8 Appendices

8.1 Appendix A: History of distribution network earthing practices

The history of earthing practices in distribution networks is a powerful aid to a sound understanding of the challenges to be faced in adoption of resonant earthing. This brief history has been compiled from a review of relevant technical literature and discussions with utility engineers with European experience, equipment manufacturers, and New Zealand utilities. Though brevity requires it to be incomplete in many details, the following broad outline of developments over the last 120 years can provide useful insights for those struggling with the complexity of the issues involved.

Before 1915

After a decade of feverish development[6], three phase alternating current was established globally as the basis of public electricity networks by 1890. In such networks, the neutral is the single point of connection of the three individual phase windings of the substation transformer. It is so named because it is the only conductor in the power system not compelled to any particular voltage by the needs of network operation. It is normally extended outside the transformer tank to allow the network owner to decide its treatment. Hence, most substation transformers have four connections on the 22kV side – three phases plus the neutral. Customer loads are connected between phases.

The neutral can be left isolated or it can be earthed via a variety of arrangements. The choice of whether and how to earth the network neutral largely determines network protection philosophy in two areas: earth faults and over-voltages.

Table 18: network earthing practices 1890-1915

Practice	Earthed Neutral	Isolated Neutral
Adoption	US, British Empire	Europe
Strength	All network voltages closely controlled – most network equipment can be rated to operate at phase-to-neutral voltage (13kV on 22kV networks), thus reducing costs. High earth fault currents allow easy fault detection using current sensing devices.	No current flows when earth fault occurs - earth fault arcs self-extinguish[7] and no supply interruption is necessary. Neutral voltage rise is a very sensitive indicator of earth faults and can detect high resistance faults.
Weakness	Supply interruption is the only way to extinguish arcs due to faults. Earth fault detection sensitivity is limited – cannot always detect high resistance faults. High earth fault currents can create safety and network damage risk. Earthing systems must be more robust to handle high currents and avoid dangerous earth potential rise.	Earth faults cause over-voltage on un-faulted phases – all network equipment must be rated for operation at full phase-to-phase voltage (22kV on 22kV networks), increasing costs and making this approach unsuitable for very high voltage (>220kV) networks where over-voltage control is critical. Only reduces fault current in single-phase-to-earth faults; other fault types still produce high currents. Fault current can be so low, some types of permanent fault are not easy to find.

In many of the earliest European networks built from 1890 to 1910, the neutral was left isolated, i.e. it was not connected to anything. In most of the then British Empire and in many areas of the US, it

[6] See http://www.edisontechcenter.org/AC-PowerHistory.html for coverage of 1880-90.

[7] 50Hz current goes briefly to zero every ten milliseconds. If the electric field along the arc path after a current zero (called the Transient Recovery Voltage) is insufficient to re-ionise the hot air, the arc will cease to exist.

was connected solidly to earth[8]. Though very different, these approaches were (and remain) two alternative ways of dealing with earth faults and over-voltages. National utilities in most countries had settled on one or the other by the early 1900s[9].

In the early 1900s as small isolated-neutral networks grew in size, it was clear that even with no connection to the neutral, earth fault current was not actually zero. The capacitance (i.e. the electric fields) between the un-faulted powerline wires and the ground constituted a second connection that, together with the fault, could create current flow. By 1915, some networks with isolated neutrals were getting so large that this capacitive current flow was sufficient to sustain a continuous electric arc, i.e. earth faults did not extinguish themselves[10]. A new approach was required.

From 1915 to 1990

In 1917, Waldemar Petersen of Germany proposed resonant earthing to solve this problem[11] and his solution was promptly adopted by many owners of isolated-neutral networks and by some owners of earthed-neutral networks[12]. He proposed the neutral be connected to earth through an inductor (a coil of wire wrapped around an iron core with some air gaps in the iron). If the inductance of this coil was selected for resonance[13] with the network line capacitance at the system frequency (50Hz):

- In normal operation very little current would flow in the coil – the network voltages are balanced and the capacitive currents to ground from each phase sum to zero.
- If an earth fault occurred, the capacitive current that had previously prevented arcs from self-extinguishing would be cancelled by equal and opposite current from the coil.

With resonant earthing, arc extinction without a supply interruption was re-established as a normal outcome of earth faults even for large European networks. Momentary earth faults continued to be cleared without any supply disturbance at all. Permanent earth faults could remain on the network until operator action isolated them, i.e. even some permanent earth faults did not necessitate a supply interruption. The Petersen Coil became a standard item in network design toolkits worldwide, both under that name and as the 'Arc Suppression Coil' (ASC).

The invention of the Petersen Coil took place in the midst of World War 1. Germany, Eastern Europe and Scandinavia subsequently adopted resonant earthing as a standard. It was also widely adopted around the world in specialised networks such as those in mines where safety (especially absence of electric arcs) was paramount. Some public utilities in the UK and US experimented with it, but most ignored it as they did not have any problem with their earthed-neutral approach. Their customers accepted supply outages as a natural consequence of earth faults. Once fast auto-reclose was

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[8] A. Newbould and K. Chapman, *Improving UK power quality with arc suppression coils*, IEE, 2001. The author considers it possible the neutral was earthed to provide enough fault current to drive induction-disk relays - the prevailing protection technology in England at the time.

[9] Connecting the neutral to earth through a resistor was a compromise approach. A low value resistor approached the British/US practice and a higher value resistor was aligned with the European approach.

[10] In a 22kV network, this can happen if the capacitive current exceeds about 35 amps. (see footnote 14)

[11] W Petersen, *Limitation of Earth Current and Suppression of Earth Fault Arcs by the Earthing Coil*, Elecktrotechnische Zeitschrift, June 1921.

[12] E M Hunter, *Some Engineering Features of Petersen Coils and Their Application*, AIEE, Jan 1938.

[13] A capacitance stores energy in an electric field, whereas an inductance stores energy in a magnetic field. If the two devices are connected in a circuit, they will have a natural resonance frequency at which energy is swapped back and forth between them at that frequency with minimal net current in the rest of the circuit.

introduced, the brief supply interruptions required to clear momentary earth faults presented few problems in what were then the main uses of electricity: heating, lighting and electric motors.

Over the following decades, both approaches evolved through progressive refinement:

Table 19: Evolution of network earthing practices after 1915

Resonant earthed neutral	Effectively earthed neutral
• Initial Petersen Coil was a fixed inductor – as networks grew and capacitance increased, the coil had to be replaced with a higher capacity one. • Coil fitted with tapped winding to allow off-line changes of inductance over a range to keep pace with network development without coil replacement. • European design standards[14] were developed to specify maximum earth fault current limits for arc self-extinction. • Parallel resistor placed across the coil provides additional fault current to assist in locating permanent faults while remaining below the arc self-extinction limit • Coil with motor-driven moving iron cores to vary inductance to maintain resonance tuning as network capacitance varied due to e.g. network switching. A digital controller maintained accurate tuning with an optional offset to provide defined fault current for fault location purposes. • Coils with banks of capacitors to allow effective inductance to be rapidly varied by switching of combinations of capacitors. • Digital controller with non-50Hz current injection to maintain accurate tuning in presence of harmonics and cross-talk interference from load current. • Digital earth fault relays to detect high resistance earth faults in the presence of other factors that varied neutral voltage.	• Initial earth fault protection was an over-current relay that tripped the feeder. • Fast auto-reclose control systems to restore supply after momentary faults have been cleared by a brief supply interruption. • Sensitive earth fault systems developed to interrupt supply to high resistance faults after a time delay. • Neutral earthing resistors (NERs) to limit earth fault currents on high capacity networks. • Network sectionalising schemes that use multi-shot reclose to identify and isolate the section of the network containing a permanent earth fault. • Earth fault protection systems dispersed along length of feeders (automatic circuit reclosers) • Smart grid systems that communicate with dispersed protection schemes.

By 1990, both approaches were facing new challenges as supply networks and industry regulation evolved. Resonant earthing challenges included:

- In the 50 years after World War II, as European cities established large underground cable networks, a known issue with the Petersen coil became increasingly present – the re-striking cable fault[15]. Some European cable networks adopted earthed-neutral approaches to manage this problem.
- Some governments started to mandate public safety standards for earth faults, e.g. the Swedish government mandated that high-resistance earth faults up to 20,000 ohms must be detected and earth faults up to 5,000 ohms must be effectively disconnected.
- A new limit on the size[16] of resonant-earthed networks started to emerge. Even with the Petersen coil, extremely large networks produce enough residual earth fault current to sustain

[14] Such as DIN standard VDE 0228-2 which gives limit curves for resistive and capacitive fault currents.

[15] A cable develops a fault (an internal electric arc between the cable core and the outer shield) which is extinguished by neutral voltage displacement in the normal way. However, it re-strikes because once the fault current disappears, the Petersen coil allows the cable to revert to normal voltage levels which leads to another flashover and a new arc at the fault site. Videos showing a cable fault re-striking every few seconds dramatically illustrate the problem.

[16] An example of this limit was the railway power supply network in the re-unified Germany, probably the largest integrated distribution network in the world.

an arc purely due to energy losses on the network and leakage current across the thousands of insulators on the un-faulted phases – this current cannot be cancelled by the Petersen coil because it is resistive, not capacitive[17].

The UK/US earthed-neutral approach also faced pressures:

- It could not match the performance of resonant earthing in assurance of public safety, especially in detection of very high resistance faults.
- Utilities world-wide were adopting common standards for reporting distribution network supply reliability performance[18], i.e. the superior reliability with resonant earthing was becoming visible to a wider audience and regulators were demanding continuous improvement in response to customers' unhappiness with momentary supply interruptions that disturb their new digital electronic equipment.

Both approaches were benefiting from the adoption of embedded digital 'intelligence' but the basic advantage of resonant earthing (it clears momentary earth faults without a momentary supply interruption) remained.

