4 Findings

Stated at a high level, the findings of the REFCL ignition research program were:

1. In worst case fire conditions, 'wire on ground' powerline faults on networks with traditional non-REFCL protection create inherent risk of fire.
2. Existing non-REFCL protection schemes have the potential to prevent some fires but cannot eliminate the majority of fire risk from 'wire on ground' powerline faults.
3. REFCLs dramatically reduce energy release into the environment from 'wire on ground' powerline faults.
4. REFCLs can detect and respond to 'wire on ground' powerline faults that traditional non-REFCL network protection does not 'see'.
5. REFCLs can significantly reduce fire risk for a wide range of 'wire on ground' powerline faults.
6. There are some 'wire on ground' powerline earth faults where today's REFCL products may not prevent ignition.
7. Though both REFCL variants reduce fire risk, GFNs offer superior fire risk reduction benefits compared to ASCs.
8. REFCL designs can be improved to further reduce fire risk.
9. REFCLs offer benefits to public safety.
10. REFCLs offer benefits to supply reliability.

The supporting rationale and evidence for each of these findings is outlined in the following sections.

The findings outlined in this section guided the comparative analysis set out in the preceding section of this report and the observations and recommendations set out in the next section on optimal operational settings for REFCL fire risk benefits.
4.1 Finding 1: In worst case fire conditions, ‘wire on ground’ powerline faults on networks with traditional non-REFCL protection create inherent risk of fire

Ignition tests with NER-based protection commonly produced fires. The only exceptions occurred where soil conductivity was so low that insufficient conductor-soil arc current flowed to produce ignition through pyrolysis of dry grass fuel. Fire risk from solidly earthed networks is likely to be no better and may be worse than fire risk in NER-based networks.

4.1.1 Rationale

The test program covered a wide range of ‘wire on ground’ powerline fault circumstances and ignition was most frequently and consistently observed in tests with a REFCL out of service, i.e. with traditional NER-based network protection systems. The NER installed at Frankston South zone substation is a standard eight ohm unit similar to those used in many other zone substations throughout Victoria.

Victoria’s network owners report that about 30 to 50 per cent of regional rural zone substations do not have an NER, i.e. the neutral of the transformers in those substations is directly connected to earth. These are known as solidly earthed networks. Such networks would in many cases have capability to supply even higher earth fault currents than those supplied by a zone substation fitted with an NER, i.e. fire risk in such networks could reasonably be expected to be equal to or higher than that in NER-based networks.

Inherent or ‘raw’ risk is the fire risk from powerline faults before the effect of controls is taken into account. In NER-protected networks, the only applicable controls are the earth fault protection systems. These do not reduce the magnitude of the current that flows but can reduce the duration of current flow. This finding relates to fire risk with faults of indefinite duration. Finding 2 outlines the effects of controls on that risk.

4.1.2 Evidence

A total of 47 valid NER ignition tests were carried out in Tranches 2 and 3 of the program. Sustained ignition was produced in 39 of these tests.

The eight NER tests that did not produce sustained ignition are listed in Table 1. It can be seen that in all but two (Tests 218 and 236) the soil current was at or below the minimum ignition current threshold of 0.06 amps (equivalent to 0.15 amps per metre of conductor on the ground).

Test 218 had a shorter than normal duration – 20 seconds instead of the usual 60 seconds. The video record indicates that ignition was likely had the test extended to the full 60 seconds.

Test 236 was a short duration test in which the current duration was externally constrained to 100 milliseconds. Based on other test results, if the test had extended to a longer duration, ignition would certainly have occurred.
Table 4: Valid NER ignition tests that did not produce sustained ignition

<table>
<thead>
<tr>
<th>Test</th>
<th>Current (amps)</th>
<th>Duration (seconds)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>218</td>
<td>0.15</td>
<td>19.5</td>
<td>Smoke but no flames, likely to have ignited in 60 seconds test</td>
</tr>
<tr>
<td>219</td>
<td>0.04</td>
<td>59.5</td>
<td>No sign of likely ignition</td>
</tr>
<tr>
<td>224</td>
<td>0.03</td>
<td>59.5</td>
<td>No sign of likely ignition</td>
</tr>
<tr>
<td>233</td>
<td>0.06</td>
<td>59.5</td>
<td>No sign of likely ignition</td>
</tr>
<tr>
<td>234</td>
<td>No data captured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>236</td>
<td>11.6</td>
<td>0.1</td>
<td>Short duration, fulgurite formed at 90 milliseconds</td>
</tr>
<tr>
<td>246</td>
<td>0.002</td>
<td>59.5</td>
<td>No sign of likely ignition</td>
</tr>
<tr>
<td>249</td>
<td>0.0015</td>
<td>59.5</td>
<td>No sign of likely ignition</td>
</tr>
</tbody>
</table>

It was concluded from the NER ignition test results that, provided the soil current exceeded the ignition threshold of 0.15 amps per metre of conductor on the ground, the probability of ignition under worst case fire conditions was close to 100 per cent.
4.2 Finding 2: existing non-REFCL protection schemes have the potential to prevent some fires but cannot eliminate the majority of fire risk from 'wire on ground' faults

At low fault current levels, ‘time to ignite’ can exceed the operating time of sensitive earth fault (SEF) protection schemes. Such schemes can therefore prevent some fires from high impedance ‘wire on ground’ powerline faults. However, ‘time to ignite’ was shown to exhibit wide variation and if circumstances favour fast ignition, SEF protection may not act fast enough to prevent it.

At higher current levels, the potential for traditional over-current protection to prevent fires appears very limited.

4.2.1 Rationale

If fault current is high (greater than 25 amps per metre of fallen conductor), ignition can be so fast it appears explosive and traditional network protection systems are most unlikely to have capability to act quickly enough to prevent a fire.

At very low current levels (less than 0.15 amps per metre of fallen conductor), ignition may not occur at all because the production of flammable gases through pyrolysis of the fuel in the presence of a low power electric arc is slow and the gases dissipate rather than building to the concentration threshold required for ignition to occur.

At intermediate levels of fault current, ignition will occur but it can take time. The ‘time to ignite’ varies randomly over a wide range though it is generally shorter at higher currents and longer at lower currents. At some levels of fault current the ‘time to ignite’ exceeds the operating time of SEF protection, i.e. SEF protection can operate quickly enough to prevent some fire starts.

4.2.2 Evidence

SEF protection settings in Victoria’s larger regional rural networks vary by network within the ranges shown in Table 5. Settings used for networks serving peri-urban rural areas are different again, with lower minimum detected fault currents of around five amps. These have not been included in Table 5 as the networks to which such settings apply cover only a small proportion of the state’s rural areas.

Table 5: Sensitive earth fault protection on Victoria’s rural networks

<table>
<thead>
<tr>
<th>Setting</th>
<th>Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum detected fault current</td>
<td>9-11 amps</td>
<td>Often set by Master Earth Fault protection ‘gate’</td>
</tr>
<tr>
<td>Operation time (constant)</td>
<td>0.5-3.1 seconds</td>
<td>Includes high voltage switch operation time</td>
</tr>
</tbody>
</table>

Using the time-to-ignite data from tests (see Figure 9 on page 24), together with the assumptions outlined in the preceding section relating particular test results to assumed worst case ‘wire on ground’ powerline faults, the diagram shown in Figure 14 can be drawn to show the potential benefit of SEF protection schemes with settings as shown in Table 5.

In Figure 14, ignitions to the right and above the SEF coverage boundaries would have been prevented by SEF protection response. It can be seen that this analysis indicates SEF may have the potential to
offer significant fire risk reduction benefits at low fault current levels, especially if operating time settings are short.

*Figure 14: potential benefits of SEF protection with 40 metres of conductor on the ground*

Some significant caveats must be recognised in interpretation of Figure 14:

1. The fires that happen in real ‘wire on ground’ network faults may have a very different distribution to those shown by the test results. It is quite possible that in real networks many more faults and ignitions happen at higher currents than those recorded in tests. The ‘time to ignite’ test program was designed to explore the full 60 second range using only a limited number of tests - the distribution of soil currents in tests was set by this experimental goal rather than by any research into the relative frequency of occurrence of real earth faults at different current levels. This means the number of ignitions on each side of the SEF coverage boundary shown in Figure 14 cannot be taken as a reliable guide to the proportion of fires that could be prevented by SEF protection on real networks.

2. The benefits of SEF protection are extremely sensitive to the assumed length of fallen conductor that constitutes a worst case ‘wire on ground’ fault. The SEF coverage areas shown in Figure 14 are based on 40 metres of fallen conductor and they will move if this assumption changes. For example Figure 15 shows that if the assumed worst case is not 40 metres of conductor on the ground but only four metres, then SEF protection would do little to reduce fire risk. This is because the fault current drawn by the shorter length of conductor is lower than the minimum operating current setting of the SEF protection scheme, i.e. the protection scheme will not detect the fault even though the fault current is sufficient to start a fire.

3. The random variations in the ‘time to ignite’ data for any particular level of fault current should not be taken to reflect the situation in real faults. In a real fault with many metres of conductor on the ground, chances are that at some point along the length of fallen conductor, circumstances will favour fast ignition, i.e. in assessment of the fire risk benefits of SEF
protection, the fastest ignition shown on Figure 14 should be taken as reflective of real situations, not the average. This may greatly limit the fire risk benefits of SEF protection.

Figure 15: SEF coverage of faults with only four metres of conductor on the ground

The other protection scheme normally used on rural powerlines is over-current protection. This works at higher current levels and acts faster than SEF protection. Its speed of operation often varies inversely with the level of fault current, provided that level exceeds its minimum operating current. Typical over-current settings for earth faults on Victoria’s regional rural networks are shown in Table 6.

Table 6: over-current protection settings for earth faults on Victoria’s regional rural networks

<table>
<thead>
<tr>
<th>Setting</th>
<th>Values</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum operating fault current</td>
<td>120-180 amps</td>
<td></td>
</tr>
<tr>
<td>Operation time at minimum fault current</td>
<td>0.2-0.4 seconds</td>
<td>Includes HV switch operation time</td>
</tr>
<tr>
<td>Fault current for instantaneous operation</td>
<td>420-450 amps</td>
<td></td>
</tr>
<tr>
<td>Operation time (instantaneous operation)</td>
<td>0.1 seconds</td>
<td>HV switch operation time only</td>
</tr>
</tbody>
</table>

With 40 metres of fallen conductor on the ground, these protection schemes will operate only for faults equivalent to test soil currents above one amp. The test program did not yield detailed ‘time to ignite’ data for soil currents between one amp and ten amps. However observations at the two extremes of this range provide guidance on likely ignition performance at intermediate values:

- High soil currents: at soil current levels greater than ten amps, bounce ignitions with a REFCL in service were recorded with ‘time to ignite’ values typically in the range 40 to 120 milliseconds. Time to ignite with an NER in service could be expected to be significantly shorter than this. It
was not possible to use high speed video records to determine time to ignite in NER tests with higher currents as continuing high power arcs masked the first flames. However, some short duration tests at higher currents were performed – Test 236 shows ignition at 11.6 amps soil current took less than 100 milliseconds; Test 240 shows ignition from 12 amps average soil current in 83 milliseconds.

- Low soil currents: the ‘time to ignite’ investigation included tests that produced ignition in 100 milliseconds at only 0.3 amps and 200 milliseconds at 0.8 amps.

Based on this limited data, it could be conservatively assumed that time to ignite remains at or below 200 milliseconds for soil currents between one amp and ten amps. REFCL bounce ignition results showed that ignition was possible in 50 milliseconds at soil currents above ten amps, even with the rapidly collapsing current profile characteristic of REFCL response to the fault. Hence, the 50 milliseconds is a conservative assumption for ‘time to ignite’ at soil currents above ten amps. In such a short period, it is unrealistic to assume 40 metres of conductor on the ground – the assumption of four metres as outlined in Figure 4 on page 19 must be used.

