EFD SWER Trial

Final report

23 June 2019

IND Technology Pty Ltd

EFD: Early Fault Detection – a proprietary powerline monitoring technology that detects incipient powerline faults before they occur. The patented EFD product has been developed and is manufactured by IND Technology Pty Ltd in Melbourne Victoria Australia.

SWER: Single Wire Earth Return – a powerline technology that uses a single high-voltage wire to carry current to remote customers, the current returning to the source through the Earth.

Disclaimer

This report outlines the results of a trial carried out for the Victorian Government's Powerline Bushfire Safety Program at various locations in rural Victoria from late 2017 to mid-2019 in accordance with a Funding Agreement between IND Technology Pty Ltd and the Victorian Department of Environment Land Water and Planning dated 20th June 2017.

This report contains observations, analysis, commentary, interpretation, findings and recommendations.

Subject to the Funding Agreement, no warranty can be offered to third parties for:

- The application of anything in this report for any purpose other than those required by the specific objectives of the Trial as outlined in the body of this report.
- The direct application of anything contained in this report to any situation other than those specific Trial situations that are recorded in this report.

Readers should in particular note the following qualifications:

- The information in this report relates to 12.7kV SWER powerlines only. Readers who wish to use information in this report to derive conclusions for other types of networks or networks in other locations or environments should rely on their own investigations.
- Reasonable care has been taken to outline the rationale and evidence for findings. Readers should make their own judgements of the merits of any of the findings set out in this report before relying on them.
- Quantification of statistical uncertainty has not generally been possible and readers should form their own judgement of the level of confidence they should have in the observations and findings set out in this report.
- Many assumptions were used to generate insights, derive findings and interpret data obtained from the Trial. All reasonable care has been taken to explicitly document these assumptions and explain the rationale in each case, but no warranty can be offered that such documentation is complete or that any implicit or explicit assumptions used are valid.
- Where mathematical theory has been used to derive insights from Trial data, care has been taken to indicate the theory and how it was applied. However, no warranty is offered that the theory employed is valid or correctly applied.

Readers are advised to rely on their own analysis if they wish to use this report for any purpose other than the specific objectives of the Trial as outlined in the body of this report.

Contents

1 Headline finding: EFD fire-risk benefits proven in SWER Trial

The EFD SWER Trial tested EFD technology on eleven SWER networks in rural Victoria to gain experience and assess its value as a fire-risk mitigation tool. EFD technology provided continuous powerline monitoring to detect network asset damage or deterioration, vegetation encroachment and other incipient faults that may cause fires, supply outages, or both.

The EFD SWER Trial was the product of a partnership between the Government of Victoria (which provided the enabling grant), IND Technology Pty Ltd (manufacturer of EFD technology), and Victoria's two major rural network owners, AusNet Services and Powercor. This partnership successfully achieved the objectives set for the Trial.

The Trial demonstrated the materiality of fire-risk reduction available from EFD technology. It covered less than one per cent of Victoria's SWER powerlines for a period of 18 months. Despite that limited scope and duration, it identified a number of real powerline bushfire risks in high fire consequence areas and demonstrated how EFD data could transform asset management in network businesses. Experience gained during the Trial also drove major enhancements to EFD technology's incipient-fault detection performance.

This report documents the EFD SWER Trial and outlines the rationale for EFD technology to be considered for a role in Victoria's future powerline bushfire safety.

1.1 Summary of EFD SWER Trial findings and recommendations

The EFD SWER Trial findings and recommendations are listed in Table 1 and spelled out in more detail in Sections 13 and 14.

Table 1 List of findings and recommendations from the EFD SWER Trial

Findings	
1	The EFD SWER Trial met its objectives.
2	EFD technology can cut fire-risk on rural SWER powerlines.
3	EFD data can support pre-emptive asset replacement and maintenance programs.
4	EFD technology has been greatly improved by the SWER Trial.
Recommendations	
1	Consider EFD SWER Trial findings in Victoria's powerline bushfire safety regulatory context.
2	Retain the EFD SWER Trial installations for a longer period of learning.
3	Develop new procedures, skills and tools to investigate EFD signal sources.
4	Consider EFD systems for REFCL operational challenges.
5	Review standard substation designs to cut EFD deployment cost.

1.2 The EFD SWER Trial objectives were achieved

The EFD SWER Trial had two specific objectives, both of which were fully achieved:

Table 2: Trial objectives were achieved

Trial objective	Achieved
Gain experience of IND.T's EFD technology operation on real SWER networks	Eighteen months of experience on eleven SWER networks led to identification of several practical issues and enabled enhancements to EFD technology's fire-risk mitigation benefits.
Measure the potential of EFD technology for fire-risk reduction in rural Victoria	Material fire-risk mitigation benefits were identified: three fire-risk situations were detected and addressed in high fire consequence locations. Three other asset issues were identified that may pose indirect longer-term fire risks.

The Trial allowed Host Network Owners, AusNet Services and Powercor, to gain in-depth understanding of EFD technology and its potential to benefit their businesses, their customers, and the communities they serve.

The Trial also excited strong interest among interstate and overseas network businesses, particularly those with powerline bushfire safety challenges similar to Victoria. Network businesses in Australia, the US and China have studied the experience gained in the Trial and decided to install EFD systems on additional networks.

1.3 EFD technology identified three fire-risk situations in the Trial

Three fire-risk situations were detected early by EFD technology during the Trial as summarised in Table 3. Each was addressed by the network owner to mitigate fire risk.