From 1990 to the present

In the early 1990s, Klaus Winter of Swedish Neutral developed the concept of active residual current compensation[19]. In this solution the fault current is minimised not only by the natural cancellation of network capacitive current by the coil's inductive current, but an additional current is injected into the neutral to cancel much of the residual current that persists[20].

Active residual current compensation promised solutions to all the strategic challenges then facing resonant earthing:

1. It can limit fault currents to extremely low values even in very high resistance faults. The system progressively adjusts its injected current to reduce voltage at the fault site to zero. It offers maximum fault detection sensitivity and maximum public safety for high resistance faults.
2. It can eliminate re-strike in cable faults. The system exhibits 'memory' and does not reset the network voltages to normal immediately the fault arc extinguishes. Hence it can provide high supply reliability on cable networks just as on overhead ones.
3. It can compensate any form of residual current, resistive as well as capacitive. It can even compensate harmonic currents. The limit on total network size can thus be overcome.

Within the EU community, the common performance reporting standards made it obvious that resonant earthing offered superior supply reliability over earthed neutral approaches. In the 1990s, both France[21] and Italy[22] formally adopted programs to introduce resonant earthing on their entire

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[17] The self-extinction limit is higher for resistive current: 60 amps in a 22kV network (VDE 0228-2).

[18] IEEE standard supply reliability indices include SAIDI: system average interruption duration indicator and SAIFI: system average interruption frequency indicator. Resonant earthing can make a dramatic difference especially in respect of the newer MAIFI measure (Momentary Average Interruption Frequency Indicator).

[19] Winter, K *The RCC Ground Fault Neutraliser A Novel Scheme for Fast Earth Fault Protection*, CIRED 2005.

[20] Initially, Swedish Neutral proposed residual current compensation using electromagnetic technology (Swedish patent No 637 096) via phase-shifting transformers, but it soon moved to a much more flexible and cost-effective compensation capability using power electronics when these became available.

[21] Karsenti L, Michel ODDI, *A New Generation of Directional Fault Indicators in the ERDF Network*, CIRED 2009.

[22] A. Cerretti, G. Di Lembo, and G. Valtorta, *Improvement in the continuity of supply due to a large introduction of Petersen coils in HV/MV substations*, CIRED 2005.

medium voltage public networks. More recently Ireland has done the same. At least one privatised UK utility[8] facing supply reliability regulatory challenges also opted for resonant earthing solutions.

Many utilities have elected to move to resonant earthing selectively to improve quality of supply only where circumstances warrant, i.e. each substation network is assessed on its merits[23]. Many use bypass switches to revert to an earthed-neutral arrangement for permanent faults after a set time delay[24], i.e. not all adopt the practice of leaving a permanent earth fault on the network until it can be located - a practice still sometimes used where high resistivity soil creates public safety risk.

Today

Resonant earthing now has an active presence in most areas of the world and its spread in mature economies continues to be driven by demands for improved quality of supply and enhanced public safety[25] (lower risk of electrocution from fallen lines). Reduction of fire risk is not yet a driver of resonant earthing adoption[26], though those who use it for other reasons freely state their confident expectation it would have clear benefits in this area.

The global resonant earthing market remains dominated by ASC installations, with local agents offering products from at least three manufacturers to network owners in Australia and New Zealand: Swedish Neutral, Czech company EGE, and Austrian company Trench (part of Siemens).

Swedish Neutral's GFN has established itself as a premium product for networks where public safety, network size and cable re-strike imperatives exist. Around 170 GFNs have been installed world-wide to date, some 30 of them in New Zealand[27].

In Victoria, one resonant earthing installation has been in service for five years, two more are on order for installation in 2014 and a third is currently subject to a tender process. No other Australian state yet has firm plans to adopt this technology, though many utilities both here and overseas are watching Victoria's Powerline Bushfire Safety REFCL research with great interest.

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[23] In New Zealand, areas of intensive dairy farming demand a very low level of momentary supply interruptions. To quote one utility engineer: "if the power goes off even briefly during milking, the cups can drop off 100 cows and the subsequent disinfection procedure and work required to resume milking doesn't make us look like the farmer's friend".

[24] At FSH, this time delay is five seconds. In France it is 700 milliseconds. In one UK utility it is 30 seconds.

[25] For example, in New Zealand there are now nearly 30 installations but only Orion has adopted a long term plan to introduce it across the majority of its network (for public safety reasons). Orion's territory includes the Canterbury Plains area which like some other areas of NZ has extremely high resistivity soil. Earth faults can cause large (and dangerous) voltage rises in the vicinity of the fault.

[26] Fire risk reduction has been mentioned (but not quantified) in one NZ business case where changing land use is leading to increased presence of pine plantations near powerlines.

[27] For perspective, Czech manufacturer EGE sells around 400 ASCs <u>per year</u> world-wide.

8.2 Appendix B: Operation of REFCLs[28]

A thorough understanding of how REFCLs operate in distribution networks is essential to identification and effective response to the challenges of REFCL adoption. One NZ utility estimates it takes about four years after first REFCL installation for engineering and operations staff to gain sufficient understanding to express enthusiasm for REFCL benefits – and that this culture change is a far greater challenge than the technical issues involved in REFCL adoption.

In some respects, resonant earthing makes little difference to the operation of distribution networks. In other respects, the differences are dramatic. It all depends what is happening on the network at the time:

Normal network operation

If there are no faults or transients on the network, there is little material difference between the operation of a network with resonant earthing and one without it. Technical operating procedures will be different and a small voltage will exist on the network neutral, but the network will function (deliver energy to customers) exactly the same as a traditional 'effectively earthed' one.

Response to network faults

Many different types of network faults occur in Victoria and the effect of resonant earthing varies greatly by the type of fault:

- It has little or no effect on three-phase faults.
- It has little or no effect on phase-to-phase faults.
- It has a limited effect on two-phase-to-earth faults.
- It has a dramatic effect on phase-to-earth faults[29].

Because of this variation, the overall effect of resonant earthing will depend on the mix of fault types that occur on the network. However, rigorous accurate evidence on the comparative frequency of different fault types is notoriously hard to obtain.

The predominance of earth faults on typical networks

Estimates[30] developed in 2011 indicate momentary earth faults comprise 50 per cent of all network faults that result in supply interruptions in rural Victoria. This is consistent with a globally accepted 'rule of thumb' that, averaged over all medium voltage networks world-wide, earth faults comprise about 65 per cent of all faults and on overhead networks, the great majority of earth faults are momentary. NZ utilities' analyses of experience on individual substation networks produced estimates of earth faults as high as 80 to 90 per cent of all faults, again the vast majority of them momentary.

All these estimates are consistent with anecdotal reports by network operations staff that the majority of network faults are earth faults (or at least start as earth faults before developing into

[28] The terms 'resonant earthing' (the technology) and REFCL (Rapid Earth Fault Current Limiter, the device) can be taken as synonymous and are used interchangeably throughout this document.

[29] Referred to throughout this document simply as 'earth faults'

[30] The estimates were developed by the Powerline Bushfire Safety Taskforce based on data from a 2010 national survey of network owners. See *National workshop on rural electricity network options to reduce bushfire risk*, April 2010 and *Powerline Bushfire Safety Taskforce Final Report*, September 2011, both available at www.esv.vic.gov.au.

other fault types) and the great majority of these are momentary, e.g. lightning strikes, tree branch touches, bird/possum touches, etc.

Sustained earth faults are much less frequent and tend to be a fallen conductor/pole or a fallen tree/structure/crane, etc. resting against a conductor.

It seems reasonable to adopt a working assumption that of all faults that cause supply outages (including momentary supply outages) on Victoria's rural networks:

- momentary earth faults make up about 50 to 70 per cent of the total number of all fault types; and
- sustained earth faults make up a further ten to 15 per cent.

Since resonant earthing has a dramatic effect on network response to earth faults, it may have the potential to have a dramatic effect on up to 85 per cent of all network faults.

REFCL operation when an earth fault occurs

When an earth fault occurs on a 22kV distribution network, the presence of resonant earthing results in a large neutral voltage displacement[31], i.e. the voltage[32] of the neutral connection of the zone substation transformer(s) increases from a low level (generally less than 1kV) to a value close to 13kV. As a consequence, the voltage on the faulted phase falls to a value close to zero and the voltage on each of the two un-faulted phases increases from 13kV to 22kV.

The time this takes depends on the severity of the fault (as represented by the notional fault resistance). When a 'heavy' fault (low resistance - line fallen on wet ground or earthed structure, internal short circuit in pole mounted transformer or surge diverter, etc.) occurs, the effect of resonant earthing is virtually immediate – within 50 milliseconds. If the fault is high resistance (dry tree branch touching line) the neutral voltage displacement can appear over time – a second or two in extreme cases – and be partial rather than the full 13kV.

The consequences of the neutral voltage displacement are:

- The current drawn by the earth fault is very low (typically less than 20 amps compared to up to 1600 amps in Victoria's non-REFCL network designs) as there is little voltage left on the faulted phase to drive current after the neutral voltage displacement takes effect.
- At the same time, the un-faulted phases of the network are exposed to over-voltage stress (22kV or 75 per cent greater than normal). This over-voltage stress on the two un-faulted phases creates the first and biggest technical challenge for Victoria's network owners – the risk of so-called 'cross-country' faults.

Different REFCL types

REFCLs come in two main types: ASCs (Arc Suppression Coils)[33] with no power electronic components and GFNs (Ground Fault Neutralisers)[34] with active residual current compensation using power electronics. Simplistically, a GFN can be thought of as comprising an ASC plus an RCC (Residual Current Compensator).

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[31] See Different REFCL types below

[32] The term 'voltage' in this document usually implies voltage with respect to ground.

[33] ASCs are manufactured by EGE (sold here by NZ company HV Power) and Siemens (since its acquisition of Trench) as well as by multiple Chinese companies. There are no ASCs installed on Australian public networks.