This estimate of time to ignite in the one to ten amp range of test soil current has implications for the operation of over-current protection systems in real ‘wire on ground’ faults as indicated in Table 7.

### Table 7: assessment of potential benefits of instantaneous and time delayed earth fault protection systems

<table>
<thead>
<tr>
<th>Fault current</th>
<th>Soil current: 40 metres fallen</th>
<th>Soil current: four metres fallen</th>
<th>Test result: time to ignite</th>
<th>Protection response time</th>
<th>Fire risk reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;420 amps</td>
<td>n/a</td>
<td>&gt;42 amps</td>
<td>&lt;0.05 seconds</td>
<td>0.09 seconds</td>
<td>None</td>
</tr>
<tr>
<td>120-420 amps</td>
<td>1.2-4.2 amps</td>
<td>12-42 amps</td>
<td>&lt;0.2 seconds</td>
<td>0.2-0.4 seconds</td>
<td>None</td>
</tr>
</tbody>
</table>

This analysis indicates that instantaneous and time-delayed earth fault protection systems as they are currently set are most unlikely to offer significant fire risk reduction benefits for ‘wire on ground’ faults because at the fault current levels required to trigger their operation, fires ignite faster than the systems’ ability to interrupt power supply to the fallen conductor.
4.3 Finding 3: REFCLs dramatically reduce energy release into the environment from ‘wire on ground’ powerline faults

When a live powerline conductor falls to the ground, ignition is caused by conduction of arc energy into vegetation, which is primarily cellulosic material. This exact energy flow is a result of random contact between electric arcs and stalks of vegetation and is impossible to predict or accurately measure. Total energy release in the vicinity of vegetation is more amenable to estimation and analysis. The total energy release is proportional to both arc power and arc duration – both of which are reduced by REFCLs.

Tests confirmed REFCLs dramatically reduce energy release in ‘wire on ground’ faults. They very rapidly reduce fault current by allowing the voltage on the faulted conductor to collapse as soon as fault current is drawn from the network. This reduces arc current, which hastens arc self-extinction (shortens arc duration). It also results in shorter, straighter arc ‘thread’ length which further reduces arc power.

The overall result of REFCL action is a dramatic reduction in energy release from the fault.

4.3.1 Rationale

The energy release into surrounding vegetation in a ‘wire on ground’ fault is via the electric arcs that carry the fault current between the fallen conductor and the soil. This arc energy causes a vegetation fire by ignition of flammable gases (methane, hydrogen, carbon monoxide, etc.) produced by pyrolysis of cellulosic material in the fuel – pyrolysis that occurs when the arc touches the fuel.

Some current can also flow directly from the conductor into the soil through points of conductor-soil contact. This current does not contribute to ignition as it does not create arcs that touch vegetation, cause pyrolysis and produce flammable gases.

Total energy release in the electric arcs created by a powerline fault is equal to the total arc power times the arc duration. These two quantities are not independent (see also Figure 33 on page 59 and Figure 36 on page 62):

1. **Arc power**: This equals the arc current times the arc voltage. In the Powerline Bushfire Safety taskforce’s 2011 arc-ignition tests, arc voltage was observed to be proportional to arc ‘thread’ length, with a coefficient of proportionality estimated to be of the order of 0.5 volts per millimetre (refer Section 8.4 of HRL Technology report *Final Report Probability of Bushfire Ignition from Electric Arc Faults*, 2011).

2. **Arc duration**: This time starts from when the arc first appears and ends when it self-extinguishes or the fault current is interrupted. The starting point is when the conductor separates from the soil with arcs extending between them. Arc self-extinction is a complex process best described as a race between the recombination of the ions in the arc plasma in the absence of current (they recombine to create very hot but non-ionised air, i.e.an insulator not a conductor) and the rise of the voltage between the conductor and the soil after the current passes through a zero-crossing in the 50Hz sinusoidal fault current waveform. The amount of plasma that must recombine to prevent re-strike of the arc increases with arc current and decreases with arc ‘thread’ length, i.e. shorter, higher current arcs persist longer.

If arc current is reduced, arc ‘thread’ length is shortened or arc duration is cut short, energy release due to the fault will be reduced. REFCLs produce all three of these effects in ‘wire on ground’ earth faults, greatly reducing energy release into surrounding vegetation.
4.3.2 Evidence

Tests confirmed soil current is reduced by REFCLs. This occurs in both phases: pre-RCC in which period a GFN and an ASC are equivalent; and, post-RCC in which a GFN reduces current more than an ASC.

Because a REFCL allows the voltage on the fallen conductor to collapse, the fault current rapidly diminishes. Arcs usually extinguish between conductor bounces providing an interval of zero current. As the conductor settles on the ground, fault current falls to a low residual current.

There were striking differences in visual appearance of high speed video records of tests with REFCLs in service compared to tests with NER in service, as illustrated in Figure 16 and Figure 18:

**Figure 16: Comparison of similar high current tests of NER-based and REFCL-based protection**

Test 114 (NER) 18 amp current increasing to 24 amps by test end at 900 milliseconds. Arcs continued throughout. Vigorous ignition occurred along full conductor length.

Test 161 (REFCL) 18 amp bounce current – current decreased to zero at 91 milliseconds when the arc self-extinguished. RCC acted late. Two bounce ignitions occurred, with no arcs on second bounce.

In all tests where ignition occurred, it was always observed to be produced by the presence of electric arcs in very close proximity (one or two millimetres) to the fuel. Arcs not touching grass did not cause ignition. There was also no evidence of ignition through heating caused by conduction of electricity through vegetation or soil. In most tests, dry grass fuel appeared to act as an effective insulator as the conductor pushed through it on its way to impact the soil bed below.

Only rarely did pre-impact flashover to the soil occur (see Figure 18 on page 42).
Often with the conductor lying on dry grass and dry soil and conductor voltage levels of thousands of volts, only bursts of high frequency 'noise' current were recorded. This is illustrated in Figure 17 which shows the gradual increase of current as conductor voltage rises in response to the switching off of the RCC. It can be seen that with more than 1,000 volts on the stationary conductor, there is zero current. It is only when the conductor voltage rises to 5,000 volts that some 50Hz current starts to appear, and even then it is highly distorted. During this transition period, there is a progressively increasing amount of high frequency (hundreds of kilohertz) current 'noise' during each 50Hz half cycle of conductor voltage.

Figure 17: Test 196 illustrating the non-linear resistance characteristics of conductor-vegetation-soil interface

Figure 17 vividly illustrates the challenge facing REFCL designers in the development of a practical test to confirm sustained faults, such as 'wire on ground' faults, that will work reliably on high fire risk days when soil and vegetation moisture content can both be extremely low. Fault-confirmation tests and faulted feeder identification both require reliable measurements of 50 Hz capacitive and leakage current to earth on each feeder, including the faulted feeder.

Two different arc geometries were observed to cause ignition: bounce ignition and ground ignition. In both, the arc energy in contact with fuel was assessed as much lower in REFCL tests than in NER tests.

### 4.3.3 Bounce ignition

At higher current levels, arc energy in contact with fuel reached a maximum during the initial conductor rebound. As the conductor leaves the soil after the first impact, the relatively small horizontal arcs spread uniformly along its length tend to concentrate to form one, two, or three extended arcs between the soil and the conductor as it rises into the air. These arcs pass through the fuel and are often the primary cause of ignition.

In higher current NER tests, bounce arcs are high energy, with long 'thread' lengths and prolonged durations. They do not generally extinguish between conductor bounces and they cause rapid ignition of the fuel all along the length of the conductor. Figure 16 above shows a typical set of NER bounce arcs.
REFCL tests produced fewer, much lower energy arcs with relatively short ‘thread’ lengths. The REFCL bounce arc shown in Figure 16 is unusually strong due to delayed RCC response, i.e. slower than normal collapse of conductor voltage with a REFCL in service. A more typical REFCL bounce arc situation was Test 85 (a GFN ignition test with five amps peak bounce current) which is shown in Figure 18. To judge the scale of the arcs, the conductor diameter is slightly less than 20 millimetres.

Figure 18: typical conductor-soil arcs with REFCL in service

Test 85: GFN ignition test, 5 amps peak, 34 milliseconds of arcs, one pre-strike arc and two bounce arcs

Figure 19: Test 85 conductor voltage and soil current (REFCL in service)

The main characteristics of most first bounce events with REFCL in service can be seen in Figure 18 and Figure 19: the arcs involved are small and extinguish early provided the collapse of the conductor voltage is rapid. Test 85 was a GFN test, so the voltage collapse shown is a consequence of RCC action.
Pre-strike arcs like the one shown in Figure 18 for Test 85 were rare, but the small bounce arcs shown were very commonly observed in tests with REFCL in service.

Test 85 was also performed before the RCC was recalibrated and the residual voltage was measured at close to 1,000 volts. Hence, small burst of high frequency current ‘noise’ can be seen at the time of the second and later bounces (but no significant 50Hz current). Once the RCC was recalibrated, residual voltage was typically less than 250 volts and later bounces did not appear at all on the soil current records for GFN tests, i.e. fault current was zero after the first bounce until the GFN initiated its fault-confirmation test some seconds later.

4.3.4 Ground ignition

Ignition can occur after the conductor has come to rest on the soil. If there is still voltage on the fallen conductor, arcs continue to appear, extending vertically from the conductor to the soil wherever the uneven soil surface creates a gap. At higher current levels, these arcs extend laterally across the surface of the soil some distance to each side of the conductor. As there is no conductor movement to stretch them to the point of self-extinction, ground arcs continue until the driving voltage is removed.

NER tests tended to produce larger more energetic ground arcs that extended laterally each side of the stationary conductor. REFCL tests tended to have little lateral extension into surrounding fuel and were of visibly lower energy. NER tests produced a relatively steady current which increased slowly rather than decreasing with time, as shown in Figure 20. If the test duration was long enough, fulgurite formation was possible (see Appendix D)

Figure 20: Test 105 - earth fault voltage and current on an NER-protected network with fulgurite formation at end of test

Tests confirmed that energy release during the ground ignition phase was much lower in the case of REFCL ignition tests than in NER ignition tests.
With an ASC, the result often looked like that in Figure 21. Whereas an NER-based network would exhibit current at a similar or even higher level than that which occurs in the initial conductor bounce, the current in an ASC-protected network falls to a much lower value as the conductor voltage collapses. In Test 127 shown in Figure 21, the residual current was about one seventh of the level that would have occurred with an NER-based protection scheme – but still high enough to produce ground ignition.

Figure 21: Test 127 - voltage and current in an earth fault on an ASC-protected network

In long duration tests at low current levels the soil current varied considerably during the test (see Figure 37 on page 63)
In GFN ignition tests, residual current compensation reduced the fault current even further; generally to zero (see Figure 16 and Figure 19 above). This means there is no energy release into the local environment after the first bounce until some fault current flow is required to confirm if the fault is still present and if so, to identify the faulted feeder (see Figure 38 on page 65 and Figure 39 on page 66 below). With the GFN, the fire risk no longer comes from the fault itself, but from the subsequent test to see if the fault is still there.

In summary, tests confirmed that both REFCL variants dramatically reduce the amount of energy released into the local environment when a ‘wire on ground’ earth fault occurs.
4.4 Finding 4: REFCLs can detect and respond to ‘wire on ground’ powerline faults that traditional non-REFCL network protection does not ‘see’

Tests confirmed the extreme sensitivity of REFCL-protected networks to earth faults. Existing Sensitive Earth Fault protection is usually set to detect faults that draw nine amps or more. Sometimes SEF can be set to detect fault current as low as five amps. However, SEF sensitivity is limited by considerations of supply reliability and security, i.e. risk of ‘false positive’ detections.