Table 3: Summary of fire-risk situations detected early by EFD technology

Date	Location	Situation	Response
28th May 2018	Ross Creek	Broken strand on powerline	Immediate repair.
12th June 2018	Ross Creek	Arcing low-voltage service line	Repair under ESV temporary exemption, followed by replacement with underground line.
Up to 3rd January 2019	Midway between Beechworth and Chiltern	Suspected high energy partial discharge inside substation transformer	Asset replacement after risk analysis (high fire risk weather, high fire consequence location, increasing risk of asset failure).

The three detected situations were:

1. **Broken steel strand on a powerline:** This case received attention from regional media. It was exactly the same pre-fault situation as that implicated in the disastrous Kilmore-East/Kinglake fire on Black Saturday which caused huge loss of life and property. The broken strand was above a grassy paddock in rolling hills south of Ballarat, i.e. the fire consequence of a fallen powerline in worst-case conditions could be high.
2. **Arcing low-voltage service line:** The failure of this privately-owned overhead low-voltage service line was of a type that has led to fires in the past. Regulatory changes in 2009 require such lines be progressively replaced with underground cable to prevent fires. This fault was detected only half a kilometre from the broken strand detection. Again, fire consequence in worst-case conditions could be high.
3. **Deteriorating substation transformer:** This transformer problem was at an unoccupied house next to an extensive heavily wooded area north-east of Beechworth, i.e. with very high fire consequence. Signals received by the nearest EFD sensor were becoming more intense at the same time as the weather was deteriorating towards extreme fire risk levels. The decision to replace the transformer was informed by all the circumstances and by historical experience of transformer failures starting fires. It was also designed to reveal whether the detected discharge was in the transformer or on the low voltage supply to (or within) the customer's premises. Replacement of the transformer appeared to fix the immediate problem and monitoring is continuing in case it recurs.

The three EFD-detected situations had clear significance to fire-risk. It was concluded that on the evidence from the Trial, EFD technology offers potential fire-risk benefits sufficient to be of material significance to Victoria if it were to be applied more widely across the State's rural SWER networks.

1.4 EFD technology identified the one or two per cent of assets with heightened risk

In addition to the situations listed in Table 3 above, EFD technology detected and continuously monitored a small number of network assets that exhibited intermittently high levels of signals indicating abnormal electricity discharge. Among the 924 poles (311 of which had substation transformers mounted on them), three poles appeared to have assets that were actively deteriorating by intermittent abnormal electricity discharge.

Two of the three sources of abnormal signals were located by EFD systems to an accuracy of ten metres on inter-sensor network paths. They both proved to be at substation poles. The third was located at the end of a spur line beyond the inter-sensor network path and again, was considered to be most likely located at the termination substation pole. The circumstances are summarised in Table 4. All three sites were inspected with no cause found. EFD data, local fire-risk and inspection reports were considered and decisions taken to continue monitoring but take no immediate action.

In earlier trials on urban networks, EFD technology has detected vegetation encroachment and damaged insulators, but no instances of these problems were identified in the EFD SWER Trial.

Table 4: Network assets identified by EFD technology with abnormal electrical discharge signals

Location	Asset situation	Observations
Between Mt Doran and Bungal	Wood pole with substation transformer supplying one property.	High discharge energy, intermittent, very active in Summer, quiescent in Winter; discharge type similar to in-tank transformer discharge, no visible fault.
West of Bungal	Concrete pole with substation transformer supplying one property.	Medium discharge energy, intermittent, not seasonal, unknown discharge type, no visible fault.
Between Springhurst and Peechelba East	Wood pole with substation transformer supplying multiple residences and farm sheds.	Medium discharge energy, very intermittent, not seasonal, unknown discharge type, no visible fault.

1.5 EFD technology demonstrated excellent performance

The EFD SWER Trial confirmed that EFD technology had sensitivity, signal-to-noise ratio and location accuracy that exceeded all stakeholder expectations. The first sign of EFD technology's sensitivity was when it was realised that the EFD systems were detecting and locating the impacts of individual raindrops on the powerline conductor during heavy storms. Deep investigations into the EFD data revealed background noise levels were generally at least one order of magnitude less than the smallest signals from network assets. At higher signal strengths the signal-to-noise ratio was around one million to one. Detailed investigations also demonstrated that signal sources were located to an accuracy of plus or minus ten metres, which was the same order of accuracy as pole location records in network owners' databases.

The EFD SWER Trial demonstrated the performance of the EFD system exceeded any level that could reasonably be required for network operation and asset management.

1.6 EFD technology was greatly enhanced in the course of the SWER Trial

The EFD SWER Trial provided the opportunity and drive for a major redesign of EFD technology. The hardware redesign greatly reduced manufacturing cost and allowed the Trial scope to be expanded beyond the original plan within the original budget. The torrent of data from the 61 EFD units was channelled to users through a web portal with map-based intuitive visualisations of network condition and full drill-down to individual assets. Early Trial experience led to further system enhancements that achieved excellent accuracy and signal-to-noise ratios by eliminating sources of error and extraneous noise.

2 SWER powerlines started major fires on Black Saturday

Powerlines can cause catastrophic bushfires and have done so in past episodes of fire in Victoria. On Black Saturday the 7th of February 2009, SWER powerline failures caused some of the worst fires.