[34] The GFN is a single product family manufactured by Swedish Neutral and sold in Australia by Connetics, a subsidiary of NZ utility Orion. The only GFN in Australia is installed at Frankston South (FSH).

In the initial 40-60 milliseconds post-fault period (prior to commencement of RCC operation in a GFN) there is essentially no difference between an ASC and a GFN in how the neutral voltage displacement comes about when an earth fault occurs. However, there is an important difference in the way the neutral voltage displacement is established and maintained beyond the first 40 to 60 milliseconds, i.e. once the GFN's RCC operates.

In the case of ASCs, the resonant combination of the ASC inductance and the total network capacitance to earth exhibits very high impedance at 50Hz[35] and since voltage in the 'earth fault current loop' is distributed in proportion to impedance, most of the available voltage appears across the resonant ASC/network combination as neutral voltage displacement rather than across other parts of the 'loop' where it would be available to drive high levels of fault current. This is simply another way of saying the fault current is reduced to a low level by the very high impedance the resonant ASC/network combination introduces into the 'earth current loop'. There are two consequences of this:

- In the case of high resistance faults, the voltage at the location of the fault can remain substantial because the fault impedance is comparable to the high impedance of the resonant ASC/network combination. The ASC may produce neutral voltage displacement somewhat less than the full 13kV network voltage as the 13kV is divided pro rata across the two impedances.
- The fault current is required to maintain the neutral voltage displacement, i.e. if the fault current disappears, the neutral voltage displacement will quickly collapse.

A GFN exhibits a more pro-active response to an earth fault. Once an earth fault is detected (usually when the neutral voltage exceeds a set threshold) and the RCC operates, it injects a voltage equal to and opposite to the normal phase-to-earth voltage, so the total voltage around the earth fault 'loop' is reduced to near zero[36] – the only voltage remaining to drive fault current is the voltage drop on the faulted phase conductor between the substation and the fault location. This voltage drop is caused by load current (not fault current) and line impedance[37]. Over the subsequent 10-20 seconds, the GFN controller calculates network parameters and adjusts the voltage injected by the RCC to ensure this voltage is cancelled as well. The end result is a very low (near-zero) voltage on the faulted conductor at the location of the fault - hence the adoption of GFNs in places where high resistance soil makes public safety (from electrocution) a special priority.

The difference between an ASC and a GFN is highlighted with high resistance faults since the GFN will actively produce full neutral displacement using its RCC[38] whereas an ASC may produce less than complete voltage displacement. In effect, GFNs are designed to reduce residual fault current to near-zero levels within about 20 seconds regardless of the resistance of the fault.

A second major difference is with momentary earth faults. An ASC will quickly return to normal voltage levels after a momentary earth fault arc extinguishes itself and the fault current falls to zero. The neutral voltage displacement collapses and both the faulted and the un-faulted phases quickly return to normal operating voltage levels. With a GFN, because the neutral displacement is actively maintained (rather than occurring as a natural consequence of the fault current and the high

[35] Practice in some countries is to tune the ASC slightly off resonance. Alternatively it is fitted with a parallel 'damping' resistor. These approaches reduce the risk of false earth fault detection by limiting the volatility of the neutral voltage. They also provide a guaranteed (low) level of fault current to aid fault location.

[36] A somewhat similar effect can be produced without an RCC by using FPE (Faulted Phase Earthing) whereby an earth switch is used to solidly earth the faulted phase within the substation.

[37] In the worst case, this may reach ten per cent of nominal network voltage, but rarely exceeds 500 volts.

[38] Provided the initial neutral displacement has already exceeded the fault detection threshold – this constitutes detection of the fault by the GFN and is the trigger for RCC action.

impedance of the resonant ASC/network combination) the voltage at the fault location will remain close to zero regardless of the continued presence (or absence) of the fault.

This means the network operator must define control logic for the GFN to remove the neutral voltage displacement if the fault is a momentary one. The GFN has functions to assist this choice, including an automated test for continuing fault presence after a defined period.

8.3 Appendix C: Test records

The following tables summarise the tests and their results.

8.3.1 Valid ignition tests

All ignition tests were audited against a number of criteria to verify the result could reliably be regarded as valid. The tests shown in Table 20 were confirmed to be valid tests.

Table 20: Valid ignition tests

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 2 - Day 1	98	NER ignition tests, low resistivity soil	26/05/2014	14:51	NER	100	-	3.3	37	3.75	723	1	N/A	
	99		26/05/2014	15:10	NER	100	-	1.5	46	1.7	743	1	N/A	
	100		26/05/2014	15:26	NER	100	-	2.5	53	3.15	776	1	N/A	
	101		26/05/2014	15:34	NER	100	-	2.7	46	3.2	760	1	N/A	
	102		26/05/2014	15:40	NER	100	-	3	64	3.65	759	1	N/A	
	103		26/05/2014	15:45	NER	100	-	2.4	45	3.4	767	1	N/A	
	104		26/05/2014	15:52	NER	100	-	1.7	38	2.1	744	1	N/A	
	105		26/05/2014	15:56	NER	100	-	18.3	1110	22.9	1110	1	N/A	Fulgurite formed.
	106		26/05/2014	16:01	NER	100	-	2.5	48	3.25	747	1	N/A	
	107	GFN ignition tests	26/05/2014	16:42	GFN	0	600	21	38	-	-	0	-	
	108		26/05/2014	16:52	GFN	0	600	20	39	-	-	0	-	
Tranche 2 - Day 2	109		27/05/2014	11:25	GFN	0	600	10	39	-	-	0	-	
	110		27/05/2014	11:34	GFN	0	600	12.7	38	-	-	0	-	
	111		27/05/2014	11:46	GFN	0	600	12.3	36	-	-	0	-	
	112		27/05/2014	11:53	GFN	0	600	16.2	36	-	-	0	-	
	113	NER ignition tests	27/05/2014	12:08	NER	100	-	24	920	21	920	1	N/A	
	114		27/05/2014	12:19	NER	100	-	24	920	21	920	1	N/A	
	115		27/05/2014	12:34	NER	100	-	22.5	918	19.75	918	1	N/A	Fulgurite formation. Peak at 110A RMS
	116		27/05/2014	12:50	NER	100	-	24.5	918	21.25	918	1	N/A	

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 2 - Day 2	117	ASC ignition tests	27/05/2014	14:35	ASC	100	600	12	55	-	-	0	-	No residual current through soil, all through shunt resistor.
	118		27/05/2014	14:49	ASC	100	1600	13	58	1	1007	1	Ground	
	119		27/05/2014	15:07	ASC	100	1600	13	63	0.8	983	1	Ground	
	120		27/05/2014	15:19	ASC	100	1600	12.5	57	1	970	1	Ground	
	121		27/05/2014	15:30	ASC	100	1600	14.8	114	2.25	992	1	Bounce	
	122		27/05/2014	15:38	ASC	100	1600	4.8	43	0.18	800	0	-	
	123		27/05/2014	15:53	ASC	100	1600	13.5	110	0.75	1000	1	Bounce	
	124		27/05/2014	16:06	ASC	100	600	17	36	-	-	0	-	
	125		27/05/2014	16:13	ASC	100	600	11	46	-	-	0	-	
	126		27/05/2014	16:19	ASC	100	600	7.5	35	-	-	0	-	
	127		27/05/2014	16:37	ASC	100	-	12.5	75	5	1022	1	Bounce	
	128		27/05/2014	16:45	ASC	100	-	12.5	76	4.75	1017	1	Bounce	
	129		27/05/2014	16:56	ASC	100	-	15	82	4.75	1020	1	Bounce	
Tranche 2 - Day 3	130	ASC ignition tests	28/05/2014	9:49	ASC	100	-	-	-	-	-	1	Ground	DAQ didn't trigger. RCC didn't act
	131		28/05/2014	9:57	ASC	100	-	1	29	-	-	1	Ground	DAQ triggered on noise
	132		28/05/2014	10:09	ASC	100	-	1	35	1	998	1	Ground	
	133		28/05/2014	10:22	ASC	100	-	5	41	3	1005	1	Ground	
	134		28/05/2014	10:39	ASC	100	1600	0.8	35	-	-	0	-	
	135		28/05/2014	10:54	ASC	100	1600	1.5	28	-	-	0	-	
	136		28/05/2014	11:02	ASC	100	1600	1	26	-	-	0	-	
	137		28/05/2014	11:11	ASC	100	600	0.8	29	-	-	0	-	
	138		28/05/2014	11:19	ASC	100	600	0.9	26	-	-	0	-	
	139		28/05/2014	11:29	ASC	100	600	0.7	26	-	-	0	-	

