5 Optimal operational settings for REFCL fire risk benefits

Based on the test results and findings outlined above, the following considerations apply to operational settings to obtain maximum fire risk reduction benefits from REFCLs installed on Victoria's rural networks.

Prescription of specific detailed settings is not appropriate for a number of reasons:

1. Network owners must consider the full range of faults in choosing settings. Test results in this program relate to 'wire on ground' earth faults, whereas networks experience many different types of faults during high fire risk periods, not all of them affected by REFCL protection.
2. Judgement and consideration of local circumstances is required to properly address the optimum balance of overall risk. Some settings that may reduce fire risk can also reduce supply reliability to the point where community capability to fight fires and manage emergencies may potentially be affected.
3. Settings must be chosen to accommodate a wide range of possible fault geometries. While the quality of data on powerline fire starts has improved with the implementation of new reporting arrangements administered by ESV, this does not yet extend to statistics on the specific fault geometries that most commonly cause fires in high fire risk conditions.
4. The test program did not evaluate the typical digital relays that would normally be used in conjunction with REFCL installations. The characteristics of these relays would have a direct bearing on fire risk and settings must be chosen in the light of their capabilities.

Nevertheless, it is possible to list the issues to be considered and state the general principles that can be used in decisions on operational settings to obtain optimum fire risk results. It is also possible based on the total project experience to make meaningful suggestions as to what will prove effective in reaching the long term goal of minimum powerline fire risk in Victoria.

The following sections outline implications of the test program for protection settings in Victoria's rural networks if minimum fire risk is to be achieved:

1. Fully exploit modern technology in non-REFCL protection systems
2. Monitor transient faults in REFCL networks to assess relevance to fire risk
3. For sustained faults in REFCL networks trip the faulted feeder and do not reclose
4. Temporarily increase REFCL fault detection sensitivity on high fire risk days
5. Promote continued development of the GFN fault confirmation test:
6. Confirm network 'hardening' prior to each fire season
7. Calibrate RCCs regularly and before each fire season
8. Prove fire performance by real tests.

These topics and recommendations, together with the product development areas listed in Finding 8 (page 72), are offered for the consideration of network owners facing the challenges of REFCL adoption. The extent to which action can be taken will depend on many factors – the current inventory of network equipment and protection systems in service, local fire loss consequence levels, the challenge of fault location on very long feeders, the prevalence of long two-wire spur lines, specific customer loads that create transient disturbances on their networks, etc.

5.1 Fully exploit modern technology in non-REFCL protection systems

The test program demonstrated that sensitive earth fault (SEF) protection systems may have the capability to prevent some 'wire on ground' fire starts. This capability depends on SEF fault detection sensitivity and speed of action. Discussions with Victoria's network businesses during the test program revealed a diversity of settings used today for these two aspects of SEF performance across Victoria. The basis of the current diversity of settings is not completely clear, though local circumstances vary widely across the State and are reflected in some SEF settings. For example, long feeders with multiple ACRs along their length require multiple steps of device-to-device grading of SEF time settings and this can force much longer SEF response times at the zone substation than can be used on feeders without ACRs.

Over the last few decades, SEF relays have changed from analogue devices with internal moving parts to digital devices offering very high precision and reliability in both current measurement and timing of response. It is not clear to what extent these developments have been fully exploited by network owners, e.g. by shortening grading time margins to speed up SEF response times across the network. Many of these new devices offer improved measurement technology such as 50Hz filters to reduce their sensitivity to network transients. Again, it is not clear if these capabilities offer opportunities to increase fault detection sensitivity beyond traditional levels.

Over the same period, customer appliances have evolved in ways that reduce the risk of large sudden transient impacts on the network. Today, most consumer and industrial equipment containing large electric motors includes 'soft start' or inverter speed control, both of which greatly reduce shocks to the network. Again, it is not fully clear how much the opportunities presented by these evolutionary developments have been exploited by network owners to make SEF fault detection more sensitive and faster acting than it was fifty years ago.

Even network switching now often employs remote controlled pole mounted switches which switch all three phases within a few milliseconds of each other which produces a very different level of network 'shock' than traditional 'stick-operated, phase-by-phase' switching.