Standard widely-used settings on REFCLs reliably detect faults down to two amps and in the test program this detection sensitivity was extended temporarily to one amp. Reliable detection of earth faults that draw less than one amp of current would be an unprecedented departure from the traditional performance standards of Victoria’s rural networks.

4.4.1 Rationale

Three-wire and two-wire high voltage powerlines in Victoria's rural electricity networks can have earth faults that produce currents that range from five amps to more than 1,000 amps, though anecdotal reports indicates that most ‘wire on ground’ faults on 22kV networks do not generally exceed about 200 amps and most draw more than ten amps. Of course, this anecdotal evidence of long term experience is coloured by the fact that nothing in most of today’s networks detects fault currents below nine amps. If there are faults such as ‘vegetation pruning faults’ that draw less than this, no one would know.

Today’s networks are protected by sensitive earth fault protection systems that are typically set to detect fault currents of five, seven, nine or eleven amps (depending on the network) that persist longer than a set response time between one half and three seconds. These traditional sensitive earth fault protection settings have evolved over decades to become an accepted trade-off between the risk of undetected faults and the risk of unnecessary power interruptions.

Today, if a ‘wire on ground’ powerline fault draws less than five amps (nine amps in most rural areas) it is not detected and will continue to draw current until either the current increases above the detection threshold or the network operator interrupts supply to the powerline in response to, for example, phone calls from emergency services personnel reporting the fallen wire and its arcing on the ground.

In total contrast to this, REFCLs allow the voltage of the whole network to move in response to an earth fault, providing a much more sensitive indication of its presence. The traditional barriers to sensitive earth fault detection in non-REFCL networks are lowered in the REFCL approach. The test program confirmed manufacturers’ claims that REFCL-protected networks can operate at much higher levels of earth fault detection sensitivity than traditional arrangements used in Victoria.

High sensitivity of earth fault detection is important to fire risk reduction for two reasons:

1. The lower the earth fault current that can be detected, the more fire-risk fault types might be detected, such as ‘wire on very high resistance ground’ and even high impedance vegetation ‘touches’
2. More sensitive detection usually translates into faster detection and faster protection system response which can reduce the time available for fault current to cause ignition.

Manufacturers naturally claim their products offers superior performance. However, it was beyond the scope of this test program to assess the comparative merits of such claims. For the purposes of this particular finding, it is safe to assume the laws of physics and the laws of information processing apply equally to all and at the very low fault current levels where fault detection is at the limit, the behaviour of GFNs and ASCs will be identical, i.e. the fault detection capability of a GFN and an ASC should be
similar. Hence, tests carried out on the GFN at Frankston South are taken to be indicative of the fault detection performance of REFCLs as a class of technology.

### 4.4.2 Evidence

Two series of ‘bolted fault’ tests (Tests 32-39 and Tests 162-174) were performed to measure the sensitivity of REFCLs to earth faults. In these tests, the conductor in the ignition test cell was shorted to earth rather than passing current through the soil bed. The fault current in the tests was controlled by insertion of high voltage resistors in the power supply to the test cell. Both series of tests were performed on the GFN REFCL variant. In some tests, the RCC was disabled so the GFN acted as an ASC.

The results of the tests confirmed that with normal (manufacturer recommended) settings, earth faults with two amps fault current were easily detected by the GFN. With the sensitivity setting modified (set less conservatively) in the light of experience during the test program, earth faults producing one amp of fault current were reliably detected.

### 4.4.3 Normal sensitivity setting

Test 37 demonstrated that with the GFN fault detection setting at the normal manufacturer’s recommended level (30 per cent neutral displacement voltage) the GFN detected a two amp fault (6,400 ohms fault resistance) in 540 milliseconds. The detection is revealed in the conductor voltage profile shown in Figure 22 where the voltage collapse due to RCC action marks detection of the fault by the GFN.

**Figure 22: Test 37 - detection of two amp fault by GFN**

### 4.4.4 Heightened sensitivity setting

As tests progressed and experience was gained with the GFN’s response to faults, it considered that sensitivity might be increased without major risk. A detection threshold of 20 per cent neutral voltage displacement was tested. Test 163 demonstrated that with this heightened sensitivity, a fault that drew...
0.95 amps of current was detected in 800 milliseconds. The spike of current and voltage that occurred in this test 1.25 seconds after the fault was not relevant to the test result. It was later found to be due to an independent distribution substation fault that was cleared by the operation of fuses.

Figure 23: Test 163 - detection of a one amp fault in 800 milliseconds
4.4.5 Opportunities to increase fault detection sensitivity

Consideration of REFCL fault detection methods and discussions with REFCL manufacturers identified the main barriers to further increases in fault detection sensitivity. They arise from the need to avoid unnecessary ‘false positive’ detections caused by:

1. Network imbalance
2. Variations in network damping
3. Tuning mismatch due to variations in network capacitance
4. REFCL tuning processes
5. Network switching operations

It was concluded that on Code Red days, temporary increases in REFCL sensitivity may be possible to allow detection of faults down to one half of an amp fault current at acceptable risk. This would require improvement of current algorithms to make them adaptive (i.e. to continuously take into account the current state of the REFCL and network) and more sensitive to the speed of change in neutral voltage when a fault occurs. It may also require changes in operating procedure to temporarily de-sensitise the REFCL during network switching.

Reliable fault detection down to half of one amp of fault current could possibly extend REFCL fire risk reduction benefits into the area of ‘vegetation touch’ faults not directly covered in this ‘wire on ground’ fault test program.

4.4.6 Factors that affect fault detection sensitivity

Today’s REFCLs detect faults by the rise in neutral voltage displacement they cause. If the neutral voltage exceeds a set threshold, then a fault is deemed to have occurred. However, the neutral voltage rise is affected by a range of network parameters as well as the fault current. Also, there is usually a
standing level of neutral voltage that limits how low the threshold can be set. All of this means three network features will affect a REFCL’s achievable fault detection sensitivity (see also Finding 8 below):

1. **Network damping:** if the leakage current from conductors to earth across the network is high, this reduces the rise in neutral voltage when a fault occurs, i.e. it desensitises the REFCL. This leakage is weather dependent (see Figure 29 and associated discussion), so with a constant neutral voltage threshold fault detection sensitivity will vary with weather. REFCL designs might be improved to address this effect, e.g. by taking the current value of damping as measured during the most recent coil tuning process into account in setting the neutral voltage threshold.

2. **Network imbalance:** with current REFCL designs, the fault detection threshold must be set higher than the standing value of neutral voltage caused by network imbalance, most of which is normally capacitive imbalance. A severely unbalanced network cannot support high detection sensitivity. Imbalance also means that sensitivity will vary by phase. A one amp fault on red phase might be easily detected, while a fault on white phase may only be detected if it draws more than one and a half amps. REFCL designs might be improved to address this effect.

3. **Network size:** small networks have less leakage to earth and less capacitance to earth, which makes their neutral voltage much easier to disturb. Hence, they can support much higher levels of fault detection sensitivity. REFCL manufacturers already offer designs which split a network into sub-networks, e.g. one network for each transformer in the zone substation, to exploit this.

Overall, the experience of the test program and the above considerations indicate that fault detection sensitivity of one half of one amp or better may be feasible as a temporary fire risk reduction measure on high fire risk days, without resorting to reconfiguration of the network into smaller sub-networks.
4.5 Finding 5: REFCLs can significantly reduce fire risk for a wide range of ‘wire on ground’ powerline faults.

By detecting earth faults that traditional protection systems cannot ‘see’ and by dramatically reducing energy released into the local environment when earth faults occur, REFCLs can reduce the chance of ignition across a wide range of earth faults on multi-wire lines, i.e. three phase and single phase powerlines.

4.5.1 Rationale

REFCLs reduce fault currents in network earth faults. For ASCs, the level of reduction varies depending on the fault resistance, network damping, network imbalance and coil tuning. For GFNs, provided the fault is detected, the fault current will quickly reduce to nearly zero, regardless of fault resistance or other factors.

The reduction in fault current produced by a REFCL can be sufficient in itself to prevent a ‘wire on ground’ fire, i.e. the residual fault current is so low ignition will not occur. In many other cases, it can increase the time required for ignition which gives protection systems a better chance to cut off supply to the fallen conductor before a fire starts.

4.5.2 Evidence

NER ignition tests at any test soil current level above 0.06 amps (the threshold for ignition, equivalent to 0.15 amps per metre of fallen conductor) produced sustained ignition 100 per cent of the time. Below this fault current threshold ignition did not occur no matter what type of network protection was in place.

Theoretical calculations indicate that ASCs and GFNs will reduce residual current in earth faults to levels well below those that would occur with non-REFCL protection. In the case of a GFN, the reduction is due to the RCC response to the fault; it is usually about 98 per cent if the RCC is accurately calibrated and it does not vary with fault current. In the case of an ASC, the reduction depends on fault current and must be calculated using a quantity called the network damping resistance. This resistance cannot be directly measured as it is an equivalent quantity that accounts for all the network energy losses caused by current that normally flows between network conductors and earth in the absence of any faults. However, the value of damping resistance can be derived from the voltage changes recorded in ‘bolted fault’ tests.

Using the results of Tests 165 and 166, the FSH network was found to exhibit a network damping resistance of around 4,000 ohms on the early afternoon of Thursday the 29th May 2014. The network damping is thought to vary with weather, particularly humidity. Day to day, it may vary perhaps between half and twice an average value (see Figure 26 and Figure 28 below), i.e. damping resistance may be as low as 2,000 ohms or as high as 8,000 ohms. Neither the NER nor the GFN residual faults current are affected by network damping (until the current is so low, the GFN does not detect the fault - whereupon it acts like an ASC).

The calculated residual currents for the FSH network with an NER, an ASC and a GFN are shown in Figure 25 for a wide range of fault resistance values. The ASC values are shown for an indicative range of network damping variation, giving residual currents of one and a half to six amps for low impedance faults.
The ASC residual current values shown in Figure 25 are calculated for a perfectly balanced network with a perfectly tuned REFCL and damping resistances of 2,000 ohms, 4,000 ohms and 8,000 ohms.

In practice, ASC residual fault currents can be higher. To estimate likely ASC residual current levels, data collected on the Frankston South network over the last five years was analysed. The average residual current for an ASC on the Frankston South network based on 34 measurements taken by the Frankston South GFN over the last four years was 3.3 amps, within four per cent of the value that would result with a damping resistance of 4,000 ohms. The distribution of calculation results are shown in Figure 26.

This data also reveals correlation of network damping (and hence, ASC residual fault current) with weather, as shown in Figure 27.
This analysis also indicated that network capacitive imbalance contributed little to the calculated ASC residual current. Network dissymmetry (capacitive and resistive imbalance) measurements were virtually constant over the whole period.

To see if this value of ASC residual current also applied in high fire risk conditions, 130 measurements taken by the GFN over December 2013 and January 2014 were analysed. The average of these measurements was only slightly lower at 3.15 amps that the average of the 34 readings from the last four years shown in Figure 26. The results are shown in Figure 28.

However, close examination of both sets of GFN measurements revealed occasional outliers, one of which (8.2 amps at 3:40 pm on 20 February 2014) is visible in Figure 27.

Of all the 164 sets of GFN tuning data reviewed, the highest estimate of residual current was 15.1 amps at 8:02 pm on 17 January 2014. This was a single reading – those taken 40 seconds before and 20 seconds afterwards were both close to six amps. Readings three hours before and twenty minutes afterwards showed the normal level around three amps.