Schedule								Bounce behaviour		Ground behaviour		Ignition		
Day	Test ID	Test series	Date	Time	FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	Notes
Tranche 2 - Day 3	140	GFN ignition tests	28/05/2014	12:56	GFN	0	600	1	27	-	-	0	-	Timers not reset from ASC settings. Did not bias GFN action or test result.
	141		28/05/2014	13:11	GFN	0	600	0.3	23	-	-	0	-	
	142		28/05/2014	13:22	GFN	0	600	0.8	33	-	-	0	-	
	143		28/05/2014	13:28	GFN	0	600	0.6	27	-	-	0	-	
	144		28/05/2014	13:38	GFN	0	600	0.9	31	-	-	0	-	
	145		28/05/2014	13:50	GFN	0	600	0.7	26	-	-	0	-	
	146		28/05/2014	14:01	GFN	0	600	0.9	27	-	-	0	-	
	147		28/05/2014	14:10	GFN	0	600	0.7	31	-	-	0	-	
	148		28/05/2014	14:16	GFN	0	600	1.4	27	-	-	0	-	
	149		28/05/2014	14:32	GFN	0	600	1.2	29	-	-	0	-	
	151	NER ignition tests	28/05/2014	15:04	NER	100	-	3	270	4.5	505	1	Bounce	
	152		28/05/2014	15:15	NER	100	-	2	38	2.4	499	1	Ground	
	153	GFN ignition tests	28/05/2014	16:24	GFN	0	1600	17.5	77	-	-	0	-	GFN sensitivity increased to 20%
	154		28/05/2014	16:32	GFN	0	1600	13	76	-	-	1	Bounce	
	155		28/05/2014	16:42	GFN	0	1600	14.8	88	-	-	1	Bounce	
	156		28/05/2014	16:54	GFN	0	1600	12	44	-	-	1	Bounce	
	157		28/05/2014	17:03	GFN	0	1600	11	74	-	-	1	Bounce	
	158		28/05/2014	17:13	GFN	0	1600	15	45	-	-	0	-	
Tranche 2 - Day 4	159	GFN ignition tests	29/05/2014	10:49	GFN	0	-	13.5	120	-	-	1	Bounce	Test used to confirm rig timing
	160		29/05/2014	11:01	GFN	0	-	13	47	-	-	0	-	
	161		29/05/2014	11:10	GFN	0	-	17	92	-	-	1	Bounce	Rig damaged during attempted test #162. Slot cover left closed.
Tranche 3 - Day 1	192	GFN ignition tests	14/06/2014	17:41	GFN - new firmware	0	5000	1.17	39	0.24	754	0	-	GFN reverted to old fault confirmation check, i.e. disabled RCC
	193		14/06/2014	18:08	GFN - new firmware	0	5000	0.34	28	0.004	1050	0	-	

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 3 - Day 2	194	Sandpit current	16/06/2014	8:59	NER	100	5000	3.4	114	3.9	476	1	Bounce	2.5A in sandpit
	195	GFN ignition tests	16/06/2014	10:02	GFN - new firmware	0	5000	0.55	37	0.001	1580	0	-	GFN parameters modified to increase likelihood of soft fault confirmation, threshold changed to reduce residual voltage. Conditions considered to be more conservative. Voltage collapsed to ~420V residual, (more than on Tranche 3 - Day 1)
	196		16/06/2014	10:39	GFN - new firmware	0	5000	1.2	47	0.26	1202	0	-	
	197		16/06/2014	10:53	GFN - new firmware	0	5000	0.1	32	-	-	0	-	
	198		16/06/2014	11:12	GFN - new firmware	0	5000	0.54	47	0.031	1182	0	-	
	199		16/06/2014	11:25	GFN - new firmware	0	5000	0.17	44	0.005	1118	0	-	
	200		16/06/2014	11:40	GFN - new firmware	0	5000	0.28	45	-	-	0	-	
	201		16/06/2014	13:16	GFN - new firmware	0	5000	0.44	45	0.003	1001	0	-	
	202		16/06/2014	13:33	GFN - new firmware	0	5000	0.19	44	0.012	1136	0	-	
	203		16/06/2014	13:45	GFN - new firmware	0	5000	0.2	38	0.003	783	0	-	
	204		16/06/2014	14:00	GFN - new firmware	0	5000	0.26	36	<.001	653	0	-	
	205		16/06/2014	14:56	GFN - new firmware	0	5000	0.14	36	0.007	1197	0	-	
	206		16/06/2014	15:13	GFN - new firmware	0	5000	0.07	42	0.006	1146	0	-	
	207		16/06/2014	15:25	GFN - new firmware	0	5000	0.17	37	0.003	1164	0	-	
Tranche 3 - Day 4	218	NER ignition test	25/06/2014	9:13	NER	3200	-	0.09	35	0.145	19513	0	-	Lots of smoking but no flames
	219		25/06/2014	9:41	NER	3200	-	0.03	27	0.035	59496	0	-	
	220		25/06/2014	10:04	NER	3200	-	0.24	35	0.375	14250	1	Ground	Ignition following 5 sec
	221		25/06/2014	10:29	NER	3200	-	0.23	26	0.335	12880	1	Ground	Ignition following 1.2 sec
	222		25/06/2014	10:40	NER	3200	-	0.22	27	0.315	14587	1	Ground	Ignition following 9.3 sec
	223		25/06/2014	10:50	NER	3200	-	0.26	28	0.38	11231	1	Ground	Ignition following 1.7 sec
	224		25/06/2014	11:08	NER	3200	-	0.04	32	0.03	59467	0	-	
	225		25/06/2014	11:16	NER	3200	-	0.1	27	0.095	43088	1	Ground	Ignition following 32 sec
	226		25/06/2014	11:31	NER	3200	-	0.19	26	0.32	9760	1	Ground	Ignition following 3.2 sec
	227		25/06/2014	11:47	NER	6400	-	0.18	27	0.225	15762	1	Ground	Ignition following 3.8 sec
	228		25/06/2014	13:38	NER	3200	5000	0.15	33	0.28	59476	1	Ground	Ignition following 54 sec
	229		25/06/2014	13:56	NER	3200	5000	0.11	22	0.12	41670	1	Ground	Ignition following 31 sec
	230		25/06/2014	14:15	NER	3200	5000	0.38	32	0.445	6560	1	Ground	Ignition following 2.3 sec
	231		25/06/2014	14:28	NER	3200	5000	0.16	25	0.31	10080	1	Ground	Ignition following 3.6 sec
	232		25/06/2014	14:46	NER	6400	5000	0.31	25	0.09	24684	1	Ground	Ignition following 10.8 sec

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 3 - Day 4	233	NER ignition tests for live line sequence	25/06/2014	14:56	NER	6400	5000	0.25	27	0.06	59455	0	-	
	234		25/06/2014	15:21	NER	100	-	1	27	-	-	0		
	235		25/06/2014	15:47	NER	100	-	~16	816	13	820	1	Bounce	
	236		25/06/2014	15:59	NER	100	-	~11.6+fulgurite	99	-	-	0		Fulgurite for half a cycle after 90ms. 732A (p-p)
	237		25/06/2014	16:14	NER	100	-	~12.4+fulgurite	128	-	-	1	Bounce	Fulgurite following ~50ms
	238		25/06/2014	16:23	NER	100	-	9.6	125	-	-	1	Bounce	
	239		25/06/2014	16:36	NER	100	-	12	105	-	-	1	Bounce	
	240		25/06/2014	16:44	NER	100	-	13.9	83	-	-	1	Bounce	Current settled to 10.8A RMS.
	241	NER ignition tests	25/06/2014	17:35	NER	3200	-	0.09	34	0.2	28936	1	Ground	Test 241-249 performed with 3/12 steel conductor. Appeared to have more arcs along conductor length than 19 strand Al. Ignition following 32.1 sec
Tranche 3 - Day 5	242	NER ignition tests	26/06/2014	9:40	NER	3200	-	0.2	36	0.345	9717	1	Ground	Scaling factor on blue phase changed to account for error in CVD measurement. Ignition following 4.55 sec
	243		26/06/2014	9:57	NER	6400	-	0.26	32	0.305	10440	1	Ground	Instantaneous. Ignition following 0.1 sec
	244		26/06/2014	10:17	NER	12800	-	0.2	35	0.24	9457	1	Ground	Ignition following 1.8 sec
	245		26/06/2014	10:33	NER	15200	-	0.26	35	0.315	7662	1	Ground	Ignition following 0.1 sec
	246		26/06/2014	10:55	NER	15200	5000	0.21	27	0.002	59495	0	-	Sand pit connected through 100 Ohm resistor.
	247		26/06/2014	11:11	NER	6400	5000	0.3	30	0.03	10184	1	Ground	Ignition following 2.5 sec
	248		26/06/2014	11:27	NER	12800	5000	0.2	26	0.075	15753	1	Ground	Ignition following 8.2 sec
	249		26/06/2014	11:39	NER	12800	5000	0.26	32	0.0015	59492	0	Ground	Ignition following 60 sec
	251	ASC ignition tests	26/06/2014	13:31	ASC	100	5000	1.8	37	0.58	4405	1	Ground	Ignition following 670ms. Fault interrupted.
	253		26/06/2014	14:39	ASC	100	5000	0.1	25	0.0125	1824	0	-	Red phase used henceforth. Current increased to 12ms following 5 sec, suspected fault detection by GFN. Feature disabled. No ignition.
	255		26/06/2014	15:19	ASC	100	5000	0.14	25	0.055	19505	0	-	Smoking but no fire.
	256		26/06/2014	15:33	ASC	100	5000	0.33	30	0.0955	44488	0	-	Lots of smoke but no fire.
	257		26/06/2014	15:52	ASC	100	5000	0.26	28	0.225	18762	1	Ground	Ignition following 12.5 sec
	258		26/06/2014	16:02	ASC	100	5000	0.31	35	0.16	9679	1	Ground	Ignition following 5.6 sec
	259		26/06/2014	16:10	ASC	100	5000	0.31	37	0.16	9107	1	Ground	Ignition following 2 sec

8.3.2 Bolted fault tests

The following tests were performed with the test rig shorted out by a length of flexible welding cable. They were performed to for setup purposes and to explore and measure the performance of each REFCL type.