Given the high priority of fire risk reduction, there would appear to be value in a review of SEF design approaches to see if there are opportunities to better use SEF to reduce powerline fire risk on Code Red days. Specific questions to be considered would include: Can it be made more sensitive? Can it be made faster? Trials using parallel-connected protection relays set for greater sensitivity and faster action could provide a useful indication of the risk of squeezing margins on SEF settings. On Code Red days, this risk must be weighed against the risk of a major fire from an undetected fault or from a fault where the SEF response time exceeds the 'time to ignite'.

5.2 Monitor transient faults in REFCL networks to assess relevance to fire risk

REFCL protected networks deal with transient faults by temporarily displacing network voltages to reduce the fault current to such a low level that most faults simply go away (arcs self-extinguish), whereupon the network can return to normal voltage levels. Customers do not experience any disturbance at all in this process.

It is not clear what sort of event could start a fire while presenting to a REFCL-protected network as a transient fault. In traditional non-REFCL network protection, there are many examples of transient faults that can start fires, including conductor clashes (that emit molten metal particles) and bird/animal contacts (that result in a burning carcass falling into the dry vegetation under a pole):

- Conductor clashes have always dominated fire risk from low voltage lines because of their smaller conductor spacing and because the risk relates to available current levels rather than voltage. However, they can also occur on high voltage powerlines. The involvement of conductor clashes in fires in Victoria has greatly diminished following the widespread implementation of powerline conductor 'spreaders' following the 1977 and 1983 fires.

- Reports from overseas network operators indicate that some REFCL protected networks do not appear to kill birds and animals – network owners no longer find burnt carcasses under powerlines when a REFCL is in service. These reports relate to 11kV networks and experience with 22kV networks is not known.

These two classes of transient fault may not feature in future fire causes with REFCL network protection.

The question remains open. The possibility of transient earth faults that start fires in REFCL-protected networks cannot be ruled out, though examples are not currently obvious. It may be that the only earth faults that could potentially cause fires in REFCL-protected networks are sustained ones. If experience reveals some transient earth fault events start fires, system settings can be reconsidered to deal with them. For now, it might reasonably be assumed that they are a secondary issue with priority given to low fire risk solutions for sustained earth faults.

5.3 For sustained faults in REFCL networks trip the faulted feeder and do not reclose

The test program has shown that REFCLs can greatly reduce fire risk from sustained earth faults such as fallen conductors. On a Code Red day, once a REFCL fault-confirmation test has demonstrated that an earth fault is permanent, there is little option available to a network owner but to trip the faulted feeder - provided of course that it can be confidently identified.

Unlike traditional non-REFCL network protection, reclosing onto a known permanent earth fault serves little purpose in a REFCL-protected network – the REFCL reduces the fault current to such an extent that downstream devices will not operate to isolate the section of the network containing the fault. Hence the rule on high fire risk days should be to 'trip and do not reclose' which immediately highlights the challenge of fault location. Some feeders are very long (50-100 kilometres) and physical patrol is a task not undertaken lightly.

There are many methods used around the world for fault location in REFCL-protected networks. However, all of them require the earth fault to remain in place on a live network and many of them would increase fire risk, e.g. adding parallel damping resistor across the REFCL coil to increase residual current. The best solution in high fire risk conditions is likely to rely on current development efforts to provide more sensitive Fault Passage Indicators (FPIs). These send information to central network automation systems which can then switch ('sectionalise') the network so healthy sections of feeder can be restored to supply while the section containing the fault is left isolated for line crews to find and repair the problem. The network automation systems required to do this are mature technology. The sensitive FPIs required to feed information to them are under active development.

The adoption of REFCL technology in Victoria's rural networks will require some investment in research and trials to address this issue.

5.4 Temporarily increase REFCL fault detection sensitivity on high fire risk days

Every REFCL system faces the same hierarchy of decisions when a fault occurs: Is there a fault on the network? What phase is it on? Is it permanent? What feeder is it on? The challenge of answering these questions increases as the hierarchy is traversed. As a first step, it is relatively easy to detect faults with very high sensitivity.