Figure 1: catastrophic fires have been started by powerlines in Victoria

There are three ways powerline faults start fires:

1. High voltage electric arcs near vegetation, usually dry grass (wire down).
2. Vegetation conducting high voltage current (tree touching wire or wire dropped into bush).
3. Incandescent particles landing in dry grass (when live wires clash).

The most catastrophic fire on Black Saturday (the Kilmore East – Kinglake fire), started when a SWER powerline fell to the ground and ignited dry grass. Two other major fires that day (the Horsham and Coleraine fires) were started by SWER powerlines that came loose and contacted nearby vegetation.

Since Black Saturday, the Government of Victoria has sponsored a major program of research to better understand how powerlines start fires and to find ways to cut powerline fire-risk. This research has shaped a multi-faceted program of work to improve powerline bushfire safety. Action on SWER powerlines has included selective undergrounding and use of covered conductor, and the installation of more than 2,000 high-sensitivity, fast-acting, remotely-settable automatic circuit reclosers (ACRs) to more quickly detect and isolate faulted SWER powerlines when fire-risk is high.

ACRs can operate fast enough to prevent fires from SWER powerline faults provided the fault causes sufficient increase in powerline current to be quickly detected. However, ACRs cannot detect low-current faults because the fault current cannot be distinguished from normal variations in customer load current. Unfortunately, low-current faults can still cause fires. The detection of low-current faults on SWER powerlines is one of the last remaining gaps in the powerline bushfire safety tool kit. As yet, there is no reliable method to detect low-current SWER faults quickly enough to prevent a fire so there is a high focus on improved network operation and maintenance to prevent such faults.

This situation led to the Victorian Government's sponsorship of the EFD SWER Trial reported here.

3 EFD offers ground-breaking high-technology for SWER networks

EFD technology is a continuous powerline monitoring system that detects radio frequency (RF) signals emitted by incipient powerline faults, i.e. situations likely to develop into faults if left unremedied. EFD works independently of the mains-frequency operation of the powerline and finds incipient low-current faults on SWER powerlines just as well as it finds incipient high-current ones.

RF signals emitted by electricity distribution network assets can be an early indicator of risk of failure. They can be caused by abnormal electricity leakage, high levels of corona discharge into the air and internal micro-arcing inside electrical equipment. Information on the location, intensity and nature of these RF signals can be used to detect incipient equipment failure. Suitably processed, such information can be used to launch preventive maintenance in time to avoid equipment failure and remove risk of consequential fire-starts and customer supply interruptions.

The RF signals produced by degraded equipment can radiate outwards through the air and be detected by mobile vehicle or helicopter patrols to identify sections of the powerline network for more detailed investigation. On-site surveys using ultrasonic acoustic sensing and corona cameras can then pinpoint specific components that are arcing, tracking or leaking current.

This approach has severe limitations: it is inherently a point-in-time check and offers no guarantee of detection of faults yet to emerge; emissions from degraded components are very intermittent and may not be present when a patrol or survey is performed; patrol identification of areas for on-site investigation may not be sufficiently accurate; and, radiated emissions may be masked by other sources of RF interference such as industrial or agricultural machinery or nearby radio transmitters.

The other transmission channel for RF emissions from failing components is along the powerline itself. Powerline wires can act like wave-guides enabling long-range transmission of weak RF signals. A network of regularly-spaced fixed sensors can continuously 'listen' for RF signals carried along powerline wires. The GPS satellite network offers very accurate time-synchronisation for RF signal detection, so detections from multiple sensors can triangulate the location of the RF signal source.

Because mobile surveys are not involved, this monitoring can be automatic and continuous (24/365) and the location algorithm inherently discriminates against RF interference from extraneous sources that are not powerline related. EFD technology applies this approach as shown in Figure 2 below.

EFD technology is a patented award-winning product of a Melbourne-based company, IND Technology Pty Ltd. It has been deployed by a number of electricity network companies in Australia, USA and an electric train company in Hong Kong.

EFD technology has been proven to successfully detect:

- Deteriorating and damaged equipment along powerlines;
- Powerline vegetation encroachment; and
- Underground cable deterioration.

EFD technology can reveal many of these conditions before they develop into powerline faults. This can guide preventive maintenance responses including vegetation trimming, replacement of failing and damaged equipment, and site assessment and remedy of poles that it identifies as fire-prone. In conditions of high fire-risk, even faster response processes can address fire-risk in rapidly emerging high-risk situations detected by the EFD equipment.