Table 21: Bolted fault tests

Schedule					FSH Protection	Series Resistance (Ω)	Max Current (A_{rms})	Duration (ms)	Notes
Day	Test ID	Test series	Date	Time					
Tranche 1A - Day 1	1	Electrical commissioning	8/04/2014	14:06	GFN	400	-	-	DAQ false trigger.
	2		8/04/2014	14:13	GFN	400	-	-	Did not record current
	3		8/04/2014	14:42	GFN	200	-	-	Rogowski coil was set to 300A whereas DAQ scaling assumed setting of 3000A
	4		8/04/2014	15:09	GFN	100	-	-	Peak current at 420 A. Rogowski coil setting changed to 30A
	5		8/04/2014	15:30	GFN	0	-	-	Peak current very small. Rogowski coil setting changed to 300A
	6		8/04/2014	16:01	NER	400	-	-	DAQ didn't trigger
	7		8/04/2014	16:11	NER	400	-	-	DAQ manually triggered
	8		8/04/2014	16:15	NER	400	-	-	DAQ manually triggered
	9		8/04/2014	17:45	NER	400	-	-	
Tranche 1A - Day 2	10		9/04/2014	11:05	NER	200	-	-	Rogowski coil replaced with shunt. Current not detected by DAQ
	11		9/04/2014	11:19	NER	200	-	-	Shunt checked. Current not detected by DAQ
	12		9/04/2014	11:37	NER	200	-	-	Resistor checked. Current not detected by DAQ
	13		9/04/2014	12:05	NER	200	-	-	HV lines from resistors were reversed. RCGS1 open 65ms faster than RCGS1 close/ 135ms duration.
	14		9/04/2014	12:27	NER	100	-	-	Stationary steel conductor.
Tranche 1A - Day 3	27	Fault current waveform tests	10/04/2014	10:19	GFN	3200	-	-	Error in range and scaling multiplier in Perception software in previous tests addressed. RCC operated, DAQ did not trigger
	28		10/04/2014	10:24	GFN	3200	3.07	220	RCC operated
	29		10/04/2014	10:36	GFN	3200	3.16	300	Blue phase
	30		10/04/2014	11:35	NER	3200	3.98	500	
	31		10/04/2014	12:51	NER	3200	2.7	500	
	32		10/04/2014	12:52	GFN	3200	0.775	330	
	33		10/04/2014	13:22	GFN	15200	0.775	2000	RCC did not operate. Neutral displacement ~50 70% of threshold
	34		10/04/2014	13:29	GFN	15200	0.795	2447	RCC did not operate. Neutral displacement ~50 70% of threshold
	35		10/04/2014	13:34	GFN	12800	0.915	2435	RCC did not operate. Neutral displacement ~50 70% of threshold
	36		10/04/2014	13:36	GFN	12800	0.915	2427	RCC did not operate. Neutral displacement ~50 70% of threshold
	37		10/04/2014	13:41	GFN	6400	1.6	600	RCC operated.
	38		10/04/2014	14:36	GFN	300	20.3	78	RCC operated after only ~70ms.
	39		10/04/2014	14:43	GFN	100	64	50	
	40		10/04/2014	14:53	NER	100	117	500	

Schedule									
Day	Test ID	Test series	Date	Time	FSH Protection	Series Resistance (Ω)	Max Current (A_{rms})	Duration (ms)	Notes
Tranche 1A - Day 3	41		10/04/2014	14:54	NER	100	116	500	
	42		10/04/2014	15:06	NER	100	118	500	
	43		10/04/2014	15:09	NER	100	117	503	
	44		10/04/2014	15:17	NER	100	117	500	
	45		10/04/2014	15:19	NER	100	117	500	
	49		10/04/2014	17:38	GFN	0	-	-	
Tranche 1B - Day 3	76	Additional network capacitance	7/05/2014	12:02	GFN	0	107 (p-p)	2074	Initial cycle at 436A (p-p). Suspected ferro-resonance observed. ACR opened following 2s
	77		7/05/2014	13:51	GFN	100	24 (p-p)	2430	RCC acted, tripped and reverted to NER following 5s
	78		7/05/2014	13:51	GFN	100	23 (p-p)	2410	Initial ~30ms at 173 A (p-p). RCC acted, tripped and reverted to NER following 5s
	79		7/05/2014	14:00	GFN	300	10 (p-p)	2440	Initial ~94ms at 94 A (p-p). RCC acted, recovered without tripping to NER
	80		7/05/2014	14:03	GFN	300	9 (p-p)	2350	Initial ~84ms at 90 A (p-p). RCC acted, recovered without tripping to NER
	81		7/05/2014	14:11	GFN	100	23 (p-p)	2390	Initial ~40ms at 182 A (p-p). RCC acted, tripped and reverted to NER following 5s
	86	RCC disabled	7/05/2014	16:49	ASC	300	12.2 (p-p)	230	Initial current at 88 A (p-p)
	87		7/05/2014	16:56	ASC	100	18 (p-p)	230	Initial current at 178 A (p-p)
Tranche 2 - Day 4	162	GFN and ASC bolted faults	29/05/2014	12:21	GFN	15200	0.79/0.65	2432	
	163		29/05/2014	12:58	GFN	12800	0.95/0.73	873	
	164		29/05/2014	13:51	GFN	6400	1.9/0.12	2432	
	165		29/05/2014	13:59	ASC	6400	1.9/1.1	2432	
	166		29/05/2014	14:03	ASC	3200	3.7/1.5	2432	
	167		29/05/2014	14:14	GFN	3200	3.7/0.24	2432	
	168		29/05/2014	14:25	GFN	1600	7.4/0.46	2432	
	169		29/05/2014	15:17	GFN	800	14.1/0.83	2432	
	170		29/05/2014	15:25	GFN	600	18.6/1.1	2432	
	171		29/05/2014	15:34	GFN	400	26.4/1.6	2432	
	172		29/05/2014	15:47	GFN	300	34.5/2.2	2432	
	173		29/05/2014	16:07	GFN	200	47.4/3.0	2432	
	174		29/05/2014	16:28	GFN	100	82.6/5.8	2432	
Tranche 3 - Day 1	188	GFN bolted fault tests	14/06/2014	14:25	GFN - new firmware	400	26.8	78	White phase collapsed to ~250V. GFN could not identify faulted feeder
	189		14/06/2014	16:40	GFN - new firmware	400	25.8	83	GFN tuned. White phase collapsed to ~200V. GFN tested for sustained fault.
	190		14/06/2014	16:57	GFN - new firmware	200	46.3	122	
	191		14/06/2014	17:10	GFN - new firmware	100	81.2	56	

8.3.3 Setup and invalid tests

The following tests were performed for the purposes of setup or they were ruled invalid for some reason and excluded from the set of ignition results used in the analysis.

Table 22: Setup and invalid tests

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 1A - Day 2	15	Rig tuning	9/04/2014	13:44	NER	100	600	-	490	-	-	-	-	3/12 steel conductor.
	16		9/04/2014	14:08	NER	100	600	-	493	-	-	-	-	3/12 steel conductor. Wet soil
	17		9/04/2014	14:17	NER	100	-	-	494	-	-	-	-	3/12 steel conductor. Shunt resistor earth removed
	18		9/04/2014	14:36	NER	100	-	-	494	-	-	-	-	3/12 steel conductor. Shunt removed in container.
	19		9/04/2014	15:05	NER	100	-	-	500	-	-	-	-	Al conductor and thoroughly wet test bed
	20	Preliminary ignition tests	9/04/2014	16:14	NER	100	-	-	317	-	1140	1	-	First ignition test. ~1.2s duration
	21		9/04/2014	16:14	GFN	100	-	-	1240	-	-	1	-	First ignition test with GFN. RCC did not operate
	22		9/04/2014	16:31	GFN	0	-	-	-	-	-	1	-	RCC did not operate DAQ did not trigger
	23		9/04/2014	16:56	GFN	0	-	-	200	-	-	0	-	RCC acted
	24		9/04/2014	17:15	GFN	0	600	-	100	-	-	0	-	RCC acted
	25		9/04/2014	17:24	GFN	0	600	-	-	-	-	0	-	
	26		9/04/2014	17:41	NER	100	600	-	200	-	737	1	-	Error identified in Perception software range and scaling multiplier in previous tests
Tranche 1A - Day 3	46	Fault current waveform tests	10/04/2014	16:42	NER	100	-	-	-	6.2	490	1	-	Extinguished by CO2
	47		10/04/2014	16:56	NER	100	-	6.7	290	108.6	205	-	-	Arcing on soil bed and fulgurite formation
	48		10/04/2014	17:19	NER	100	-	-	-	3.8	494	-	-	Arcing on soil bed
Tranche 1B - Day 1	50	Optimising current measurement	5/05/2014	16:28	GFN	100	600	4 (p-p)	90	-	-	-	-	RCC operated. Large difference between RC and shunt current measurements.
	51		5/05/2014	17:26	GFN	100	-	-	1800	-	-	-	-	Noise present but no 50Hz component of current recorded. Earth removed from shunt resistor to increase fault current. RCC did not operate.
	52		5/05/2014	17:40	GFN	100	-	20 (p-p)	75	14.5 (p-p)	140	0	-	Sinusoidal current recorded. Fewer spikes in shunt recording. Lots of arcing in video but no ignition