Today's REFCL products operate to reliably detect faults that draw two amps of current from the network. This level of sensitivity is a marked improvement on traditional non-REFCL systems, but could be even further improved. The limits to fault detection sensitivity are determined by a number of factors. Finding 8 on page 72 includes an outline of the issues facing product developers to achieve even higher levels of fault detection sensitivity.

If networks are smaller, higher levels of sensitivity can be achieved easily. This has motivated some European networks to split their networks into sub-networks each with a dedicated REFCL. This option has not yet been seriously considered by Victoria's network owners, which is entirely appropriate given the early stage of REFCL technology development in Victoria. Its merits are unlikely to be clear without considerable detailed investigation.

Similarly, if the network is closely balanced with the same capacitance to earth on each phase, higher sensitivity can be easily achieved. The extent to which capacitive imbalance can be minimised in Victoria's rural networks is the subject of Challenge 4 outlined later in this report (see page 95).

Experience in the test program supports the concept of over-arching risk balance to set sensitivity in a more granular fashion, i.e. if fire risk is extreme for a Code Red day, then on that day other risks may be less important than prevention of ignition. If increased fault detection sensitivity can play a role in the reduction of fire risk, its use on a short term basis is worth serious consideration.

In Finding 8 (see 4.8 at page 72 above), sensitive fault detection has been nominated as an area of ongoing REFCL product development. As higher fault detection sensitivity becomes available, network owners should review overall risk to decide how far to temporarily increase fault detection sensitivity on days of extreme fire risk.

5.5 Promote continued development of the GFN fault confirmation test

Whilst it is relatively easy to detect faults with very high sensitivity, it is much harder to identify the feeder on which the fault has occurred – to do that, some accurately measurable 50Hz fault current is essential. Unambiguous identification of the faulted feeder without allowing enough current flow to start a fire is perhaps the toughest challenge facing REFCL developers. There is little point in knowing there is a fault on the network if there is no information to identify the feeder that has to be tripped to prevent a fire.

The alternative (interrupting all supplies out of the zone substation) would black out a significant part of the State. Community advice to the Powerline Bushfire Safety Taskforce in 2011 was that this was not acceptable as it would reduce local firefighting and emergency management capabilities just at the time they were most needed.

REFCL manufacturers who market their products in Australia have developed them over many decades of experience focused on European conditions that are completely different to those which apply here. In Europe, faults can be more safely assumed to act like a linear resistance, networks to be balanced (or at least capable of being balanced), damping resistors or deliberate de-tuning of the coil available to guarantee enough fault current to easily locate the fault, etc. None of these assumptions hold true in Victoria under high fire risk conditions. Fire risk minimisation is a new priority in REFCL product development and it will take time to produce results.

Utilities that have made the transition to REFCL-based protection have commented freely on the cultural adjustment their engineering and operations staff have made to get value from REFCL investment. However, REFCL manufacturers are facing a similar challenge in addressing fire risk in Victoria. Collaboration and joint endeavour must be the hallmark of efforts to arrive at the optimum REFCL solution to reduce Victoria's powerline fire risk.

The top priority in this endeavour is the GFN fault-confirmation test. This test both confirms the fault is permanent and identifies the feeder which must be tripped to allow the rest of the network to return to normal conditions.

The on-site test team were struck by the progress made in thinking through this challenge in just two days of joint working with a manufacturer on the test site. This was in contrast to the preceding months of email exchanges. Co-location, expert visits and exchanges, regular informal group communication are all methods that should be considered if Victoria is to make the fastest possible progress with manufacturers in the development of improved solutions.

5.6 Confirm network 'hardening' prior to each fire season

In a program of 259 tests on the Frankston South network, instances of cross-country faults were experienced. These are faults where the over-voltage produced by the REFCL response to a fault produces a new fault in one of the two other phases that are exposed to the full 22kV line-to-line voltage of the network. In effect, the test program revealed three pre-existing vulnerabilities in the Frankston South network – an underground cable, a kiosk substation and a pole-mounted ACR.

Overseas utilities that have successfully made the transition to REFCL protection have commented on the necessity of using the REFCL to identify and remedy network vulnerabilities at an early stage in the transition, i.e. to identify items that are susceptible to over-voltage failure. Such failures create cross country faults which negate the REFCL's capability to prevent ignition.