Figure 2: EFD technology concept

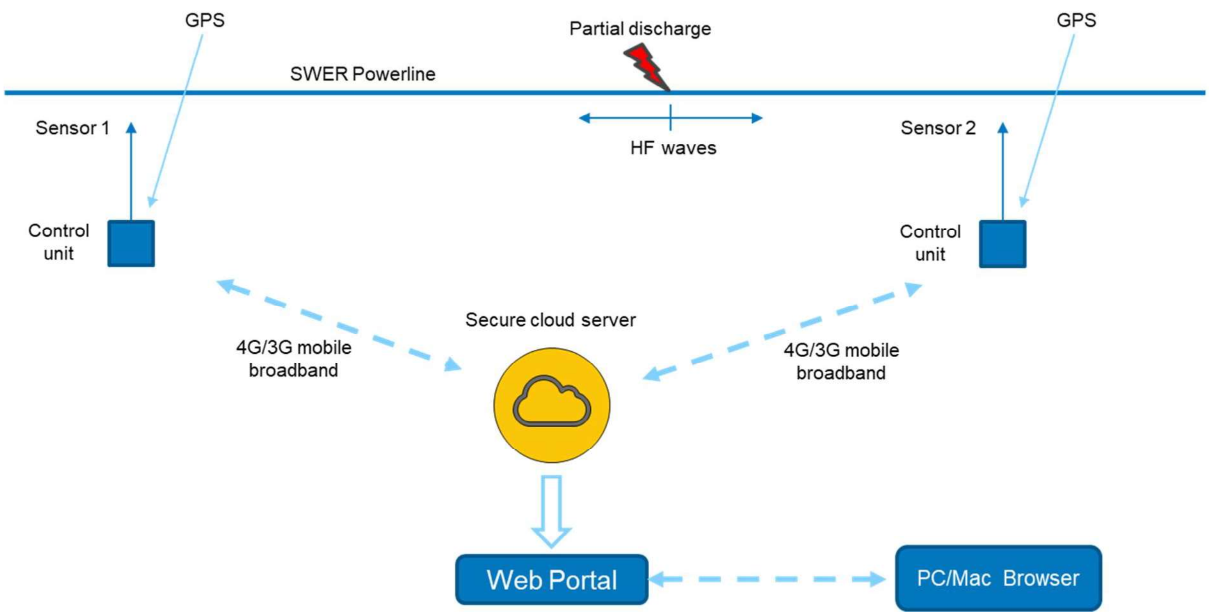


Figure 2 shows how data streams from EFD sensor units typically located four to five kilometres apart are sent over a 4G/3G communication network to a secure cloud server where complex algorithms correlate and analyse data from multiple sensors. The cloud server database populates a web portal with rich data visualization. Network businesses can thereby identify emerging issues and develop preventive maintenance strategy and take operational decisions in response to detected asset deterioration or damage and incipient or actual faults.

The EFD SWER Trial provided valuable experience of a medium scale rollout of EFD technology on real networks. It addressed many technical questions, including those about the detection range for powerline RF sources and the best ways to differentiate emission patterns produced by different types of equipment deterioration and faults. Algorithms to identify the comparative risk of a network fault at each signal source location were refined as experience was gained in the Trial.

The Trial revealed that EFD technology works well on real networks and can deliver material fire-risk reduction benefits. It also revealed that enhancement of work processes in network businesses would deliver further benefits in asset management activities. Further changes in operational activities to effectively respond to rapidly changing situations such as sudden emergence of strong signals that indicate an imminent fault would likely yield even more benefit.

Existing business processes in electricity distribution companies are designed around the concept of fast, effective response to network faults after they occur (and have resulted in supply outages or fires). For maximum benefits from EFD technology, new business processes must respond to warnings of imminent faults that have not yet happened. This is a profound change.

4 EFD SWER Trial – a government/industry research partnership

The SWER Trial of EFD technology followed successful detection by an EFD system of vegetation ignition tests in 2015 during a major ignition research program carried out by the Victorian Government as part of the Powerline Bushfire Safety Program. IND.T approached the Victorian Government with a proposal to trial its EFD technology on rural SWER networks to assess its fire-risk reduction benefits. From this initial discussion, the EFD SWER Trial project was eventually formed with major contributions from the Victorian Government, IND.T, and Victoria's two rural network businesses, AusNet Services and Citipower Powercor. The $1.3M project ran from mid-2017 to mid-2019.

4.1 IND.T's Proposal and the Victorian Government Grant

IND.T's proposal submitted to the Government on the 1st of September 2016, was for a total of 30 EFD units to be installed across two SWER networks, each of about 80 kilometres total route length. This prompted an extended conversation that culminated in execution of a Funding Agreement on the 20th of June 2017 between the State of Victoria (represented by the Department of Environment, Land, Water and Planning) and IND Technology Pty Ltd. Key terms of the Agreement documented the following features of the Trial:

Objectives:

1. Gain experience of IND.T's EFD technology operation on real SWER networks; and
2. Measure the potential of the technology for fire-risk reduction in rural Victoria.

Phases:

1. **Establishment:** Six months of design development, production and installation of multiple EFD detection units on SWER networks selected in consultation with Host Network Owners. This phase included development and commissioning of a web 'dashboard' portal to portray results of analysis of the data flowing from the detection units.
2. **Monitoring and reporting:** Eighteen months of monitoring of network health and continuous improvement of incipient fault detection algorithms with progress reports every six months.
3. **Final report:** Production of a report (this report) suitable for wide publication, setting out the findings from the Trial and any appropriate recommendations for further action.

A grant of $650,000 was agreed to be paid in instalments on completion of four milestones up to the end of June 2019. This amount was required to be matched by IND.T, creating a total project budget of $1.3 million plus in-kind contributions from network owners.

4.2 Host Network Owners (HNOs)

IND.T approached both owners of rural SWER networks in Victoria, AusNet Services and Citipower Powercor Australia, to seek support for the project. Agreements were established between IND.T and the HNOs setting out the following commitments by both parties:

IND.T commitments:

- Provide an agreed number of EFD units and run training sessions for installation teams. The units to be solar powered to cut installation costs.

- Calibrate and commission the units to ensure they successfully provide data flow to the EFD secure cloud server.
- Provide access to a web portal 'dashboard' to allow HNOs to monitor the results of the EFD data analysis in near-real-time during the trial.
- Consult on draft project progress reports as well as in the drafting of the final project report.