The weather data around this time is shown in Figure 29. It can be seen that on the date of this outlier, a cool change (with no rain) moved across Melbourne at about 8 pm after temperatures had reached 43°C on the third day of a heat wave, i.e. it was a day likely to produce high fire risk.
This very limited analysis raises the possibility that on days of high fire risk, ASC residual currents may at times be higher than average due to variations in network damping. Further investigation of this possibility may be warranted to fully assess ASC fire risk benefits under worst case conditions.

Despite this, especially for low impedance faults, fault currents in ASC-protected networks would still be greatly reduced from those that occur in NER-protected networks. For example, a real ‘wire on ground’ fault that might draw 150-200 amps in a NER-protected network can quickly settle to perhaps to less than fifteen amps in an ASC-protected network (even in worst case conditions) and less than 0.1 amps in a GFN protected network.

4.5.3 Reduction of bounce ignition risk

In many situations, the reduction in ignition probability due to a REFCL depends on how fast the fault current is reduced. The test program demonstrated that REFCL ignition tests produced less bounce ignitions than NER ignition tests with first bounce peak currents above ten amps.

Soil current was not easily controlled – it depended primarily on soil moisture content which could take weeks to stabilise and was very difficult to measure without destroying the soil bed. Whilst the test team gradually developed techniques to predict in broad terms the expected soil current, tests often produced surprises. The REFCL ignition tests covered a wide range of peak soil current levels as shown in Figure 30 and Figure 31. Analysis of results from a diversity of tests covering a wide range of different soil current levels produced reliable conclusions.
Tests with peak soil currents greater than ten amps sometimes produced bounce ignition, i.e. ignition due to the arcs in the first bounce of the conductor after it hit the soil. In RECL ignition tests that produced peak currents above ten amps, the likelihood of bounce ignition was of the order of 50 per cent - well below the 100 per cent observed in NER ignition tests. Not enough tests were conducted to fully establish the exact bounce ignition probability with statistical confidence, but the reduction in bounce ignitions due to the REFCL is clear in Figure 32 on page 59. The reduction would be greater than 50 per cent with today’s GFN product which does not have the RCC delay experienced in tests that produced GFN bounce ignitions (see Table 8 on page 61).

4.5.4 Reduction in ground ignition risk

In tests with lower soil currents, the main ignition risk was ground ignition, i.e. ignition from arcs that continue after the conductor has come to rest. The test program included many REFCL ignition tests with soil currents below two amps as shown in Figure 31.

Figure 31: Distribution of peak soil currents in 36 RECL ignition tests with soil current below two amps
The probability of ground ignition depends on the level of residual current and is governed by the powerline fire risk equation set out in Figure 7 on page 22 and the ‘time to ignite’ data set out in Figure 9 on page 24.

The test program demonstrated that:

1. REFCLs reduce residual current in ‘wire on ground’ earth faults. ASCs reduce it to an extent that depends on both network damping and the fault resistance (spot checks on individual tests revealed that ASC residual current was within ten per cent of the value predicted by theory). GFNs often reduce it to zero. If a GFN does not detect the fault, then the reduction is the same as that produced by an ASC.

2. An ASC would greatly reduce ground fire risk in earth faults involving forty metres of conductor on the ground. In the ideal case (perfectly balanced network and perfectly tuned coil) an ASC would reduce the residual current, assuming the network is similar to that at Frankston South, to about five amps or less, which would produce only 0.125 amps per metre of current spread along the fallen conductor – equivalent to an ignition test with soil current below the threshold for ignition. In this idealised situation, an ASC would eliminate most of the risk of ground ignition.

3. In a more realistic situation, the fire risk reduction benefits of an ASC would depend on a range of factors. Firstly, the residual current could exceed the ignition threshold (equivalent to a fault current of six amps with forty metres of conductor on the ground) if any one or a combination of the following conditions were to occur:
   a. The network damping resistance were to reduce by a factor of two or more (this level of variation has been experienced in the Frankston South network (see Figure 28 above).
   b. The capacitive imbalance of the network was sufficient to generate about five amps of capacitive current or more. Some capacitive imbalance is inevitable and imbalance current levels may approach this level on some rural networks.
   c. The coil tuning was imperfect to the extent residual current under earth fault conditions was increased by five amps. Analysis of Frankston South GFN tuning data shows an occasional outlier at six amps, though generally mismatch is less than two amps.
   d. The length of conductor on the ground was less than 20 metres.

Second, the fault-confirmation and faulted feeder identification functions performed by ASC ancillary relays must operate in less time than the ‘time to ignite’ for any level of current above the ignition threshold. Figure 14 on page 36 indicates a time less than 500 milliseconds might produce substantial benefits. The time settings of ASC ancillary relays were not investigated in this test program so no conclusion on this can be drawn. However, a brief review of the factors that must be taken into account in design and setting of these functions would indicate 500 milliseconds may be shorter than prudent practice.

4. The fire risk reduction of a GFN would be total (i.e. zero risk) only up until the fault-confirmation and faulted feeder identification processes a few seconds after the initial fault detection, when the risk would increase to a similar level to that produced by an ASC. In this case, the time to act is known to be one second. In GFN ignition tests a mix of results was obtained – in some tests the one second period of ASC-level residual current produced ground ignition. In others, it didn’t. The GFN manufacturer is currently working on product development to reduce this risk.

5. In very high impedance faults that the GFN could not detect, it performed identically to the ASC to reduce residual fault current.

Current ASC products have been designed to IEC standards which require only that the residual current is less than about 35 amps. Indeed many ASC installations include damping resistors or are deliberately
mistuned to generate a guaranteed minimum level of residual current to assist in fault location. Victoria’s requirement to minimise fire risk will place much more stringent demands on ASC design and operating procedures to keep residual currents below five amps so the soil current in worst case faults remains below the ignition threshold.

4.5.5  The threshold current for ignition

This test program was the first known investigation to confirm that there is a threshold below which ignition does not occur, i.e. at extremely low rates of energy release, ignition may not occur even if the fault current continues indefinitely. Ignition appears to require a certain rate of heating of a certain mass of cellulosic material. Otherwise pyrolysis occurs on too small a scale or too slowly and the flammable gases it produces are dispersed before they reach the concentration levels required for ignition. Each of the gases normally produced by pyrolysis (methane, hydrogen, and carbon monoxide) has a well-defined concentration called the Lower Flammability Limit below which they will not ignite, e.g. ignition of methane requires a concentration of at least five per cent in air.

When test soil current was less than about 0.06 amps (equivalent to 0.15 amps per metre of fallen conductor), fires did not occur and video records showed arc energy was so low that ignition was considered very unlikely to occur even with indefinitely long fault durations.

In summary, for a wide range of fault current levels, either REFCL variant will reduce fire risk and may even eliminate it for some circumstances such as long lengths of conductor on the ground. The GFN appears to have potential to reduce fire risk even further but is not yet fulfilling that potential, though product development is underway to address this.

4.5.6  Faulted-phase earthing (FPE) – an untested REFCL type

Faulted-phase earthing (FPE) was not tested in this research program. FPE is a REFCL system that uses an ASC plus three fast earthing switches on the zone substation busbars. Once a fault is detected, the faulted phase is earthed using the fast earthing switch. This reduces the voltage on the faulted phase to zero in the zone substation (and close to zero at the fault location) and is thus similar in effect to an RCC. This system has been adopted for 20kV distribution networks in Ireland, primarily for public safety. Its further development for the specific objective of reduction of fire risk in Victoria may warrant consideration.
4.6 Finding 6: There are some ‘wire on ground’ powerline earth faults where today’s REFCL products may not prevent ignition

The current designs of REFCLs will not always prevent fires from ‘wire on ground’ earth faults. There are some faults where the REFCL’s normal function will be neither fast enough nor sensitive enough to reduce the fault current below the level that will start a fire. These include heavy (high current) faults where ignition may occur on the first bounce, and undetected (low current) faults where ignition may occur from prolonged conductor-soil arcing. There is potential for both of these exposures to be addressed through improvements to GFN design (see Finding 8 below).

4.6.1 Rationale

There are two circumstances in which ignition can occur in ‘wire on ground’ faults despite the presence of a REFCL. These circumstances were identified in tests and the limits of the associated risk exposure were explored:

1. **Bounce ignition**: If the current in the first bounce is high enough and the arcing in the first bounce persists long enough, first bounce current can cause ignition before the REFCL has time to collapse the voltage on the falling conductor and quench the arcs. Tests indicated this can occur if the peak soil current in the first bounce of the conductor is higher than ten amps and the arc duration exceeds 40 milliseconds. Bounce ignition was the most common form of ignition in NER ignition tests, mainly because the arcs did not self-extinguish unless fault current was very low.

2. **Ground ignition**: Ignition can result when the conductor comes to rest and lies stationary on the soil bed if the soil current is high enough to start a fire but the associated fault current is too low to be detected as an earth fault by the REFCL. This circumstance can occur if the ongoing soil current from the stationary conductor is higher than around 0.15 amp per metre of conductor length and the associated fault current is less than the sensitivity limit of the REFCL (about one amp in the case of the Frankston South GFN with temporarily heightened detection sensitivity).

The guidelines for interpretation of test results (on page 17) suggest that neither of these circumstances may be realistic for ‘wire on ground’ earth faults that do not involve earthed metal. Further, both of these ignition risks could be addressed by design improvements to REFCLs, especially the GFN product.

4.6.2 Evidence

With a REFCL in service, instances of both bounce ignitions and ground ignitions were recorded in tests. Ignitions of both types were more common in ASC tests than in GFN tests. Analysis of the tests indicates actions that could eliminate ignition risk, at least in the case of GFNs. The following outlines the evidence distilled from tests.

4.6.3 Bounce ignition with the REFCL in service

The peak soil current and arc duration in the conductor bounce were plotted as a scatter diagram in Figure 32 with the bounce ignition results identified.
It can be seen that bounce ignition did not occur in any test with a bounce arc duration less than 40 milliseconds. If bounce arc duration exceeded this threshold, ignition sometimes occurred provided peak soil current was higher than about ten amps, i.e. bounce ignition appears to be a risk only for low impedance and heavy faults. The factors that are thought to influence probability of bounce ignition are shown in Figure 33. They interact in complex ways and it is difficult to link any particular aspect of REFCL performance to ignition probability in a quantitative way.

**Figure 33: factors that influence bounce ignition probability**
It can be seen from Figure 34 that there is no perceptible difference in the occurrence of bounce ignitions between ASC tests and GFN tests. This tends to confirm theoretical considerations that indicate REFCLs have major effects in the first cycle or two of 50Hz fault current and further that in the early period of response, GFNs and ASCs are largely equivalent.

**Figure 34: ASC and GFN bounce ignitions**

There are a number of considerations which indicate the test procedure may have been ‘worse than worst case’ in the production of bounce ignitions:

- **Damp soil and dry grass:** to get higher bounce current levels, the soil bed moisture content had to be relatively high. At the same time, the grass fuel had to be at or below five per cent moisture content to reflect worst case fire risk conditions on Code Red days. Achievement of this combination proved to be a challenge that demanded special procedures. It is not obvious that this combination is realistic for environments near rural powerlines on Code Red days.

- **Zero airflow:** the first flames in REFCL test bounce ignitions were uniformly tiny and only grew to produce a reasonable sized fire after a period of seconds despite the extremely dry fuel. This was only possible in the complete absence of airflow in the ignition test cell. Doubt must remain as to whether this is realistic in the conditions of Code Red days with wind gusts up to 100 kilometres per hour at height.

- **Bounce current level:** Tests extended to the limit of realistic fault current and perhaps beyond. Tests covered currents up to 20 amps drawn by 400 millimetres of conductor. This implies 50 amps of fault current per metre of fallen conductor, which according to anecdotal evidence may exceed the limits of realism.