Fire risk would be reduced if network vulnerabilities to over-voltage failure were revealed in advance so cross-country faults during high fire risk conditions are minimised.

In pursuing this goal, two measures warrant consideration:

1. Information sharing on equipment failures: One of the vulnerabilities revealed by the test program was a specific make and model of ACR which appears on the basis of early investigations to have a design feature that would create cross-country fault risk in a REFCL-protected network. Given the limited range of equipment models supplied to Australia's electricity distribution industry, sharing of information on equipment vulnerabilities is a strategic necessity if the risk of fires from equipment failure is to be effectively managed. It would seem appropriate that a transparent process is adopted by the VESI to achieve this.
2. Diagnostic tests in advance of each fire season: If the REFCL is a GFN, over-voltage stress can be applied in a managed and progressive way using the RCC. This can detect vulnerabilities before failures occur. It has the advantage that the RCC has a limited current capability so if a fault occurs, it will overwhelm the RCC and be managed by the GFN without major damage to the network or equipment. If the REFCL is an ASC, a low resistance earth fault can be applied to each phase in turn to expose the other two phases to full over-voltage for a period. Network owners in some countries do this for periods up to an hour. Both approaches have been used by overseas utilities to identify network vulnerabilities and provide confidence that full over-voltages can be tolerated for reasonable periods without risk of a cross-country fault.

Fire risk would be minimised if Victoria's network owners that have installed REFCL protection carry out a full network over-voltage stress test prior to each fire season to reveal any weaknesses before high risk conditions arrive.

The stringent financial sanctions that apply in Australia's regulatory regime may constitute a major disincentive for network owners contemplating such a demanding diagnostic test, given that any equipment failure could lead to a substantial supply outage and individual outages can result in penalties of the order of a million dollars. Regulatory authorities may wish to consider options to facilitate network owners' diagnostic hardness-assessment of their networks in pre-fire season conditions, i.e. ones less likely to lead to the multi-billion cost of catastrophic fires experienced in 2009.

5.7 Calibrate RCCs regularly and before each fire season

If the REFCL is a GFN, the RCC must be calibrated so compensation reduces residual conductor voltage to the minimum possible level when a fault occurs. The test program demonstrated the importance of regular RCC re-calibration. It reduced residual conductor voltage from 1,100 volts to around 200 volts. Whilst the test program recorded many tests where neither of these voltage levels was sufficient to overcome the conductor-soil barrier to produce significant arc currents, conditions in real network faults may differ and accurate calibration may provide an important advantage in the reduction of fire risk.

RCC calibration in today's GFN product is a simple automated procedure and network owners should consider performing this procedure before and regularly during the fire season. Full automation of this procedure (so the GFN performs it whenever network conditions change) has been nominated in Finding 8 on page 72 as a key product development opportunity.

5.8 Prove fire performance by real tests

The test team was gratified to see the wealth of insights and new data generated in the tests. They were left with the firm conviction that there is no substitute for rigorous objective ignition tests when assessing REFCL manufacturers' performance claims. The team were particularly aware of the limitations of ASC tests performed in this program. In contrast, more than a hundred valid tests were performed on the GFN product, both as designed five years ago when the Frankston South GFN was purchased and today's GFN product, courtesy of a temporary upgrade by the manufacturer for two full days of tests.

This test program was a defined-duration project. However, fire risk reduction is likely to rely on further product development over at least the next five years, so options for a medium term capability to test manufactures' claims and to test innovative ideas for improvement warrant serious consideration.

6 REFCL implementation challenges

If Victoria's network owners adopt REFCL technology, they must address a number of challenges, both cultural and technical. Any wide-scale roll-out of REFCLs is likely to take at least a decade if the risks posed by these challenges are to be properly managed.

Some of these challenges are outlined in the following pages:

1. Learn by doing – culture change for network owners and suppliers
2. Harden networks to reduce risk of cross-country faults
3. Upgrade networks to REFCL-compatible equipment and systems
4. Minimise network imbalance
5. Develop fault location solutions

Five years of experience with the REFCL installed at Frankston South has demonstrated that these challenges can be successfully addressed over time. However, Frankston South is a single installation supplying a peri-urban area and Victoria has more than 100 zone substations that supply rural areas, some using long-established technical designs that are not present in the Frankston South network.