HNO commitments:

- Work with IND.T to select one or more suitable SWER networks that best address the project objectives and to select the best installation locations for EFD units on those networks;
- Work with IND.T to define suitable pole-mounting hardware for the EFD units and a time-efficient installation procedure.
- Install the EFD units on the SWER networks.
- Work with IND.T to define and implement arrangements to receive alerts of incipient faults to complement the web portal dashboard monitoring facility.
- On advice of an incipient fault, arrange attendance by a field team and provide a report back to IND.T to support continuous improvement of EFD system performance.
- If EFD equipment should fail, assist IND.T to access the equipment to repair it.

4.3 Project plan and budget

The Funding Agreement defined the following project milestones which encapsulated the Trial plan:

Milestone 1: August 2017

The first part of the establishment phase comprised design of key hardware and software and placement of orders to commence manufacture, as well as selection of networks and installation sites in consultation with Host Network Owners.

Completion criteria for this milestone were:

- Finalised documentation of arrangements with Host Network Owners.
- Design of EFD unit finalised and orders placed for procurement and manufacture.
- Orders placed for manufacture of web dashboard portal.
- SWER networks selected and installation sites finalised with Host Network Owners.

Milestone 2: September 2017

The second part of the establishment phase comprised delivery of hardware and software. The completion criteria for this milestone were:

- Delivery of EFD units ready for installation by Host Network Owners.
- Delivery of ancillary hardware (sensors, sensor brackets, cables, etc.).
- Delivery of web dashboard portal software.
- Commissioning of information processing infrastructure (secure cloud server).

Milestone 3: November 2017

The final part of the establishment phase was the installation of EFD units on the networks and the completion of procurement of services for the trial. The completion criteria for this milestone were:

- Data analyst hired and on-board.
- Cloud and 3G services ordered.

- EFD units installed and calibrated.

Milestone 4: June 2019

The final milestone spanned the extended 18-month monitoring and reporting phase. The completion criteria for this milestone were:

- EFD system results analysed and reported six-monthly (December and June).
- All revealed opportunities for improvement analysed and assessed.
- Six-monthly progress reports and final project report submitted.

4.4 Deviations from project plan

The only significant deviations from the initial project plan were:

- **Expanded scale:** Expanded scope was made possible by redesign of the EFD hardware to achieve manufacturing cost savings. The scale of the Trial was increased, with 65 EFD units manufactured and 61 units installed (two were reserved for software testing and two were swap-out spares). The number of networks increased from two to eleven and the total powerline route length covered increased from 160 kilometres to 250 kilometres.
- **Phased installation:** Installation of EFD units took place in two tranches rather than one: 39 units were installed in November 2017 and the remaining 22 units were installed in February 2018. This was to accommodate HNO field work priorities as the 2017/18 fire season approached. This change was not considered to have a material impact on achievement of the project objectives.
- **Solar power:** The standard design for SWER substations at the end of SWER powerlines excluded these sites from consideration as Sensor locations. This had two effects: all units had to be supplied by solar power (without a substation on the pole, 230-volt AC power was not available); and, inter-sensor path lengths were shortened by an average of 600 metres. These effects constrained the number of units (by diverting manufacturing funds into solar power supply kits) and reduced direct-path network coverage of the EFD system. However, these impacts were considered tolerable in the context of the Trial and did not threaten achievement of the Trial objectives.

5 EFD technology was redesigned for the SWER Trial

To ensure maximum trial scope within the project budget, the EFD product was re-engineered to minimise manufacturing cost.

5.1 Equipment re-design and manufacture

The EFD technology used in the Trial was an evolutionary development of earlier EFD product versions in small-scale use in other networks at that time. The SWER Trial EFD product became the third generation of EFD technology to be installed on real networks. The redesign addressed four well defined goals:

1. **Manufacturing cost:** The lower the unit cost, the more units could be deployed within the project budget and the more learning could be achieved in the limited duration of the Trial;
2. **Sensitivity:** SWER powerlines have high resistance and it was thought that signal attenuation was likely to be high. To preserve the target of five-kilometre monitored path length between pairs of EFD units, high sensitivity was a design goal;
3. **Installation:** The mechanical design of the EFD unit, the EFD sensor, and the solar power supply must allow easy installation; installation cost (contributed by the HNOs) was a material component of the overall cost of the EFD SWER Trial; and
4. **Maintenance:** The EFD units were to be installed in relatively remote areas and support and maintenance must be done remotely - requirements to visit sites to carry out maintenance should be minimised.

These design objectives resulted in a number of significant changes to the previous design:

- All functions were combined onto the minimum number of circuit boards. The core data processing functions in particular were integrated onto a single multi-layer circuit board;
- Size and weight of the units were both reduced;
- Signal digitisation resolution was reduced from 16 bits to 12 bits (the high-speed analogue-to-digital converter was one of the highest cost items in the design);
- The units were mass-produced in one batch – many suppliers of components and assembly services offered significant discounts for a large batch run;
- A new solar power supply kit was designed with sufficient battery capacity to operate the unit for four days without sun and the solar panel size was based on the best available data on insolation levels in the deployment areas; and
- A sensor bracket was developed to allow simple pole mounting to support the EFD sensor 1.2 metres below the powerline.

The result of the redesign was that 65 units were manufactured within the project budget, more than double the originally proposed 30 units based on the previous design. Two units were dedicated to testing software/firmware upgrades and two were held as swap-out spares.