These considerations indicate the bounce ignition test results may be unrealistically pessimistic. Nevertheless, to ensure the assessment of fire risk is conservative, bounce ignition results have been included in the analysis presented in this report. The tests demonstrated the nature of bounce ignition risk and point to its potential remedy – REFCL design improvements to speed up collapse of the voltage on the fallen conductor. Of the REFCLs tested, this improvement opportunity is available for the GFN variant only.
All the GFN bounce ignition tests were performed on an older version of the GFN than today’s product. The test records of GFN bounce ignitions show RCC action was often delayed and this delay coincided with bounce ignitions. An example is shown in Figure 35 on page 62 where it is clear from the conductor voltage record that the RCC did not act until 108 milliseconds after the initial conductor-soil contact. This is 80 per cent longer than the manufacturer’s current specification of 60 milliseconds.

The RCC response times in GFN tests that produced a bounce ignition are outlined in Table 8. It can be seen that the delay beyond the current product specification is material in the context of bounce ignition and that if the current product specification (60 millisecond RCC response time) had been met in all tests, the number of observed GFN bounce ignitions may have been greatly reduced or possibly, zero.

Table 8: RCC delay in all GFN tests that produced bounce ignition

<table>
<thead>
<tr>
<th>Test</th>
<th>RCC response (milliseconds after fault)</th>
</tr>
</thead>
<tbody>
<tr>
<td>154</td>
<td>90</td>
</tr>
<tr>
<td>155</td>
<td>93</td>
</tr>
<tr>
<td>157</td>
<td>91</td>
</tr>
<tr>
<td>159</td>
<td>122</td>
</tr>
<tr>
<td>161</td>
<td>113</td>
</tr>
<tr>
<td>176</td>
<td>99</td>
</tr>
<tr>
<td>177</td>
<td>87</td>
</tr>
<tr>
<td>178</td>
<td>98</td>
</tr>
</tbody>
</table>

Some later tests (not bounce ignition tests) were performed following temporary upgrades to the Frankston South GFN firmware and hardware to bring it up to today’s standard product. It was noted that these upgrades included an additional separate fibre optic communications channel from the GFN digital controller to the RCC output contactor. The manufacturer explained this was required to enable the GFN to consistently achieve the 60 milliseconds RCC response time specification. This upgrade was not in place for the bounce ignition tests that generated the results shown in Figure 34 and Table 8 above. It is quite possible that if it had been, far fewer (if any) GFN bounce ignitions may have been observed.
4.6.4 Ground ignition with the REFCL in service

Ground ignitions also sometimes occurred in REFCL tests when residual current was relatively high. The 'time to ignite' test series carried out at the end of the test program revealed that any residual current above 0.15 amps per metre of conductor length might lead to ground ignition. At these very low current levels ground ignitions can take time – the longest ‘time to ignite’ observed in a test was 54 seconds. However, ignition can also be quite fast at relatively low currents. For example ground ignition was observed in just 100 milliseconds at a soil current of 0.8 amps per metre of conductor length.

The factors that are thought to influence ground ignition probability are shown in Figure 36.

Figure 36: factors that influence ground ignition probability
In ASC ignition tests of various durations, eleven ground ignitions were observed as listed in Table 9.

Table 9 ground ignitions in ASC tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Soil current (amps/metre)</th>
<th>Test</th>
<th>Soil current (amps/metre)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial value</td>
<td>Final value</td>
<td>Initial value</td>
</tr>
<tr>
<td>118</td>
<td>1.1</td>
<td>0.6</td>
<td>133</td>
</tr>
<tr>
<td>119</td>
<td>0.5</td>
<td>0.6</td>
<td>251</td>
</tr>
<tr>
<td>120</td>
<td>0.9</td>
<td>1.0</td>
<td>257</td>
</tr>
<tr>
<td>130</td>
<td>No data</td>
<td></td>
<td>258</td>
</tr>
<tr>
<td>131</td>
<td>No data</td>
<td></td>
<td>259</td>
</tr>
<tr>
<td>132</td>
<td>1.0</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

In long duration ASC tests, residual fault current could vary randomly over a wide range and exhibit sudden changes, while in other tests it was relatively steady. The reasons for fluctuations in soil current were not evident on the high speed video record. Some examples of long duration soil current tests are shown in Figure 37.

Figure 37: soil current in typical long duration ASC tests
The ground ignitions observed in GFN tests were those shown in Table 10. When the fault current was too low for the GFN to detect the fault, as in Test 180, the GFN was to all intents and purposes an ASC.
Table 10: GFN ground ignitions

<table>
<thead>
<tr>
<th>Test</th>
<th>Soil current (amps/metre)</th>
<th>Current duration (seconds)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.8</td>
<td>2.0</td>
<td>GFN did not detect fault, i.e. acted as an ASC</td>
</tr>
<tr>
<td>209</td>
<td>2.5</td>
<td>1.0</td>
<td>GFN fault-confirmation test did not succeed in identifying faulted feeder – RCC switched off, fault was re-detected and RCC switched back on in 1.0 second</td>
</tr>
<tr>
<td>210</td>
<td>2.25</td>
<td>1.0</td>
<td>GFN fault-confirmation test did not succeed in identifying faulted feeder – RCC switched off, fault was re-detected and RCC switched back on in 1.0 second</td>
</tr>
</tbody>
</table>

The sequence of GFN actions in Test 210 and the consequences for conductor voltage are shown in Figure 38. Ground ignition did not appear to be started by the fault-confirmation test, but by the failure of the admittance measurement to clearly identify the faulted feeder. When the RCC was switched off for one second, the conductor voltage increased to around 5,000 volts causing 0.9 amps of soil current to flow (see Figure 39) and ignite the fuel near the conductor.

Figure 38: Test 210 - GFN actions and conductor voltage profile
As in the case of GFN bounce ignitions, it is clear that if the fault-confirmation and admittance measurement (faulted feeder identification) algorithms were improved, GFN ground ignitions could be avoided.

The opportunity for similar improvement in the case of the ASC is much less certain, though the principles are the same. It is hard to see what could be done with an ASC to reduce residual current in any particular fault below the natural level set by the fault current, the ASC and the network parameters. The duration of the residual current flow might be shortened if the ancillary relays used with the ASC perform at near-ideal levels.
4.7 Finding 7: Though both REFCL variants reduce fire risk, GFNs offer superior fire risk reduction benefits compared to ASCs

Whilst tests proved conclusively that REFCLs of either variety can reduce fire risk compared to traditional non-REFCL network protection, for reasons outlined below it was a major challenge to rigorously compare the fire risk performance of the two variants (ASCs and GFNs). It was not possible to perform identical head-to-head comparative tests, so assessment had to rely on extrapolation and interpretation of a limited number of tests of each type. Overall, this assessment concluded that today’s GFNs product is superior to ASCs in reducing fire risk, though its advantage cannot be easily quantified.

4.7.1 Rationale

Today’s ASCs and GFNs both reduce bounce ignition probability. Tests showed about equal performance in this respect - a reduction of perhaps the order of 50 per cent. However, it is known the GFN bounce ignition tests did not reflect the performance of today’s GFN product but rather the older product in place at Frankston South. If allowance is made for the faster RCC action of today’s GFN product, it can reasonably be concluded that today’s GFN reduces bounce ignition probability more than does an ASC.

A bigger challenge was to assess the differences between them in their prevention of ground ignitions after a fallen conductor has come to rest – a simple comparison of residual current levels will not suffice, though that is part of the answer. To ensure a level playing field for comparative assessment, each of these two REFCL variants can be assessed against a common (idealised) performance standard, e.g.:

1. The system must successfully detect the fault.
2. If the fault proves transient, i.e. is not sustained, the system has to confirm this is the case and restore the network to normal operation, all within 20 seconds.
3. If the fault is sustained, the system has to confirm this, identify and trip the feeder on which the fault is located and restore the rest of the network to normal operation, all within 20 seconds.
4. All the above must be successfully achieved without residual current causing a ground ignition.

Performance of these tasks is managed by digital logic that is packaged differently in the two products. The GFN contains all the measurement infrastructure, decision making algorithms, control logic and coil tuning functions in the one integrated system. A typical ASC installation is quite different: the coil is procured from one supplier, its digital tuning controller from another, and its fault detection algorithms and feeder tripping logic from another (which may be the same as the supplier of the tuning controller).

In the test program, ASC performance was simulated by disabling the GFN’s RCC capability. This meant the following considerations applied to the interpretation of ASC test results:

- **Coil tuning**: Many ASCs use moveable iron ‘slugs’ to adjust an internal air gap to tune the coil to the network. They use a motor to do this and tuning is done a few times per day. Tuning in the GFN coil uses switched capacitors and the core has no air gaps or moving parts. GFNs tune themselves to the network much more frequently than ASCs. The ASC’s variable air gap method achieves fully accurate tuning, whereas the GFN tunes to within the smallest capacitance step available to it which can be equivalent to four or five amps of residual current.
- **Fault detection**: It was assumed fault detection by GFN internal algorithms is similar to fault detection by separate relays in ASC installations. Detection by monitoring neutral voltage is a relatively standard approach across the REFCL industry, so this seems a reasonable assumption.
- **ASC fault confirmation**: The earth fault protection systems usually installed with an ASC check for the persistence of neutral voltage displacement as evidence of a sustained fault. Again, this appears reasonable. Unlike the GFN, the ASC relies solely on the natural effect of the resonant
Petersen coil to clear the 80 per cent or more of faults that are transient in nature, i.e. the neutral voltage displacement increases and causes the voltage on the faulted conductor to collapse so arcs in the fault path self-extinguish. Once fault current has disappeared, the ASC’s neutral voltage displacement naturally returns to its low standing level without further action. If the ASC neutral voltage displacement does not collapse, this means significant fault current is still present and the fault must be treated as a sustained earth fault.

- **Feeder tripping:** The duration of sustained neutral displacement that will cause tripping of a feeder by ASC-based protection is set by the network owner. As there are no ASC installations in Australia, local knowledge on the best approach to this setting is limited. This duration may be shorter than the time used for admittance measurement by the GFN to confirm the fault and find the faulted feeder. Given that the decay time constant of neutral voltage collapse when fault current is removed (as seen in many tests – for example Figure 44) may be of the order of 0.5-1.0 seconds, a prudent ‘time to trip’ setting is not likely to be less than one and a half to two seconds, given that a premature decision based on still-changing network measurements may lead to risk of unnecessary and possibly major interruption of customer supplies. On balance, persistence of neutral displacement of two seconds before an ASC trips a feeder would appear to be a conservative assumption for fire risk performance purposes.

Based on these assumptions, an ASC and a GFN will both clear a transient earth fault in a similar way, though most transient fault events that might cause fires in today’s non-REFCL networks would be unlikely to do so in a REFCL-protected network. A ‘wire on ground’ earth fault is not a transient fault and the primary difference between the GFN and the ASC that is most relevant to ground ignitions is:

1. The ASC reduces fault current to a low but non-zero level for a period unlikely to be less than two seconds before tripping the faulted feeder
2. The GFN uses RCC compensation to effectively reduce the fault current to zero which eliminates fire risk from the initial fault event. However after four to five seconds, it applies its fault-confirmation test which necessarily causes some fault current to flow if the fault is sustained. This reintroduces fire risk. In the extreme (if the GFN cannot detect the ‘wire on ground’ fault is still present) it will switch off the RCC – which simply produces the same level of fault current as an ASC until the fault is re-detected and RCC compensation reapplied. Fault re-detection would normally happen in less than one second.