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	
Tranche 1B - Day 2	53	Optimising current measurement and influence of shunt resistor cable.	6/05/2014	9:41	GFN	0	-	13 (p-p)	60	14.5 (p-p)	220	1	-	Intended fault duration 3000ms, ACR opened.
	54		6/05/2014	10:31	GFN	0	-	-	-	6 (p-p)	-	0	-	Shunt cable removed from circuit entirely. Cell supply open reduced from 5000ms to 3500ms. Arm dampening increased. Gen3i triggered late. Video did not show arcing. Very little arcing, no sinusoidal current.
	55		6/05/2014	10:42	GFN	0	-	6 (p-p)	26	8 (p-p)	315	0	-	Repeat. Gen3i triggered normally. Video did not show arcing. No sinusoidal current.
	56		6/05/2014	10:50	GFN	0	-	7 (p-p)	26	7 (p-p)	390	0	-	Repeat Gen3i triggered normally. Video did not show arcing.
	57		6/05/2014	11:06	GFN	0	-	7 (p-p)	27	9 (p-p)	1438	0	-	Shunt cable re-attached. Same behaviour as before, very little current, no sinusoidal current.
	58		6/05/2014	11:25	GFN	0	-	10.5 (p-p)	60	9 (p-p)	215	0	-	Shunt cable disconnected.
	59		6/05/2014	11:38	GFN	0	-	15 (p-p)	195	-	-	0	-	Shunt cable reconnected. RCD tripped power to test cell
	60	Shunt resistor contact	6/05/2014	13:00	GFN	0	600	50 (p-p)	45	-	-	0	-	Rogowski coil moved to shunt resistor line (on earth line). Coax shunt recording soil bed current (transducers on current channels switched switched). Very short arc duration (20ms). RCC acted
	61		6/05/2014	13:30	GFN	0	3200	12 (p-p)	17	10 (p-p)	175	0	-	Very short arc duration (15ms). RCC acted
	62		6/05/2014	13:55	GFN	0	15200	12 (p-p)	28	10 (p-p)	180	1	-	
	63	GFN ignition tests. Confirm rig timing	6/05/2014	15:56	GFN	0	600	11 (p-p)	30	-	-	0	-	RCC triggered. 3.25 sec b/w fault trigger and current detection.
	64		6/05/2014	16:11	GFN	0	600	12 (p-p)	70	-	-	0	-	RCC triggered. 2.855 sec b/w fault trigger and current detection.
	65		6/05/2014	16:19	GFN	0	600	15 (p-p)	63	-	-	0	-	RCC triggered. 1.645 sec b/w fault trigger and current detection.
	66		6/05/2014	16:31	GFN	0	600	15 (p-p)	63	-	-	0	-	RCC triggered. 2.86 sec b/w fault trigger and current detection.
	67		6/05/2014	16:41	GFN	0	600	15 (p-p)	63	-	-	0	-	RCC triggered. 2.855 sec b/w fault trigger and current detection.
Tranche 1B - Day 3	68	NER tests	7/05/2014	9:53	NER	100	600	10 (p-p)	62	11 (p-p)	920	1	-	NER test. 1250ms between current start and cell supply close
	69		7/05/2014	10:06	NER	100	600	10 (p-p)	58	10 (p-p)	815	1	-	Fault duration increased by 100ms. 1150ms of between current start and cell supply close
	70		7/05/2014	10:28	NER	100	600	14 (p-p)	110	15 (p-p)	897	1	-	1150ms of between current start and cell supply close.
	71		7/05/2014	10:37	NER	100	600	9 (p-p)	88	9 (p-p)	914	1	-	1150ms of between current start and cell supply close. Ignition
	72		7/05/2014	10:51	NER	100	600	12 (p-p)	110	13 (p-p)	633	0	-	1550ms of between current start and cell supply close. 3.249 sec b/w fault trigger and current detection. Additional 400ms attributed to actuator starting in "home" position.
	73		7/05/2014	11:06	NER	100	-	22 (p-p)	1355	-	-	1	-	No shunt resistor.1350ms between current start and cell supply close
	74		7/05/2014	11:14	NER	100	-	24 (p-p)	1348	-	-	1	-	1350ms of between current start and cell supply close. Ignition
	75		7/05/2014	11:21	NER	100	-	16 (p-p)	1345	-	-	1	-	1350ms of between current start and cell supply close. Ignition

Schedule					FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Bounce behaviour		Ground behaviour		Ignition		Notes
Day	Test ID	Test series	Date	Time				Max Soil Current (A…)	Duration (ms)	Average Soil Current	Duration (ms)	Sustained Ignition Result	Ignition timing	
	82	Additional network capacitance	7/05/2014	14:40	GFN	100	600	7 (p-p)	26	-	-	0	-	
	83		7/05/2014	14:46	GFN	100	600	13 (p-p)	50	-	-	0	-	
	84		7/05/2014	14:58	GFN	0	600	13 (p-p)	50	-	-	0	-	
	85		7/05/2014	15:03	GFN	0	600	17 (p-p)	35	-	-	0	-	
	88	RCC disabled	7/05/2014	17:06	ASC	100	-	10.9 (p-p)	60	6.7 (p-p)	35	0	-	
	89		7/05/2014	17:17	ASC	100	-	12 (p-p)	30	9 (p-p)	1065	1	-	
	90		7/05/2014	17:25	ASC	100	-	15 (p-p)	30	8 (p-p)	1060	1	-	
Tranche 2 - Day 1	91	Setup, shunt resistor timing.	26/05/2014	12:16	NER	100	600	1.7	37	1.5	195	0	-	28ms delay b/w shunt contact and fault current through bed
	92		26/05/2014	12:16	NER	100	600	1.6	38	1.55	196	0	-	Shunt contact dropped 25mm. Fuel bed levelled. 11ms delay b/w shunt contact and fault current through bed
	93		26/05/2014	12:19	NER	100	600	2	48	1.75	218	0	-	No change, shunt lever reset itself to intermediate starting position. Bed re-used. 0.3ms delay b/w shunt contact and fault current through bed
	94		26/05/2014	12:23	NER	100	600	1.9	39	2	237	0	-	No change, bed re-used. 1ms delay b/w shunt contact and fault current through bed
	95		26/05/2014	12:31	GFN	100	600	1.7	37	-	-	0	-	Impacted bed. 1.7ms delay
	96		26/05/2014	12:38	GFN	100	600	1.9	38	-	-	0	-	2.3 ms delay w/fresh soil bed.
	97		26/05/2014	12:42	GFN	100	600	2	39	-	-	0	-	2.5 ms delay w/fresh soil bed.
Tranche 2 - Day 3	150	NER ignition tests	28/05/2014	14:58	NER	100	-	3.4	44	4.4	456	1	N/A	Bed used twice. ACR prevented current flow during first strike. Test not counted towards ignition result.
Tranche 2 - Day 4	175	GFN ignition tests	29/05/2014	16:51	GFN	0	-	12.4	46	-	-	0	-	Timing trial using previously impacted soil bed. Not counted towards ignition tests. Arm mechanism timing 2.875s. 50ms
	176		29/05/2014	17:01	GFN	0	-	14	79	-	-	1	Bounce	Bounce behaviour different to that before conductor arm was damaged following test #161
	177		29/05/2014	17:10	GFN	0	-	13	48	-	-	1	Bounce	
	178		29/05/2014	17:17	GFN	0	-	12.4	48	-	-	1	Ground	
	179		29/05/2014	17:27	GFN	0	-	0.9	25	0.4	1839	0	-	Ignition not sustained, review on Sony video. 25ms of 0.7A RMS arcing on first bounce. RCC did not act. 1.8s of low current following second bounce.
	180		29/05/2014	17:33	GFN	0	-	0.8	37	0.65	1716	1	Ground	0.7A RMS. RCC did not act. High speed video continued with residual arcing until arm lifts
Tranche 3 - Day 1	181	Setup - Confirm rig operation, 'sand pit' resistance, CVD measurement	14/06/2014	11:00	NER	100	5000	-	-	-	-	0	-	DAQ didn't record current signals
	182		14/06/2014	11:18	NER	100	5000	-	-	-	-	0	-	DAQ didn't record current signals - Rogowski coil battery dead and current
	183		14/06/2014	11:52	NER	100	5000	0.97	36	1.05	338	1		1A RMS into soil and 2.5A RMS into sand pit. 5000 Ohm resistance. Shunt (sand pit) engaged 3ms before soil bed
	184		14/06/2014	12:16	NER	100	5000	1.2	38	1.3	346	0	-	2.5A RMS into sand pit. Shunt (sand pit)
	185		14/06/2014	12:33	NER	100	5000	1.2	30	1.25	357	0	-	2.5A RMS into sand pit. Shunt (sand pit) engaged 5ms before soil bed
	186		14/06/2014	12:54	NER	100	5000	7.3	45	8.1	343	1		Soil bed replaced (old bed used). Shunt (sand pit) engaged 8.6ms after soil bed
	187		14/06/2014	13:41	NER	N/A	N/A	-	-	-	-	-	-	Voltage neutral displacement check to assess CVD performance

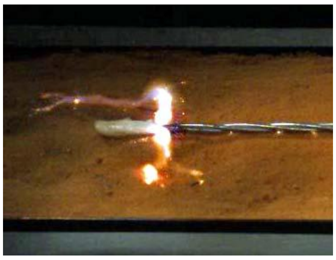
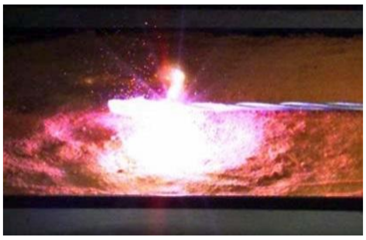
Schedule								Bounce behaviour		Ground behaviour		Ignition		
Day	Test ID	Test series	Date	Time	FSH Protection	Series Resistance (Ω)	Shunt Resistance (Ω)	Max Soil Current (A_{rms})	Duration (ms)	Average Soil Current (A_{rms})	Duration (ms)	Sustained Ignition Result	Ignition timing	Notes
Tranche 3 - Day 2	208	GFN ignition tests	16/06/2014	15:44	GFN - new firmware	0	5000	>45	19	1.9	1166	1	Bounce	Damp soil. 600A peak on GFN record. Fulgurite
	209		16/06/2014	16:23	GFN - new firmware	400	5000	9.8	60	2	1288	1	Ground	No ignition on bounce. GFN could not identify fault location during soft confirmation test. Ignition during hard fault confirmation test (~2A RMS).
	210		16/06/2014	16:57	GFN - new firmware	0	5000	3.6	48	0.9	1177	0	-	Grass not conditioned. No ignition, considerable smoking during hard fault confirmation test (~1A RMS)
	211		16/06/2014	17:14	GFN - new firmware	0	5000	0.7	45	0.2	1203	0	-	Grass not conditioned. No ignition, lower current during hard fault confirmation test
	212	NER ignition tests	16/06/2014	17:30	NER	0	5000	0.5	46	0.6	692	0	-	NER with 1.9s fault duration. ACR opened. Smoke but no fire.
	213		16/06/2014	17:36	NER	0	5000	0.34	44	0.6	1433	0	-	Increased fault duration. Smoke but no fire.
	214		16/06/2014	17:52	NER	0	5000	0.09	36	0.02	1936	0	-	Duration increased further. No fire, very small current.
Tranche 3 - Day 3	215	Media demonstration. NER and GFN ignition tests	17/06/2014	10:23	NER	400	5000	1.2	891	-	-	1	Bounce	Arc didn't extinguish during bounce
	216		17/06/2014	11:08	NER	400	5000	12.7	892	-	-	1	Bounce	
	217		17/06/2014	11:35	GFN - new firmware	100	5000	1.7	37	>100	2083	1	Ground	Multiple faults on blue phase 300ms into test.
Tranche 3 - Day 5	250	ASC ignition tests	26/06/2014		ASC	100	5000	-	-	-	~4s	1	Ground	ASC tests. NER kicked in. Gen 3i not triggered.
	252		26/06/2014	13:50	ASC	100	5000	0.52	27	0.265	11417	1	Ground	Current increased following 5 sec, due to suspected fault on red phase. Ignition following 7.6 s. Fault interrupted. Switch to Red phase following fault.
	254		26/06/2014	15:11	ASC	100	5000	-	-	-	-	0	-	Same bed used. Current peak rectified.