Figure 3: EFD equipment – EFD unit interior, sensors with brackets on pallet

5.2 The web portal

Each EFD unit generated a torrent of data – one record per second or 31 million records per year. Normally, less than one per cent of this data was able to be matched to a record from another EFD unit to identify the signal source location on the inter-sensor network path[1]. However, all the data was useful in monitoring the health of the powerline network. Even if not matched, the raw data on signal magnitude could indicate a problem with a nearby item of network equipment. This meant the secure cloud server processed and stored data at a rate of nearly two billion records per year.

Feedback from network businesses involved in previous EFD trials was that the full value of the system would only be realised when a simple way was found to communicate the implications of the EFD results in terms of risk, in particular the risk of fires and of customer supply outages. Simplicity was the over-arching goal of the EFD portal design and while further improvement will still be achieved as further experience is gained, the EFD SWER Trial web portal was a major step forward in data analysis and intuitive visualisation.

The EFD portal design reflected the following features:

- **Visual communication:** the portal presented maps, charts and pictures rather than tables and text - so technical users could more quickly grasp the essence of the EFD results.
- **Drill-down:** the portal presented a simple hierarchy of visualisations of increasing granularity: network to path to site[2] – allowing the user to drill into indications of a problem to fully understand what the EFD system was seeing and interpret the information in terms of network asset health and risk. A similar hierarchy was applied to time: 12 weeks to one week to one day, plus the most recent five seconds. A simple and consistent mechanism of 'mouse-over to view detail, click to drill-down' was used throughout.
- **'Bottom line' indicators:** the portal presented a simple risk score for each site (essentially one span), as well as simple indicator lights for dataflow status and emergent risks.
- **Security:** the portal and EFD units had strong system access security; each network business could only see their own network assets' data; data communications could be encrypted and

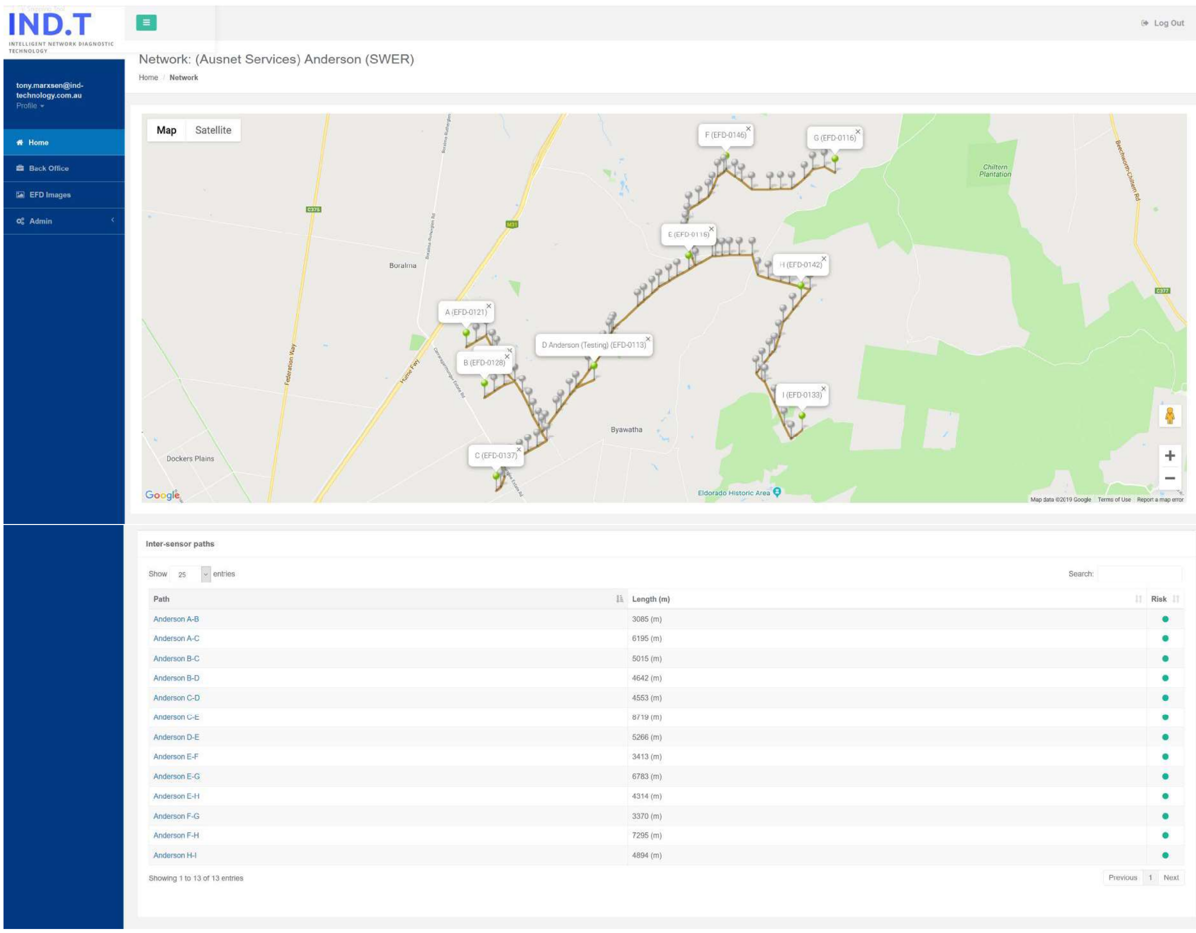
[1] If a strong continuous source was present on the monitored path this proportion increased to 50-95%.
[2] A site in the SWER Trial was generally the location of a pole. Site attributes could be added to show if it was a substation pole, a tee-off pole, etc. Pictures of the site could also be added.

authenticated by Virtual Private Network (VPN) technology; good practice security design was used for the secure cloud server infrastructure.