At the time of writing this report, two more Victorian network owners are preparing to install REFCLs in zone substations, so the journey towards wider adoption has already started. Both overseas and local experience indicates it will take at least several years before REFCL technology is a fully accepted and smoothly functioning part of Victoria's electricity distribution infrastructure.

The following sections are an updated summary of a discussion paper generated for the early stages of the REFCL Trial: *Challenges of REFCL adoption*, 29 January 2014. Readers are referred to the full paper for more detail. At the start of the description of each of the technical challenges, a summary table is provided that contains the following information:

The issue	A brief description of the issue that creates the challenge
ASC/GFN **Δ**	The degree of difference between ASCs and GFNs in this issue
Goals at risk	What objectives are at risk from this challenge
Status	Is the issue well understood or not
Occurrence	Is the issue present in all networks or only some
Solutions	Are defined solutions available or not

6.1 Challenge 1: learn by doing- culture change for network owners and suppliers

The issue	The change from non-REFCL to REFCL-based network design and operation is profound. Fire risk priority is a new challenge for REFCL developers. Intuition and integrated expert thinking about REFCL operation takes years to develop.
ASC/GFN Δ	No difference.
Goals at risk	Fire risk, supply reliability, cost
Status	An issue recognised in hindsight by those who have adopted REFCLs
Occurrence	Global – wherever networks move from NERs to REFCLs
Solutions	Not well understood – clearest in hindsight.

Overseas utilities that have made the change to REFCL network protection report the most difficult challenge is the culture change required to get full value from the new technology. They comment that it takes four to five years for network operations staff, protection and control engineers and network planners to learn the new technology and how to apply it to the point they have successfully integrated this knowledge into their work.

Experience in this test program has confirmed the depth of tacit knowledge and intuitive insights that many utility staff rely on in their work. The change from protection thinking based on current flow to protection thinking based on voltage movement is profound. Even after more than a year of deep consideration and exploration of the technology, few technical experts involved in the test program yet feel confident they have internally integrated REFCL concepts and knowledge to the point where they can reliably call upon intuitive insights to answer new questions.

The test team were also struck by the learning challenge facing suppliers. The goal of fire risk reduction is one that REFCL suppliers have not addressed anywhere else in the world. The primacy of this goal for Victoria had to be repeatedly stressed to suppliers in discussions on product design. Just like network designers and operators, supplier technical experts have often spent decades working on REFCLs in a different environment with different priorities. They face a challenge in integrating the realities of fire risk reduction into their thinking about the further development and application of their products.

Experience in the test program tends to confirm the reality reported by overseas utilities: it is likely to take at least five years of experience with REFCLs in actual service on Victoria's networks before network owners and suppliers will fully appreciate how to get best value from them.

6.2 Challenge 2: harden networks to reduce risk of cross-country faults

The issue	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.
ASC/GFN Δ	Similar operational risk; a GFN can help find network weaknesses in advance
Goals at risk	Fire risk, supply reliability, cost
Status	A well understood issue
Occurrence	Global – wherever networks move from NERs to REFCLs
Solutions	Well-defined network hardening options are available, some have high costs

Victoria's existing networks have many old items of network equipment that are not rated for continuous operation at 22kV; when an earth fault occurs on a REFCL-protected network, over-voltage on un-faulted phases can lead to failure of some of these items. Such equipment failure constitutes a second earth fault on the network, termed a 'cross-country fault' because it is usually remote from the initial fault and is always on one of the un-faulted phases subject to over-voltage stress caused by REFCL response.

REFCLs can only deal with multiple earth faults if they are all on a single phase. With a cross-country fault, the network has a two-phase-to-earth fault and high currents will flow in both fault locations; two fire starts are possible, i.e. a worse result than if a REFCL had not been installed.

This challenge occurs in all networks that move to resonant earthing from an effectively earthed design, such as those in Australia, New Zealand, France and Italy. Other networks (e.g. in central Europe) have always been equipped for continuous operation at the over-voltage levels produced by REFCLs during earth faults. In these networks, cross country faults are rare though not unknown.