8.4 Appendix D: ignition from fulgurite formation

Fulgurites are hollow tubes of fused silica formed in soil by electric arcs. They occur naturally with lightning strikes and they can occur in powerline earth faults if there is buried metal near a fallen powerline conductor (water or gas pipe, electrical or telephone cables, foundations, etc.) at a depth and of a length sufficient to offer a low resistance path to earth current.

Fulgurite formation was first observed in the test program in the February 2014 proof-of-concept tests as shown in Figure 65.

Figure 65: Fulgurite formation in February 2014 proof-of-concept tests at Ausgrid/TCA Lane Cove West facility

		
Immediately prior to fulgurite formation	Fulgurite 'punch through' to soil bed metal casing	Typical fulgurite structure dug out of soil, about 100 millimetres long

It was observed that fulgurites were a potent cause of ignition. High speed video records demonstrated that the open end of a fulgurite ejects copious amounts of incandescent molten silicaceous material which rapidly ignites surrounding vegetation.

After some consideration and consultation with the technical Working Group, it was decided that fulgurites were unlikely to feature in rural 'wire on ground' faults as those locations rarely have buried metal, with the possible exception of pole-stay anchors, so they were specifically excluded from the ignition mechanisms under study in the test program.

From the proof-of-concept test data, it was observed that:

- Fulgurites form almost instantly once the plasma tendrils from the conductor-soil arc reach earthed metal
- It can take significant time for the conductor-soil arc plasma tendrils to reach metal through soil. The reach of the plasma tendrils was observed to extend further with each half cycle of fault current. The time taken to reach earthed metal depended on the distance to be spanned by the plasma and the arc current involved. Values of 100 to 300 milliseconds were achieved with medium sized metal-sided soil trays.

On this basis, the soil bed container design was modified to reduce the likelihood of fulgurite formation in tests. The container was made of plastic not metal and the size was chosen to provide 23 cm of soil between the conductor and a 100 millimetres wide copper earth strip under the soil. These modifications successfully reduced the occurrence of fulgurite formation to a very low level.

Nevertheless, some tests produced fulgurites. These were mostly NER tests where current was high and the test duration was relatively long. Fulgurite formation also occurred in two REFCL tests – though both these events had anomalous features that resulted in their exclusion from ignition test data.

8.4.1 Fulgurite formation in NER tests

NER Tests 20, 115, 236, and 237 all contained instances of fulgurite formation. Even with the changes to soil bed container design following the proof-of-concept tests, it was recognised that fulgurite formation was possible if high enough soil current were allowed to flow for long enough to allow the progressive spread of plasma tendrils through the soil to reach the earthed copper strip at the bottom of the soil bed. The above listed tests clearly met these criteria.

Figure 66 through to Figure 69 show the soil current waveforms for NER tests where fulgurite formation occurred. Once a fulgurite occurred, it acted as a short circuit and the current was limited only by the 100 ohm series resistor in the rig supply, i.e. it was 110 amps. The on-site current records often showed clipping of peaks when a fulgurite formed as the fulgurite current was greater than the full-scale current set for the test.

Figure 66: Test 20 fulgurite formation in 1.14 seconds – soil current record

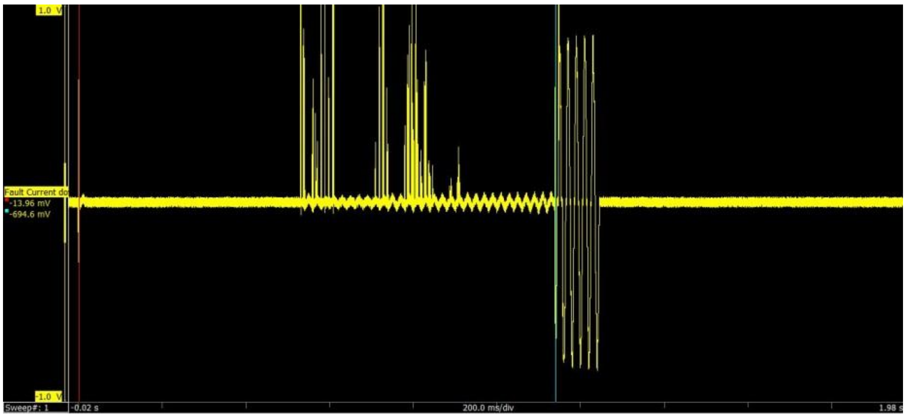


Figure 67: Test 115 fulgurite formation at 0.49 seconds (partial) and 0.81 seconds (full) at 22.5 amps – soil current record

Figure 68: Test 236 fulgurite formation after 0.094 seconds at 11.6 amps – soil current record

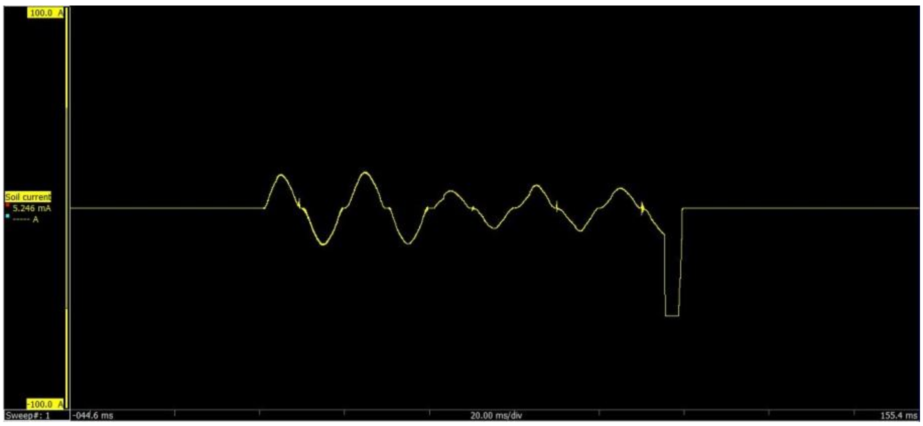
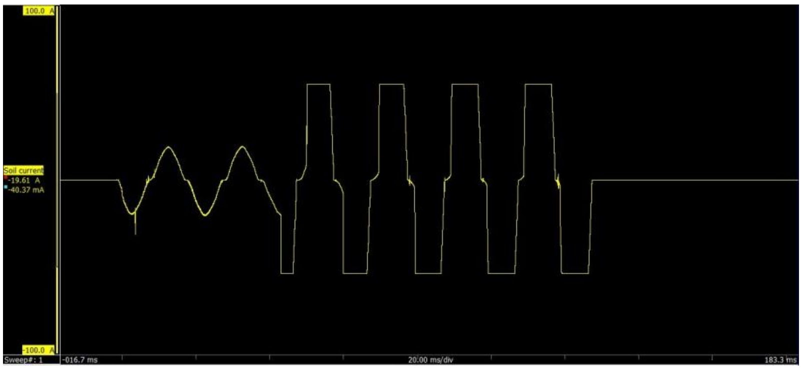


Figure 69: Test 237 fulgurite formation after 0.044 seconds at 12.5 amps – soil current record



8.4.2 Test 208: anomalous fulgurite formation in a GFN test

Test 208 was a GFN ignition test with zero series resistance in the supply to the test rig. It was the only REFCL test in which fulgurite formation appeared to have occurred without an external network disturbance to trigger it. Examination of the test records revealed several puzzling features.

Upon initial impact of the conductor on the soil bed, soil current exhibited the following behaviour: it increased to 1.4 amps in the first 0.54ms of the fault period; the rate of current growth then increased so it reached 8.0 amps by 0.62ms and 41.0 amps by 2.7ms into the fault period; at this point, fulgurite formation appeared to occur. On-site soil current measurement systems saturated at 55 amps, but GFN records revealed the current reached 620 amps in the positive direction, followed by 280 amps in the negative direction before it returned to normal levels just 9.0ms into the fault period. During this excursion, the conductor voltage dropped 17.6kV (an exponential decay to 1.1kV with a decay time constant of 17us) before exhibiting a typical high power arc voltage profile (two half cycles clipped at +600 volts and -700 volts) for 6.3ms.

On-site records revealed the fulgurite arc extinguished and normal soil current behaviour (about one amp) was recorded from that point on. The conductor voltage recovered to about 4.0kV before the RCC response at around the 60ms mark reduced it to normal residual voltage levels.