- **Scalability:** the portal and supporting cloud infrastructure were based on an underlying architecture designed to allow additional units to be easily added at lowest additional cost.

The EFD portal is a user-driven exploration tool and its value can only really be grasped when it is seen in active use. However, the following screenshots illustrate some of the portal features, using AusNet Services' Anderson network as an illustrative example:

Figure 4: AusNet Services' Anderson network page



In addition to its user-driven online functionality, the EFD portal offered powerful data download capability to support off-line analysis and investigation. The data and the time period were selected and the data downloaded to the user's browser as a csv file that could be opened in Microsoft Excel or MatLab. Many of the charts in this report have been produced using this facility.

Figure 5: The Anderson network F-G path page

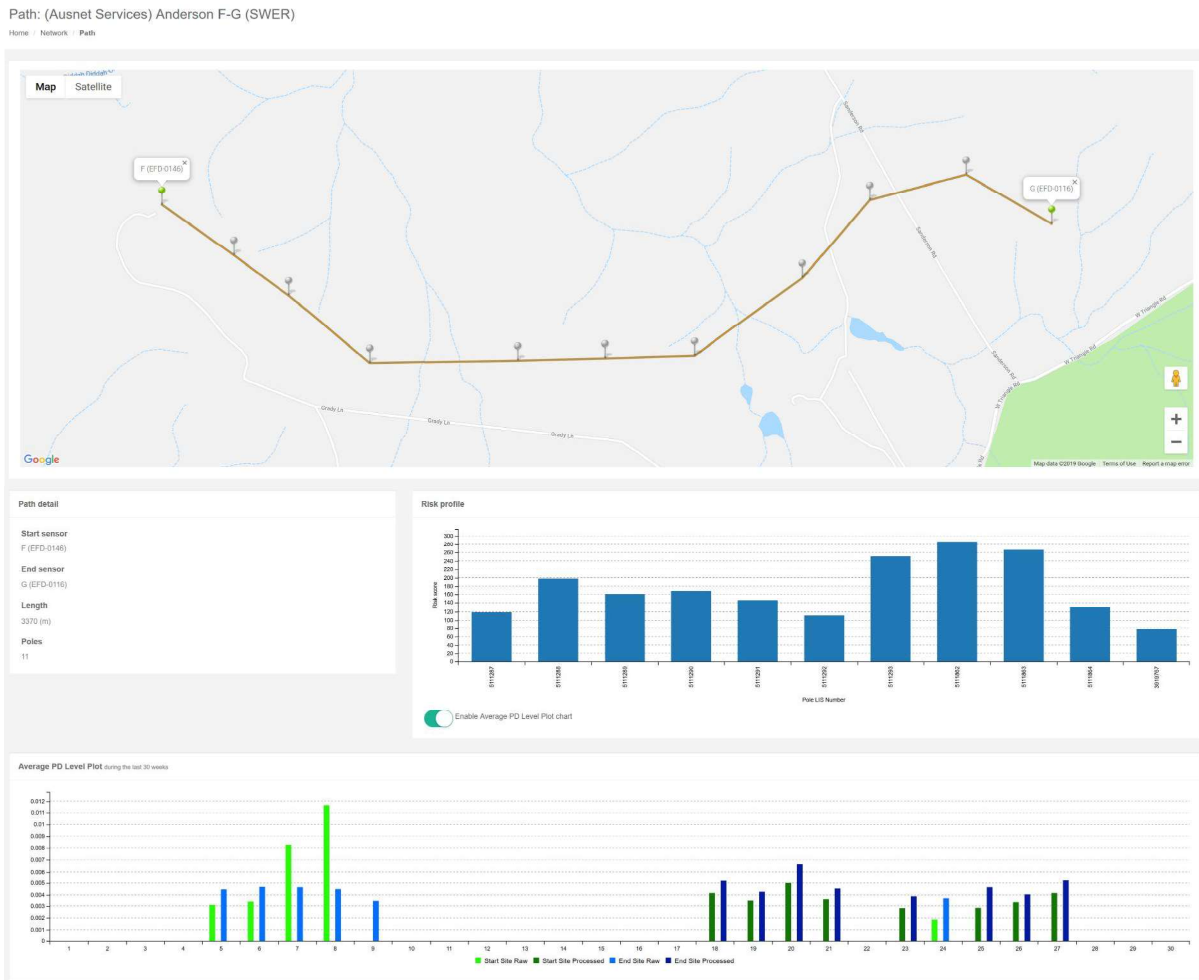
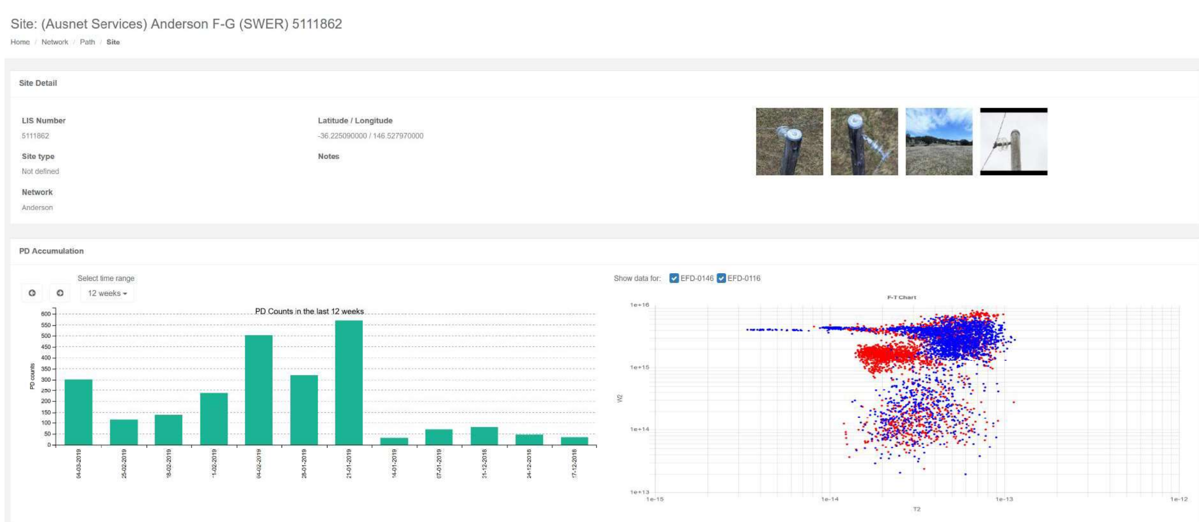