To harden networks to reduce the risk of cross-country faults, a number of options can be considered by Victoria's network owners and a strategy based on one or more options can be defined and implemented. The precise mix of options will vary depending on the circumstances of the particular network.

The solution options include:

- Upgrade the network: under-rated network equipment can be removed or replaced at the time of REFCL installation with new equipment rated to operate at 22kV. This can be a high cost option and where adopted, is usually a carefully selected combination of a 'mass upgrade' approach and a 'test/identify/remedy' approach. This strategy gives maximum supply reliability benefits – permanent earth faults can remain on the network until found and remedied.
- Limit over-voltage duration: many items of network equipment have over-voltage failure modes that take time. The 'limit over-voltage duration' strategy removes the over-voltage before equipment failure occurs by reverting to solid earthing or NER-based protection after a set period. This can mean that not all under-rated equipment has to be immediately replaced. It also means that permanent earth faults will continue to result in supply interruptions.

Combinations of these two options (such as partially upgrade the network initially, limit over-voltage duration in the short term and fully upgrade the network over the long term) are also potentially viable. Different utilities have used different blends of them when moving to adopt REFCL technology.

6.3 Challenge 3: upgrade networks to REFCL-compatible equipment

The issue	Some network equipment items used widely in Victoria cannot be used with REFCLs. These include open-delta voltage regulators, three-phase equipment in earthed star configuration, non-directional earth fault protection, etc.
ASC/GFN Δ	Material difference unlikely
Goals at risk	Fire risk, supply reliability, cost
Status	Accepted by the industry as material
Occurrence	Global, tends to be a material issue in minimum-cost rural networks
Solutions	Well defined, costs understood

Some network equipment currently used in Victoria is not compatible with REFCL operation and must be upgraded or replaced with equipment that is compatible. This is a separate issue to Challenge 2 above which is solely concerned with network equipment's over-voltage withstand capability. Incompatible equipment can prevent correct REFCL operation and may produce dangerous network conditions with a REFCL in service.

Examples include:

- Open-delta regulators – these have long been the lowest cost option to regulate voltage on long rural feeders and they are used extensively in Victoria's rural networks. They can be made REFCL-compatible by adding a third auto-transformer to 'close the delta'.
- Three phase equipment in 'earthed star' configuration – the most common example is capacitor banks, both in zone substations and along long feeders. The earth connection must be removed from the star point and protection systems modified accordingly.
- Non-direction earth fault protection – many earth fault protection systems on Victorian networks are non-directional. They act when they detect earth fault current flow without information on its direction, i.e. whether the fault is 'upstream' or 'downstream' of them. This is not a problem in non-REFCL networks, since all earth fault currents flow only one way – from the zone substation to the fault. With a REFCL in service, earth fault current flows back into the zone substation from un-faulted feeders before a portion (the uncompensated residual current) flows out along the faulted feeder to the fault. Using non-directional feeder earth fault relays with a REFCL in service will lead to tripping of healthy feeders or whole groups of feeders. Similarly, the earth fault protection in pole-mounted ACRs must also be directional. This may be a major challenge as many ACRs do not have the voltage measurement components required for directional earth fault protection.

There are possibly many tens of open-delta regulators in Victoria's rural networks. There are possibly one thousand or more ACRs. The steps required to achieve REFCL compatibility of these devices are well known but the cost of the required upgrades has yet to be quantified and may be high.

6.4 Challenge 4: minimise network imbalance

The issue	The three phases of the network have different capacitances to ground. The REFCL will tune to the total network capacitance. Residual earth fault current will differ by faulted phase and be larger than if network capacitance was balanced. Fault detection sensitivity is also constrained.
ASC/GFN Δ	Material differences, of higher relevance to fire risk in ASC-protected networks
Goals at risk	Fire risk, cost
Status	Widely recognised but not yet quantified in Victoria's context
Occurrence	Potentially material in Victoria due to long rural single-phase spur lines
Solutions	Well defined, costs understood

When an earth fault occurs on a resonant earthed network, the fault current falls to a low level made up of three components:

- Resistive leakage current from the network to earth – the sum of all the tiny currents across the surfaces of tens or hundreds of thousands of insulators, plus current due to energy lost in cable insulation and in the iron core of the REFCL coil itself. A GFN uses its RCC to cancel this current, but an ASC cannot do the same.
- Current due to mismatch in the tuning of the REFCL coil to the network. REFCL designers take pains to ensure tuning is accurate to within an amp or two.
- Current due to imbalance in the capacitance to ground in each of the three phases of the network. This is under the control of the network owner.