In summary, it is hard to envisage how the ground ignition performance of a GFN could be worse than that of an ASC. In the worst case (the GFN cannot detect the ‘wire on ground’ fault and it switches off the RCC) it may not be much better. For those faults it can re-detect, it is likely to prevent ground ignitions that the ASC cannot.

If the GFN fault-confirmation test (without starting a fire) successfully detects that the fault is still present and successfully identifies which feeder it is on and the GFN trips that feeder, then GFN fire performance would be better than ASC fire performance. The probability of this successful outcome was not able to be measured with confidence in the test program. GFN performance in this function is currently under active development by the manufacturer. Success in this endeavour may depend upon further field tests as most laboratory tests do not address the issue of non-linear conductor-soil resistance that creates the main challenge.

### 4.7.2 Evidence

The overall observations of the effect of REFCL variants on the factors that give rise to ignition are summarised in Table 11.
<table>
<thead>
<tr>
<th>Ignition factor</th>
<th>ASC effect</th>
<th>GFN effect</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bounce arc energy</td>
<td>Reduces</td>
<td>Reduces</td>
<td>Visible reduction in arc energy observed in high speed video records of tests compared to NER tests. Shorter, straighter arcs mean less arc voltage and hence less arc energy. Fulgurite formation is very rare (only one unexplained anomalous instance recorded).</td>
</tr>
<tr>
<td>Bounce arc duration</td>
<td>50 per cent reduction</td>
<td>&gt;50 per cent reduction</td>
<td>Earlier arc extinction was observed in high speed video records of tests compared to NER tests. GFN tests were conservative as RCC response was delayed by up to 65 milliseconds – this delay has been remedied in the current GFN product.</td>
</tr>
<tr>
<td>Residual current</td>
<td>Reduces</td>
<td>Eliminates</td>
<td>Residual current in ASC tests was consistent with theory – less than five amps could be expected on FSH network, assuming a balanced network and perfect coil tuning. Spread over metres of fallen conductor, this may be lower than the level required for ignition. In GFN tests, RCC response reduced conductor voltage to levels where soil current no longer flowed at all. This was despite the GFN being out of calibration for many tests and residual conductor voltage reaching 1,100 volts. After the GFN’s RCC was calibrated, residual conductor voltage was less than 250 volts and soil current was again zero.</td>
</tr>
<tr>
<td>Residual current</td>
<td>Set by SEF relay</td>
<td>Set by fault-confirm test and feeder identification</td>
<td>Specific data on ASC practice and associated SEF relays was not available, but design considerations indicate perhaps two seconds of residual current must be allowed to flow before the faulted feeder can be confidently identified and tripped. A GFN can maintain compensation indefinitely if risk from second faults is tolerated. Policy in Australia at least for the medium term is likely to limit compensation duration to minutes or less. FSH maximum compensation duration is currently set to about five seconds.</td>
</tr>
<tr>
<td>Fault confirmation test</td>
<td>Not applicable</td>
<td>Adjustable</td>
<td>The GFN fault-confirmation test is under active development. GFN admittance measurement processes de-tune the coil by about four to five amps and this was observed to cause ignition in some tests (which would also have caused ignition if they were ASC tests). If admittance measurement did not successfully identify the faulted feeder, the RCC switched off – this also led to ignition in some tests. The manufacturer is addressing these issues and performance improvement is likely if the market demands it.</td>
</tr>
</tbody>
</table>
4.7.3 Limitations of ASC ignition tests

Unlike the NER-based and GFN-based protection technologies, an ASC relies on the fault current itself to collapse the voltage on the faulted phase. In effect, it inserts a passive high impedance element into the fault current path to reduce the fault current. This means for a test result to be a valid indication of ASC performance, the test fault current must equal the fault current in the real network fault. This was not practically feasible in this test program, so ASC ignition test results must be interpreted with care and in the light of supporting theoretical calculations.

Neither of the arrangements which increased the test fault current above the test soil current provided a way around this limitation:

Many ignition tests were carried out with 12.5 metres of conductor lying on soil as a second ‘sandpit’ current path in parallel with the soil bed current. In ASC tests, the 2.5 amp current drawn by this path had a significant influence on the residual voltage available to drive ground ignition – ‘bolted’ fault tests indicate this level of fault current was sufficient to reduce the voltage on the faulted phase by 40 to 50 per cent.

The influence of the 2.5 amp ‘sandpit’ current on ignition was not material in NER or GFN tests:

- In NER tests, the ‘sandpit’ current would have only reduced the voltage on the conductor by 20 volts, i.e. less than 0.2 per cent, so it would have had no measurable effect on soil current or ignition probability.
- In GFN tests, the ‘sandpit’ current was enough to ensure the GFN detected the fault and engaged the residual current compensator. As the RCC reduced the voltage on the conductor to a very low level (typically 200-400 volts, i.e. less than three per cent of normal), both the ‘sandpit’ current and the soil current virtually disappeared.

Only in three circumstances was the ‘sandpit’ current a significant determinant of the residual voltage that can cause ground ignition:

1. ASC ignition tests
2. GFN ignition tests during any period with the RCC switched off, e.g. during the original ‘hard’ version of the fault-confirmation test when the GFN acts as an ASC during measurements to find the faulted feeder
3. GFN tests in which the GFN did not detect the fault, i.e. so the RCC was not used and the GFN acted as an ASC.

This dependence of conductor voltage on fault current invalidates the assumption used to relate particular test results to worst case network faults. The soil current varied widely from soil bed to soil bed (caused by variations in soil moisture content), whereas ‘sandpit’ moisture content did not vary from test to test and the ‘sandpit’s equivalent fault resistance was constant at a value close to 5,000 ohms or 2.5 amps at nominal voltage.

Whilst the approach used for NER and GFN tests is not valid for ASC tests, in theory each ASC ignition test can be considered equivalent to a single specific ‘wire on ground’ fault. The simplest approach is to reinterpret the 12.5 metre length of conductor lying on the sandpit soil as a different length of conductor lying on soil with the same lineal soil current density as the test rig soil bed in the test. However, even this simple method failed due to wide variations the test soil current during ground ignition phase of the test (see Figure 37). This failure again reinforces the challenge of applying approaches based on linear conductor-soil resistance to real ‘wire on ground’ faults.
4.7.4 Typical ASC protection systems were not tested

The ‘raw’ performance of an ASC was tested by suppressing the operation of the residual current compensation on the Frankston South GFN, i.e. the coil tuning and protection technology normally included in an ASC installation was not available to be tested. This technology employs different products but is similar in function to digital algorithms embedded in the GFN product. Any differential fire risk benefit of ASC systems compared to the same functions in the GFN was not able to be assessed, though there are grounds to argue they would be broadly equivalent.

In summary, the ASC ignition test results are potentially useful but require a more complex analysis before the results of any particular test can be reliably related to a real fault on an ASC-protected network.
4.8 Finding 8: REFCL designs can be improved to further reduce fire risk

The test program identified those aspects of REFCL performance that are critical to fire risk and revealed some clear opportunities for improvement in REFCL design, especially GFN design.

4.8.1 Rationale

The test program confirmed that in REFCL-protected networks, fire risk will depend on two aspects of REFCL performance:

1. Fast accurate compensation of residual conductor voltage to reduce fault current to a level below that required to start a fire.
2. Fast reliable identification of a sustained fault and the feeder on which it exists without drawing sufficient fault current to start a fire.

If REFCL performance in these two respects were perfect, no fire risk would exist in ‘wire on ground’ powerline faults – the fallen conductor would not inject enough current into the ground to start a fire and the feeder to which it belongs can be tripped to isolate the fault from the network.

The test program defined some specific levels of performance required to achieve this ideal outcome:

1. Measurements to confirm the presence of a sustained fault and identify the feeder on which it exists should create a fault current of not more than 0.15 amps per metre of fallen conductor in the presence of realistic non-linear resistance at the conductor-soil interface.
2. Compensation should start within 20 milliseconds of detection of the fault and reach a level within a further 20 milliseconds sufficient to reduce fault current to less than 0.15 amps per metre of fallen conductor.

Tests indicated that fire risk may be reduced to negligible levels even if REFCL performance approaches these very demanding standards without quite meeting them. Specifically, there may be some room for trade-offs. For example, fault current somewhat above 0.15 amps per metre of fallen conductor may be tolerated for short periods, though these are likely to be much briefer than the one second measurement period currently used in some products. Similarly, it is not essential to reduce fault current to below 0.15 amps per metre within 40 milliseconds, so long as the current is reduced sufficiently to cause arcs longer than about 50 millimetres to self-extinguish.

4.8.2 Evidence

Key evidence provided by the test program on the performance standards required to avoid ignition is provided in Figure 32 (bounce ignition – see page 59) and Figure 9 (ground ignition – see page 24).

Most of the investigation of possible REFCL performance improvements was focused on the GFN product since this was the REFCL used in the test program. Similar considerations could be applied to the ASC and its ancillary earth fault relays and coil controller systems, but this was beyond the scope of the test program.

Consideration of GFN fire risk performance identified the following four opportunities for improvement:

1. Increased fault detection sensitivity with increased tolerance for network imbalance
2. Faster RCC response
3. More accurate RCC response
4. Fast reliable fault-confirmation and identification of the faulted-feeder

Each of these is covered in more detail below.
4.8.3 Increased sensitivity with improved tolerance for standing network imbalance

In the comparative fire risk assessment set out earlier in this report, the assumed worst case condition for ground ignition was 40 metres of conductor lying on the ground. This was reasonable and convenient for the purpose, but the reality is that the diversity and variety of earth faults on electricity networks cannot be fully encompassed by such an assumption. It is necessary to consider the widest possible range of earth faults when developing strategy for fire risk reduction.

Figure 40 shows the ignition threshold for ground ignitions as revealed by test results and reexpressed in terms of fault current and length of fallen conductor. The challenge is to minimise the range of fault geometries that can result in ignition from an undetectable fault. It can be seen that if network protection can detect faults at lower current levels, a greater proportion of the possible range of earth fault geometries can be detected.

Current SEF protection may be able to reliably detect faults that draw five amps of current. This means that a fault that draws four amps will not be detected. If this four amp fault involves more than 30 metres of conductor lying on the ground, ignition will not occur. However, if the four amps current is drawn by less than 30 metres of conductor lying on the ground, ignition is likely. If the detection threshold is lowered to the current REFCL practice of two amps fault current, the critical length of conductor on the ground is 12 metres. If the GFN is improved to be able to detect faults that draw only half an amp, the critical length of conductor is only 3.3 metres.

From this logic, it can be seen that more sensitive detection enables intervention to prevent fires in a wider range of possible earth fault geometries.

Figure 40: ignition threshold for ‘wire on ground’ faults

The same logic applies to other realistic fault types such as ‘wire into vegetation’ faults that typically draw fault currents from a relatively short length of conductor.

Increased fault detection sensitivity would also speed up GFN response to a fault. The delay in fault detection and initial response is the time taken for the neutral displacement voltage to reach the detection threshold. At lower levels of fault current the rise of the neutral voltage can be slow and fault detection can take nearly a second (see Figure 23 on page 48). Reduction of the fault detection threshold means the neutral voltage reaches it earlier and the GFN responds more quickly to the fault. This is illustrated by the test data shown in Table 12 which indicates increased detection sensitivity can cut detection time for low current faults by almost half.
Table 12: ‘time to detect’ low current faults

<table>
<thead>
<tr>
<th>Test</th>
<th>GFN detection threshold (%) of nominal voltage</th>
<th>Fault current (amps)</th>
<th>Time to detect (milliseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>30 per cent</td>
<td>2.0</td>
<td>550</td>
</tr>
<tr>
<td>164</td>
<td>20 per cent</td>
<td>2.0</td>
<td>290</td>
</tr>
</tbody>
</table>

The current GFN design faces a number of barriers to higher fault detection sensitivity. The criterion for fault detection (usually a threshold level of neutral voltage displacement) must be set high to avoid false positives that might be caused by a variety of disturbances in network conditions:

- Weather induced fluctuations in network capacitive imbalance
- Weather induced fluctuations in network damping (resistive) current
- Disturbances generated by the GFN itself in coil tuning and other processes
- Changes in network parameters during network switching.