Figure 70: Test 208 fulgurite formation in a GFN test - on-site recordings

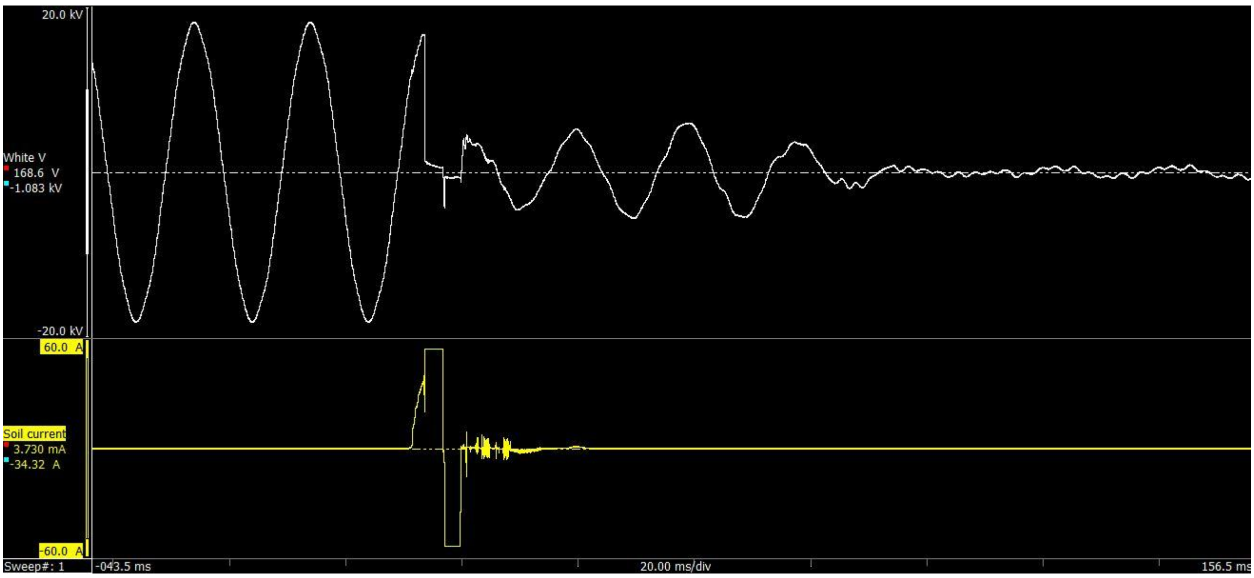
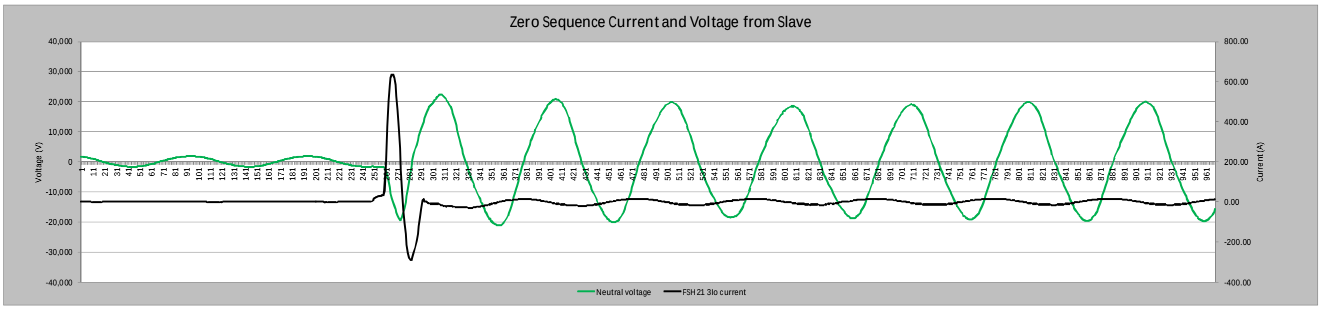
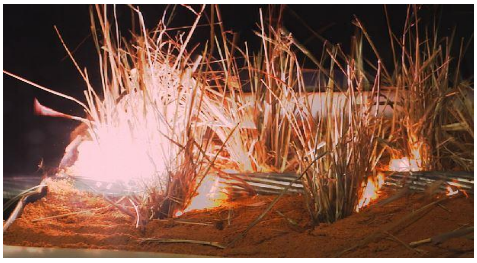


Figure 71: Test 208 - fulgurite formation in a GFN test - GFN records



High speed video showed the typical appearance of a fulgurite: extremely bright light emission and ejection of incandescent molten material flowed by ignition of vegetation.

Figure 72: Test 208 high speed video record of fulgurite formation

		
Test 208: last frame prior to fulgurite formation (normal one amp soil current arcs)	Test 208: first frame after fulgurite formation (600 amp fulgurite arc)	Test 208: 28ms after fulgurite formation (vegetation flame)

The fulgurite current in Test 208 was too brief to form the normal glass-lined tunnel through the soil bed. However, the track of the current was clearly visible as can be seen in Figure 73.

Figure 73: Test 208 fulgurite track through soil

The fulgurite formation in Test 208 exhibited a number of anomalous features:

1. It was the only instance of fulgurite formation in more than a hundred REFCL tests (apart from Test 217 described below which was the result of a heavy cross-country fault).
2. The fulgurite formed within three milliseconds of conductor-soil contact. This rapidity had never been seen before, even with the prototype metal-sided soil bed designs which were quite susceptible to fulgurites. Typically, fulgurite onset times were tens to hundreds of milliseconds.
3. The arc current in the fulgurite was not 50Hz current but appeared to be around (but not quite equal to) the third harmonic, with a period close to 6.3ms.

4. The fulgurite arc extinguished after a single cycle of heavy current. No other fulgurite had been observed that had done this. In all other cases, once a fulgurite had established itself to the extent it had conducted current for two half cycles, it persisted until the power was cut off.
5. Test 208 was a GFN test with zero series resistance between the network and the test rig. It was known that this configuration produced what appeared to be a form of ferro-resonance in bolted fault tests.

No clear conclusion was reached in the brief investigation of Test 208. However, the ignition that resulted was regarded as anomalous and not included in GFN bounce ignition results.

8.4.3 Test 217 – fulgurite formation due to a cross-country fault

In Test 217 a cross-country fault occurred during a GFN ignition test with a 100 ohm resistor in series in the rig supply. This caused the voltage applied to the rig during the test to rise to 22,000 volts and a fulgurite formed quickly after the second conductor bounce.

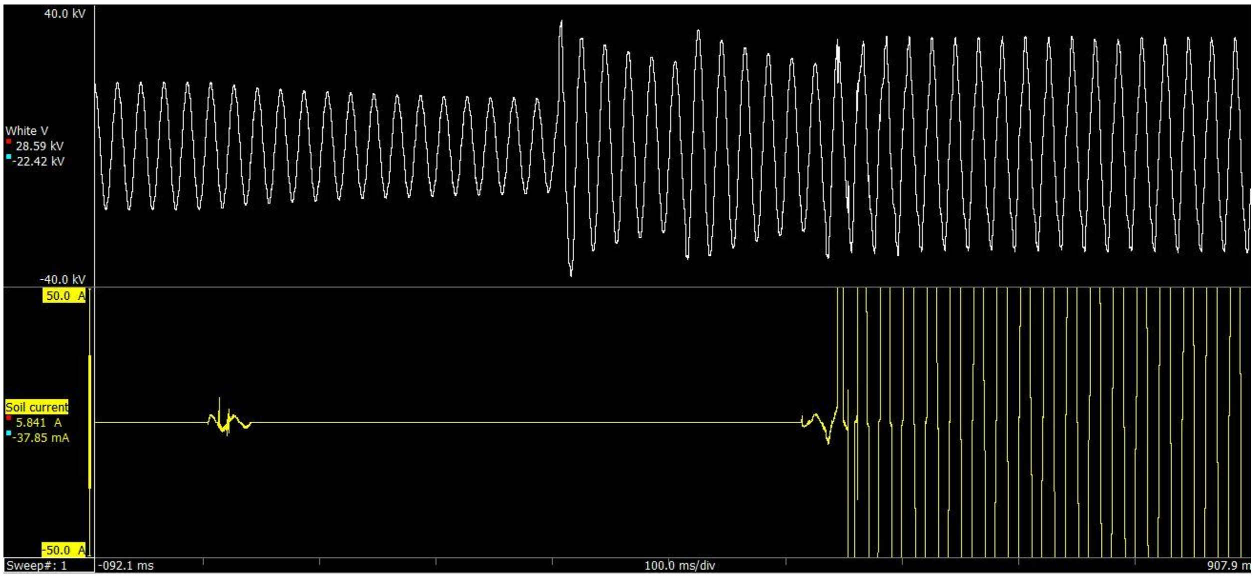
The current and conductor voltage in Test 217 are shown in Figure 75. The soil current peaked at 1.7 amps on the first bounce. The GFN did not immediately detect the fault so the initial white phase voltage collapse followed the natural ASC-style reduction due to the initial pulse of fault current. However, just as the GFN detected the fault and triggered the RCC response to reduce the conductor voltage, while the conductor was between bounces and with the conductor voltage at about 9,000 volts, a heavy cable fault occurred on blue phase instantly increasing the conductor voltage to 22,000 volts. The RCC was trying to compensate for a white phase fault and was overwhelmed by the heavy blue phase fault – the GFN log indicated it most likely tripped on overload and took no further part in events.

In the absence of RCC compensation of the blue phase cable fault, it re-struck twice by the time the conductor again contacted the soil bed. When the second bounce occurred, the soil current was a few amps for 30 milliseconds before a fulgurite formed. The current immediately increased to about 200 amps (limited only by the 100 ohm series resistor in the test rig supply) for the remaining 1.8 seconds of the test duration.

The mouth of the fulgurite formed in this event is shown in Figure 74. The glass lining of the hollow tube that contained the arc is clearly visible.

Figure 74: fulgurite formed in Test 217

Figure 75: Test 217 fulgurite formation due to cross-country fault



8.5 Appendix E: HRL Technology REFCL Trial report