to be replaced is validated to ensure all ‘unacceptable surge arrestors’ are identified and the likelihood of missing unacceptable surge arrestors is reduced. This process also ensures surge arrestors deemed acceptable are not replaced. A 100% photo audit is conducted at three stages throughout the validation process. This validation further reduces the likelihood of surge arrestors being incorrectly assessed as either acceptable or unacceptable. The process is shown below:



Critcal Feeder Cables

Similarly, with the Surge Arrestor replacement, critical feeder cable replacement activities will be completed on a staged feeder by feeder basis and where possible, feeder cable work will be integrated with other REFCL, maintenance, bushfire mitigation or safety program works.

The number of feeder cables to be replaced will vary from zone substation to zone substation however as highlighted in the options, a targeted approach ensures replacement works are minimised leading to the most prudent and efficient strategy in enabling the REFCL protected network operates at 'required capacity'.

Feeder Network

For Option 4, it is estimated that 36% of the tested cables in the network will fail both PryCAM and offline testing leading to a repair or replacement.

PryCAM testing will be integrated with other REFCL, maintenance, bushfire mitigation or safety program works. Once PryCAM testing is completed a scope of works for offline testing is established. Cable replacement activities will be completed on a staged feeder-by-feeder basis. The limiting factor on time to complete the testing aspect of the works is the quantity of tests per day that can be achieved, this is on average eight (8) PryCAM tests per day due to travel times between locations.

4.1 Risk management

The risks associated with delivery of the program of surge arrestor and feeder cable replacements are shown in the table below.

Risk	What could occur	Actions & controls
Interference / clashes with other project(s) and project scope creep.	Delivery delays leading to non- compliance with Bushfire Mitigation Regulations and the approved Bushfire Mitigation Plan. Down time for construction crews	Continual engagement with Network Planning Teams and delivery partners. Network Programs constant review of Portfolio projects. Dedicated Program Sponsor Team established.
Delivery delays and timelines not met to meet REFCL regulatory obligation	Delivery delays leading to non- compliance with Bushfire Mitigation Regulations and the approved Bushfire Mitigation Plan.	Monthly reporting of the progress of the project from delivery partners through to the Program Team / Steering Committee and Energy Safe Victoria. Regular updates of Asset Management System enabling progress to be tracked real-time. Well planned schedule of works. Early engagement with Control Energy Operations Team (CEOT), delivery partners and field personnel to ensure resourcing availability.

4.2 Procurement

Surge arrestors and 22kV cable to be installed are standard stock items. These items have been procured utilising AusNet Services' standard procurement and governance processes which include competitive tendering to ensure the cost per unit is efficient.

4.3 Works delivery

The volume of unacceptable surge arrestors and 22kV cable requiring replacement in the REFCL program varies between zone substations. The number of surge arrestor replacements is largely proportional to the number of customers the respective zones substation serves. Larger customer numbers lead to more transformers, and in turn a larger surge arrestor population. A summary of the replacement works required for each REFCL installation will be included in the respective zone substation REFCL Functional Scope.

Cable is typically installed in high vegetation areas, routes where bare conductor installations are not feasible or pose a high safety risk and underground estates in urban areas. Furthermore, critical cables will predominantly be identified as those on the feeder backbone or dependant on the amount or type of customers supplied via the cable. The cable feeder network is more substantial in newer, urban areas while there is fewer cable in older, rural networks where a majority of the infrastructure consists of above ground lines.

The hardening work will mainly be constructed using established external delivery partner relationships. Internal resources may be utilised for integration opportunities with other required works on 22kV feeders where appropriate.

4.4 Program costs

The Lines Hardening Strategy preferred option has been costed in accordance with standard costing methodology, as detailed in supporting document: Cost Estimating, unit rates and program delivery.

The costs take into count:

- Evaluation and testing of existing surge arrestor fleet
- Photo verification of all 22kV surge arrestor sites determining whether they are acceptable or unacceptable;
- Works planning and governance activities;
- Construction works for surge arrestor sites (transformer, switch and cable head locations);
- Desktop assessment of cables installed prior to 1990 to determine manufacture date;
- PryCAM & Offline testing costs for cable network;
- Replacement cost of cables manufactured prior to 1986;
- Replacement and Repair costs for cable that fails offline testing;
- Expected in-service failure replacement and repair cable cost (Potential impact only);
- Expected in-service failure STIPIS impact (Potential impact only);
- Project management; and
- Auditing.

A summary of the capital expenditure requirements for each REFCL installation will be included in the respective zone substation REFCL Functional Scope.

4.5 Program governance

While the testing and replacement program will be managed using the AusNet Services' Portfolio Framework, an overarching REFCL Program Governance Framework has been established in order to provide end-to-end Program oversight and accountability, to identify and manage program level risks.

The REFCL Program Governance Framework aligns to AusNet Services' values and commitment to mission zero with:

- Clear accountabilities, reporting and robust risk and issue management;
- Sustainable, long term, reliable, economical and workable whole of life designs;
- Delivery as per agreed timelines without compromising reliability and other service standards;
- Integration where possible with the rest of the AusNet Services work program;
- Compliance with required obligations;
- Strong relationships with all stakeholders in order to successfully manage change;
- Development of internal capability in order to facilitate the transition to business as usual; and

- Use of business as usual processes and resources where possible.

5 Concluding comments

This document has explained that:

- The proposed strategy of surge arrestor replacements is the lowest cost and highest community benefit option to address the specific issues on REFCL protected networks;
- The proposed scope of cable testing and replacements is the lowest cost, best balanced and highest community benefit option for addressing the specific issues on REFCL protected networks;
- A standard approach to estimating the costs has been used;
- The key assumptions underpinning our forecasts are reasonable;
- We have identified the key risks in relation to surge arrestor replacements and taken appropriate risk mitigation measures; and
- Our projected costs are consistent with the estimated average unit costs in the RIS

In addition, it should be noted that our forecast expenditure for surge arrestor and 22kV cable testing and replacement has been subject to our standard business case review and approval processes. This work will also be subject to our project management and governance arrangements.

For these reasons, we regard the forecast expenditure for surge arrestor and 22kV cable testing and replacement as prudent and efficient, in accordance with the Rules requirements relating to contingent projects.