These fall into two categories, each of which might be addressed by design improvements to achieve greater fault detection sensitivity:

1. **Environmental changes**: these are changes in network characteristics due to e.g. changes in weather. Capacitive imbalance and network damping fall into this category. Fluctuations due to weather occur continuously but are usually not sudden discontinuities, taking place over a period of ten seconds or more - sometimes hours or days. An adaptive detection algorithm can continuously adjust its baseline and distinguish between sudden changes caused by a fault and slower changes caused by weather. An improved adaptive fault detection algorithm which works by detecting and analysing sudden changes to the status quo rather than departures from an ideal (balanced, unchanging) network might enable greatly increased sensitivity.

2. **Network operations**: Changes in network conditions caused by the GFN itself or network operators. GFN coil tuning processes and network switching operations are both in this category. These events are known in advance, i.e. they can be predicted, and so any fault detection algorithm can allow for them if it is alerted before they occur. If required, the GFN can be temporarily desensitised while these changes take place and then recalculate its baseline and go back to full fault detection sensitivity when they are completed.

The enhanced fault detection sensitivity may only be required on days of extreme fire risk so any risk of ‘false positive’ detections might be tolerated in the interests of overall risk minimisation.

Of particular interest to owners of Victoria’s remote rural networks is increased tolerance for standing network imbalance. Networks in sparsely populated areas of Victoria have very long two-wire spurs connected to three-wire feeders and balancing the network to equalise the capacitance between each of the three phases and earth can be very difficult or impossible. An adaptive fault detection algorithm may have the potential to ease this challenge. It is of note that dissymmetry on the Frankston South network has been virtually constant for four years.

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2 This has not been observed on the Frankston South network, though it has been reported by one New Zealand utility.
4.8.4 Faster residual compensation

Examination of high speed video records of ignition tests indicates that most REFCL bounce ignitions are marginal, i.e. the arcs only just manage to create a small flame before they self-extinguish. This led test observers to conclude that even a small increase in speed of RCC response might entirely eliminate bounce fire risk in GFN-protected networks. In fact, in all the GFN bounce ignitions, the RCC response was delayed beyond the current product specification of 60 milliseconds. This delay was temporarily remedied for some later tests, but the improved GFN performance could not be tested for bounce ignition.

Once the RCC is activated, it starts to have effect immediately and reaches full effect after about 25 milliseconds to reduce the voltage on the fallen wire to a level close to zero. This period can be shortened by using a higher rated inverter to enable the RCC to inject a higher current into the ASC. However, even if the inverter rating was doubled, this would only reduce response time by ten milliseconds. A more effective improvement would be to speed up initiation of RCC action, i.e. shorten the 60 milliseconds in the current specification.

The total 85 milliseconds to achieve full RCC compensation with today’s GFN design is too long to prevent bounce ignitions when fault current is high. Test results indicate that bounce ignitions did not occur if conductor-soil arcs were extinguished within 45 milliseconds of initial conductor contact, i.e. shaving 4 milliseconds off the RCC activation time might entirely prevent bounce ignition in GFN-protected networks.

It was clear from tests that a significant portion of the 60 milliseconds RCC activation time was the operating time of the electromechanical contactor that connects the RCC inverter to the ASC coil. There would appear to be clear potential to use a solid state device for this purpose and eliminate this delay. The achievement of fast RCC compensation to eliminate bounce ignition risk appears feasible. It may require changes to control algorithms and to RCC hardware (to replace the electromechanical contactor).

4.8.5 Automated RCC tuning

To achieve minimum residual fault current, the RCC must be calibrated to match current network voltage levels so that when compensation is applied it cancels the initial conductor voltage accurately. At the start of the test program this requirement was not recognised and in early tests with the RCC un-calibrated, compensation was inaccurate with residual conductor voltages in some GFN tests exceeding 1,000 volts. After RCC calibration was performed (just prior to Test 181), residual conductor voltage levels dropped below 500 volts and in some tests were as low as 200 volts with today’s GFN product. The RCC calibration procedure is partly automated. However, it still requires manual initiation and operator acceptance of the results.

The test program confirmed that following network changes, e.g. when a feeder is tripped or part of a feeder transferred to another zone substation, the RCC must be recalibrated if residual voltage levels are to remain as low as possible on succeeding faults. The GFN includes a fully automated ASC tuning process that automatically re-tunes the coil whenever a network change is detected. A similar fully automated procedure to recalibrate the RCC after network changes would ensure residual fault currents in high fire risk conditions remain as low as possible in a dynamically changing network environment. This would minimise the risk of ground ignitions.

It would be important that any automated re-calibration process cater for standing imbalance in the network. The RCC action must cancel all the voltage on the faulted conductor, including that due to the network’s standing level of capacitive imbalance.
If a ‘wire on ground’ powerline fault occurs and bounce ignition has not occurred, the conductor remains lying on the ground with RCC compensation reducing its voltage to a low level, i.e. no ground ignition is likely. This is a good result but the situation is not sustainable. At some point (within seconds or minutes) the continued presence of the fault must be tested and if confirmed, the feeder on which it is located identified and tripped so the network and its REFCL can be restored to normal operation before another fault occurs.

Until recently, the GFN design took some seconds to carry out the required tests and in the process switched off the RCC compensation. This created obvious ground ignition risk (which was confirmed by records of ignitions in some tests). In 2014, a new algorithm became available which used a ‘gentle’ approach to the fault-confirmation test. In this algorithm, the compensation was varied by small amounts, rather than completely switched off. Both algorithms were tested in this program.

It was confirmed the older ‘hard’ fault-confirmation test causes ground ignitions. The switch-off of the RCC compensation for some seconds (generally not less than one second for high impedance faults) can generate sufficient fault current to cause ground ignition.

It was confirmed the newer ‘soft’ fault-confirmation test which included multiple one-second periods of smaller changes to the RCC compensation could avoid ground ignition. However as currently configured, it occasionally did not succeed in detecting the continuing presence of the fault. Also, the level of discrimination in its identification of the faulted feeder was less than required for high-confidence feeder tripping to allow the healthy portions of the network to return to normal operation.

The tests revealed that at least part of the challenge faced by the fault-confirmation and faulted feeder identification algorithms arises from the highly non-linear characteristics of the conductor-soil contact. On occasion, high standing conductor voltages were insufficient to do more than create bursts of small very high frequency current pulses with virtually no 50Hz fault current at all. This is vividly illustrated in Figure 17 on page 41. The GFN needs some 50Hz fault current to flow so the necessary measurements can be accurately taken to confirm the presence of the fault and identify the faulted feeder. The challenge is to get enough current to take the measurement but not so much that it starts a fire. To do this, the algorithm may need to incorporate feedback loops to control the fault current rather than control the compensation voltage that determines it.

Test observers tended to adopt a pragmatic standard along the lines of ‘if I can tell from visual inspection of the GFN voltage and current records that the fault is still there and which feeder it is on, then it is a realistic expectation that the GFN algorithm can do the same’. This criterion would indicate that reliable fault-confirmation and feeder-identification should be available with further GFN algorithm development.

The new ‘gentle’ fault confirmation test is a worthy first step towards use of the RCC as a fault current controller rather than as a compensation voltage controller. Test observers were heartened by the fine control available in the new algorithm and have expectations that a solution will be found to the challenge through further product development.
4.9 Finding 9: REFCLs offer benefits to public safety

Fallen powerlines create public safety risks in a variety of ways: they can generate dangerous 'touch' potentials by electrifying vehicles, fences and other metallic structures near people; they can generate dangerous 'step' potentials in the ground around the fallen conductor; they can be inadvertently touched or picked up by people.

National Coronial records reveal that about 30-40 people die from electrocution in Australia each year. Most electrocution deaths occur at low voltage levels (less than 600 volts) away from the high voltage network - generally at work or at home. Low voltage electricity often kills people by paralysis of the diaphragm or fibrillation of the heart – both of which are potentially reversible conditions that can be successfully treated by immediate first aid.

Electrocution from high voltage electricity is rarer and usually much more severe. It often causes irreversible damage: skin and internal tissue burns that are very difficult to treat.

REFCLs can quickly reduce the voltage on a fallen high voltage conductor to levels where only low voltage electrocution risk remains. In some cases, the voltage is reduced to levels where almost no electrocution risk remains. Many countries have adopted REFCLs for this reason alone regardless of other benefits.

4.9.1 Rationale

A fallen powerline conductor on one of Victoria’s regional rural 22kV networks with traditional non-REFCL protection will continue to be fed with electricity at 12,700 volts with respect to earth until disconnected. How this happens depends on the level of current flow:

- If the fault current exceeds about nine amps but is less than 120 amps (where it would be detected by fast over-current protection), disconnection will take between 500 milliseconds and 3.0 seconds depending on the location of the fault in the network. After this initial disconnection, power may be reconnected a number of times for periods up to a few seconds each time to see if the fault is transient or if it is sustained.
- If the fault is below nine amps, the protection system may not detect it and the fallen conductor will remain live at high voltage indefinitely, i.e. until disconnected by a network operator, usually in response to a phone call from emergency services personnel.

If the network were protected by a REFCL instead of an NER, the voltage on the fallen conductor would be very quickly reduced. If the REFCL is an ASC, the magnitude of the reduction will depend on the fault current level. If the REFCL is a GFN, any fault that draws more than two amps will be detected and the RCC will reduce the voltage on the fallen conductor to levels less than 250 volts within 100 milliseconds of this detection. In the next ten seconds, the voltage may temporarily increase again for a few seconds during fault-confirmation and faulted feeder identification tests.

If the voltage on the fallen conductor is reduced below 600 volts the nature of the electrocution risk changes and its severity reduces dramatically. Skin and tissue burns characteristic of high voltage electrocution are much less likely. Further, current can be blocked or greatly reduced by shoes, clothing and skin, because the voltage is no longer high enough to puncture these barriers.

4.9.2 Evidence

Electrocution of human beings has been widely studied for over a century and the risks, injury mechanisms and protection principles are well understood, though the detail of each individual case is still unique.

Serious injury (paralysis of diaphragm or heart) from low voltage electrocution is often reversible and death can be avoided if treatment (CPR) is provided quickly. Such injuries depend on the level of
current and the time it flows through the body. The risk is well documented in IEC publication 60479-1 (updated in 2005) which defines risk from ‘left hand to foot’ current flow. This risk is illustrated in Figure 41.

Figure 41: IEC ‘left hand to foot’ electrocution risk chart

In Figure 41, the following zones have been defined by the IEC for different levels of electric current through a human body:

- AC-1 zone: Imperceptible
- AC-2 zone: Perceptible
- AC-3 zone: Reversible effects: muscular contraction
- AC-4 zone: Possibility of irreversible effects
  - AC-4-1 zone: Up to 5 per cent probability of heart fibrillation
  - AC-4-2 zone: Up to 50 per cent probability of heart fibrillation
  - AC-4-3 zone: More than 50 per cent probability of heart fibrillation

The level of current through the human body in an electrocution event is equal to the applied voltage difference across the body divided by the point-to-point resistance of the body. Many authoritative sources publish data on this resistance, e.g. IEC, US National Institute of Occupational Safety and Health, etc. Some typical data is shown in Table 13. It can be seen that, for low voltage electrocution (voltages less than 600 volts) dry skin provides a natural barrier to current flow. Internal tissue offers low resistance paths due to the presence of ionic salts in body fluids such as blood.