Capacitive imbalance has some potential negative effects on REFCL performance:

1. It increases residual current, i.e. ground fire risk.
2. It increases the standing level of neutral voltage, i.e. it constrains fault detection sensitivity.

Capacitive imbalance is not seen as a material problem in European networks. Many European network owners deliberately detune REFCLs or use a parallel damping resistor to increase residual current for fault location purposes anyway. Extra residual current from imbalance is not a problem.

In Victoria, long single phase (two-wire) spurs teed off three-phase lines can create significant capacitive imbalance. As fire risk reduction relies on low residual fault current, capacitive imbalance can pose a risk to fire safety and so must be managed.

The realities that shape any action to balance network capacitance include:

- Two-wire spur lines must be connected to the three phase network in a way that limits capacitive imbalance, i.e. the phases to which each spur line is connected must be selected for capacitive balance, not just load balance.
- Balancing capacitance can be added by installing pole-mounted capacitors along feeders, e.g. on the third phase at a tee-off pole where a long two-wire spur leaves a feeder.

Improved fault detection algorithms with increased tolerance to imbalance might ease the scale of the challenge. GFNs can use the RCC to compensate a moderate level of imbalance current, but ASCs cannot – they will exhibit increased residual current and hence, increased fire risk in networks with high levels of imbalance.

6.5 Challenge 5: fault location

The issue	REFCLs reduce fault current to such low levels a fault may not generate enough visible evidence to reveal its location. Permanent faults may not be located for long periods.
ASC/GFN Δ	Differences of detail, GFN offers some additional functions
Goals at risk	Supply reliability, fast remedy of permanent faults
Status	Widely understood
Occurrence	Global – an issue in the ten to 15 per cent of earth faults that are permanent
Solutions	Well defined traditional solutions have partial success, emergent new solutions

When a permanent fault occurs on one of Victoria's distribution networks, protection systems isolate the section of the network that contains the fault and with some exceptions in remoter areas, a line crew then patrols the isolated section of network to find and repair the fault so power can be restored. Often the evidence of the fault is obvious – a car into a pole, a tree fallen across the line, etc. The fault current itself is often sufficient to do enough damage to make the fault location plain.

With a REFCL, the fault current can be as low as a few amps and many faults leave no evidence at all. This is not a problem for momentary faults, but it is a challenge in the ten to 15 per cent of faults that are permanent. In this small but very important category of faults, the network operator can face some potentially unpalatable options, such as:

- Allow the network to remain in a condition of full neutral voltage displacement while searching for the fault using sophisticated remote sensing devices. This option is commonly used in Europe and in some NZ networks. It has not yet been used in Australia.
- Revert to non-REFCL network protection and allow high earth fault currents to flow to expose the fault location in the usual way. The fire risk inherent in this option means it is only acceptable at times of low fire risk. This approach can lead to further challenges if the fault is not detected by traditional protection systems but only by the REFCL – a not uncommon outcome, given the REFCL's superior fault detection sensitivity.
- Trip the whole feeder to remove power supply to the fault. If a patrol finds no obvious cause, open all switches along the length of the feeder and restore power from the substation end section-by-section until the fault appears again. This can result in lengthy customer supply outages and the whole feeder may sometimes be restored to supply without the fault re-appearing.

Most stakeholders facing this challenge look to a future where smart grid schemes gather and analyse information from devices spread across the network, identify the most likely fault location and initiate appropriate switching to isolate the relevant section of network. Such devices can be built into pre-existing equipment, such as ACRs, or they may be new FPI (Fault Passage Indicator) products with sensitive current detection and remote communication facilities. There are a range of devices and network automation systems already in the market and many more are in development.

Solutions for fully hardened networks will be different to those that are only partially hardened, i.e. that rely on the 'limit duration of over-voltage' option to manage risk of cross-country faults. Network owners can review and trial existing and emergent smart grid and FPI products to identify the best solution for their particular circumstances.