Table 13: resistance values relevant to low voltage electrocution

<table>
<thead>
<tr>
<th>Path or barrier</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry body</td>
<td>100,000 ohms</td>
</tr>
<tr>
<td>Wet body</td>
<td>1,000 ohms</td>
</tr>
<tr>
<td>Hand to foot (internal path)</td>
<td>400 - 600 ohms</td>
</tr>
</tbody>
</table>

The voltage that can cause electrocution when a conductor falls is the ‘step and touch’ potential. This is the voltage difference a human can experience near a fallen conductor, either between their
two feet or between a foot and a hand when they touch for example a car (or even a wet tree) that has the fallen conductor resting on it. The accepted rule of thumb is that more than 70 per cent of the total voltage on the conductor appears in the step potential across the first metre of distance from it.

From Table 13, it can be seen that with dry skin, a voltage of less than 600 volts on a fallen conductor would be unlikely to produce more than six milliamps, i.e. it would be perceptible and may be painful if it lasts longer than a second or so, but would be unlikely to result in irreversible injury.

The above calculation does not apply to high voltage electrocution. Contact with high voltage can overcome the insulation capacity of clothing and footwear. It can destroy skin cells and break down the skin’s ability to resist current. As a result, high voltage can establish current paths across and through the skin and through lower-resistance internal tissues leading to serious internal and external burns that can be extremely difficult to treat. Death results more often in cases of high voltage electrocution than in cases of low voltage electrocution.

This test program confirmed REFCL manufacturers’ claims and statements from overseas utilities that a REFCL can quickly collapse the voltage on a fallen conductor to a level where the only remaining safety risk is low voltage electrocution. However, the two REFCL variants produce public safety benefits to different degrees.

4.9.3 Public safety benefits of a GFN

Provided the RCC was properly calibrated, GFN tests showed the residual conductor voltage was reduced to about 200-250 volts within about 100 milliseconds of fault detection. At lower fault current levels, the residual conductor voltage was slightly higher at around 400-500 volts, which is still in the low voltage range. Figure 42 shows a residual voltage of 430 volts in a fault that draws a peak current of only three amps on the first bounce, i.e. a fault that would not be detected by non-REFCL network protection.

Figure 42: Test 195 - conductor voltage reduction by GFN for a three amp fault
After the initial voltage collapse produced by the GFN, the only remaining risk period is when the GFN tests for a sustained fault. This happens a few seconds after the initial fault and during the one-second period of the test, the conductor voltage may rise in the worst case as high as if an ASC were in place of the GFN. This can be seen in Figure 42 where the conductor voltage rises first to 1,400 volts for one second and then to 6,700 volts for one second (a similar value to that produced by the ASC) before decreasing again to around 400 volts when the GFN detects the fault is still present.

The GFN includes a facility to progressively tune the RCC if the fault is sustained. Network owners overseas report this can reduce conductor voltage to less than 100 volts within 20 seconds provided there is enough measureable current flow for the GFN to perform the required calculations. However, this test program did not extensively demonstrate the action of this facility, generally because there was often insufficient current flow to support its operation. Figure 42 shows possible evidence of its operation 19 seconds after the fault where the conductor voltage falls to 180 volts.

Most electrical safety authorities accept that public safety risk with fallen powerlines tends to occur more commonly after a period of at least ten seconds, not immediately. For example, it can often occur when occupants of a crashed vehicle attempt to extricate themselves from the wreckage or when people approach a fallen tree to remove it from the road not noticing the powerline it is entangled with. This is the basis of auto-reclose periods set to less than ten seconds in non-REFCL protection schemes. In this context, the removal of RCC compensation for one second to test if the fault is still present appears potentially acceptable provided it occurs in the first ten seconds.

4.9.4 Public safety benefits of an ASC

The residual voltage produced by an ASC depends on the fault current and will always be higher than that produced by a GFN, provided the fault current is sufficient for the GFN to detect the fault. Based on Tests 165 and 166, the network characteristics of the Frankston South network were calculated to derive parameters required to predict the residual voltage on a fallen conductor in the case of an ASC. The results are shown in Figure 43.

Figure 43: calculated residual voltage on fallen conductor on ASC-protected FSH network

Figure 43 is derived from mathematical calculations that assume the network is perfectly balanced. In reality, capacitive imbalance between the phases can increase the residual voltage and the level of residual voltage will depend on which phase is carrying the fault current. Typical levels of capacitive imbalance may increase the residual voltage produced by an ASC in a perfectly balanced network by tens or hundreds of volts.

With this caveat, Figure 43 shows that for an ASC to reduce the residual voltage on a fallen conductor on the FSH network to low voltage levels, a relatively low impedance fault would be required. For example a 100 amps fault would collapse the conductor voltage to 370 volts, while a
A ten amp fault would only collapse it to 2,940 volts. Some earth faults produce currents in excess of 100 amps and in such a case, the ASC could reduce the voltage on the fallen conductor to a level where public safety would be greatly enhanced.

Public safety benefits of an ASC for higher impedance faults would be more limited. If the fallen conductor came to rest on dry sandy soil, it is possible the fault impedance would be very high and the residual voltage produced by an ASC in such an incident would be closer to the nominal 12.7kV high voltage on the power line, i.e. risk of high voltage electrocution would still be present. An example of a four amp fault is shown in Figure 44. The conductor voltage falls to 4,845 volts in about one second – a level that would still present a high voltage electrocution risk to bystanders.

Figure 44: Tests 166 - conductor voltage reduction by ASC with a four amp fault

### 4.9.5 Overseas experience

Public safety has driven the adoption of REFCL technology in specific areas of two regions of the world: New Zealand and Scandinavia. Both contain areas of very high resistance soil or more accurately, thin layers of soil on top of deep layers of very high resistance rock or rock cobbles. REFCL technology has been proven to provide enhancement of public safety in these demanding conditions, where solidly earthed and NER-based approaches do not.
4.10 Finding 10: REFCLs offer benefits to supply reliability

Improvement of supply reliability is a primary driver of REFCL adoption around the world along with improvement of public safety. REFCLs are designed to allow transient earth faults (the majority of network faults) to be cleared without any need for supply interruptions. They also offer options to allow sustained earth faults to be managed with either none or at least much less interruption to supply than is required in solidly earthed and NER-protected networks.

4.10.1 Rationale

REFCLs can greatly reduce the number of supply outages experienced by customers compared to existing non-REFCL network protection approaches. This is because the design philosophy in REFCL protected networks does not require interruption to supply to extinguish electric arcs that carry fault current. Unless the fault cause is sustained (e.g. fallen conductor), earth fault arcs self-extinguish, removing the fault from the network with little or no damage and no requirement for a supply interruption.

The network protection philosophies of the two alternative design schemes are quite different.

4.10.2 Solidly earthed and NER-based network protection philosophy

Victoria’s electricity distribution networks have been built using a design philosophy that detects faults by the current they draw from the network. The current drawn by network earth faults can be high enough to destroy network equipment and pose a danger to anyone in the vicinity of the fault.

When fault current flow is detected, protection systems quickly interrupt supply to stop electric arcs and allow the fault to disappear. Many network faults take the form of an electric arc between a powerline conductor and an earthed structure. This arc may be established by a transient event such as a lighting strike or an animal/bird touch. However, the arc will continue as long as enough 'follow-through' current is there to sustain it. If this current is interrupted, even momentarily, the arc disappears and, provided the original cause is no longer present, it will not re-strike when power is restored.

After a few seconds, supply is automatically restored and if the fault is still present the cycle may repeat once or twice more before the power is left switched off. If this happens, part of the network remains off supply until the fault is located and repaired. Network protection systems, both centralised in zone substations and spread out along powerlines, have carefully coordinated settings to ensure the minimum possible number of customers is left off supply in such a case. More recently, remote control and automation of network switches can further reduce the extent of the supply outage required to remove a sustained fault.

The great majority of network faults are earth faults and the great majority of these are transient in nature, so the approach used in Victoria (and in many other areas of the world) preserves reliability of supply at the cost of momentary interruptions while network protection systems act in a coordinated fashion to select which portion, if any, of the network must remain off supply.

4.10.3 REFCL-based network protection philosophy

REFCLs come from a very different design philosophy. REFCLs detect faults by the disturbance they cause in network voltages. The REFCL allows this voltage disturbance to be large enough that the voltage on the faulted conductor collapses to a very low level – too low for a transient fault to draw enough current to sustain itself, i.e. the arc will self-extinguish. IEC standards provide charts that indicate fault arcs will normally self-extinguish if the REFCL reduces the fault current below about 35 amps.
Once the fault disappears, network voltages return to normal levels. The GFN variant goes further and actively displaces the network voltages to the extent that very little (less than one amp) is drawn by the fault.

In a REFCL protected network, transient earth faults (the majority of faults) do not draw dangerous levels of current and do not require supply outages to remove the fault from the network.

Sustained earth faults are dealt with in two ways in REFCL protected networks:

1. The network protection can revert to a solidly earthed or NER-based protection approach so the various network protection schemes act in the usual coordinated way to ensure the minimum number of customers lose supply while the fault is found and repaired. This approach is commonly used by networks that have migrated to REFCL protection from NER protection. This approach is used at Frankston South.

2. The REFCL allows the network voltage to remain displaced without any supply interruption while line crews hunt for, locate and repair the fault. This approach is more common in networks that have always used REFCL protection. Most network owners put a time limit on ‘fault hunting’ and will interrupt supply if this limit is exceeded. Typical values of this time limit are one hour and three hours, though one NZ utility has reported it has left a sustained fault on the network for five hours before it was found. The decision on this time limit involves a trade-off between customer supply reliability and the risk of a second fault which the REFCL cannot manage.

4.10.4 Evidence

Appendix A: History of distribution network earthing practices documents the extent of REFCL adoption motivated by supply reliability benefits. This includes:

- Decades long adoption programs in France and Italy that commenced in the 1990s following the introduction of common supply reliability reporting standards (IEEE measures: SAIFI, SAIDI, CAIDI and MAIFI) across the EU.
- New Zealand utilities that are adopting REFCLs to solve supply reliability issues for particular industries with heightened sensitivity to supply interruptions, e.g. the dairy industry.
- Ireland which has decided to embark on a progressive changeover to REFCLs for both public safety and supply reliability reasons at the same time as upgrading its distribution networks from 10,000 volts to 20,000 volts.
- Other areas of the world including China, Russia, South America – though situations in those regions were not investigated to the same level of detail.

Discussions with overseas utilities confirmed that REFCL adoption was often triggered by the imposition of financial incentives on network owners to formally report and continuously improve their supply reliability performance.

United Energy reports it has had favourable supply reliability experience with the Frankston South GFN in service.

On the 11kV Orion network in New Zealand as early as 2007, Orion’s first GFN had already identified several high impedance faults, for example when a conductor came in contact with a cross arm on a wooden pole and when a tree branch touched a phase conductor. During a wind storm in Canterbury in October 2007 a tree branch broke an 11kV conductor and Orion was able to leave this fault safely in place for hours while other faults were fixed, all without losing supply to customers.

A study by Auckland University (Qixun, 2012) of the pilot GFN installation at North Power’s small rural 11kV Poroti substation showed that SAIDI reduced 62 per cent in the two-year period after installation compared to the two-year period prior to installation.
Similar studies have been published on European experience of reductions of SAIDI when REFCLs are installed. Reduction in the MAIFI index is particularly dramatic as auto-reclose is no longer used for transient earth faults.

The published experience of network owners worldwide confirms the supply reliability benefits of REFCLs.