Figure 6: The site page for Pole 5111862 on the Anderson F-G path, showing 12 weeks activity



Throughout the Trial, EFD portal functionality was progressively enhanced, both to make it more intuitive and user-friendly and to improve the system signal-to-noise ratio and the accuracy of site risk scores.

6 EFD technology was installed on eleven SWER networks

The Trial included 61 EFD units deployed to cover 250 route kilometres of powerlines in eleven SWER networks, six near Ballarat in Western Victoria and five near Chiltern in northeast (NE) Victoria.

Installation of the EFD units took place in two tranches: 39 units in NE Victoria in November 2017 and 22 units around Ballarat in February 2018. To process the data from the units, secure cloud database infrastructure and the new web portal were populated with the standing data on pole locations, EFD sensor locations, paths (sensor pairs) and site data. The EFD units were fully operational as soon as they were installed on poles with their solar power supplies.

6.1 Network plans

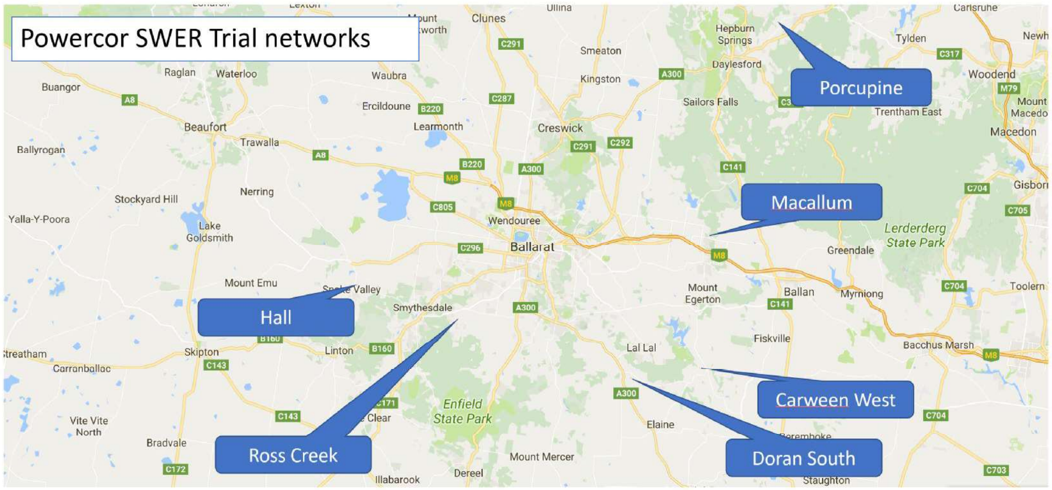
The two Host Network Owners nominated eleven SWER networks for the Trial. They reflected a diversity in size and circumstances and were selected according to specific criteria:

1. **'Troubled' networks:** Experience in previous trials was that there was little to be learned from a limited-time trial on a network that never had issues, so older networks that were considered more likely to have problems were preferred (but not ones so old they were planned to be replaced during the Trial period);
2. **High fire-risk:** The objective of the Trial was to assess the fire-risk benefits of EFD technology which could best be done in areas of the State where fire risk was a priority – at least two of the selected networks included 'codified' areas specified in the regulations as being of extreme fire risk, and many others included powerlines in heavily wooded areas; and
3. **Single depot:** The education and training challenge would be reduced if fewer operations and maintenance employees had to be involved, so sets of networks supported out of single depots were preferred. Depots at Wodonga and Ballarat North were chosen.

The SWER networks selected by the two HNOs were as shown in Figure 7 and Figure 8.

Figure 7: AusNet Services' SWER networks selected for the Trial

Figure 8: Powercor SWER networks selected for the Trial



Once the eleven networks were chosen, the EFD unit locations for each network were selected based on standard EFD planning rules to maximise the network coverage of the EFD system:

- **Path length:** No more than five kilometres between EFD units at each end of a monitored network path; and
- **Spur length:** All points on 'spur' powerlines should be within five kilometres of two EFD units wherever possible.

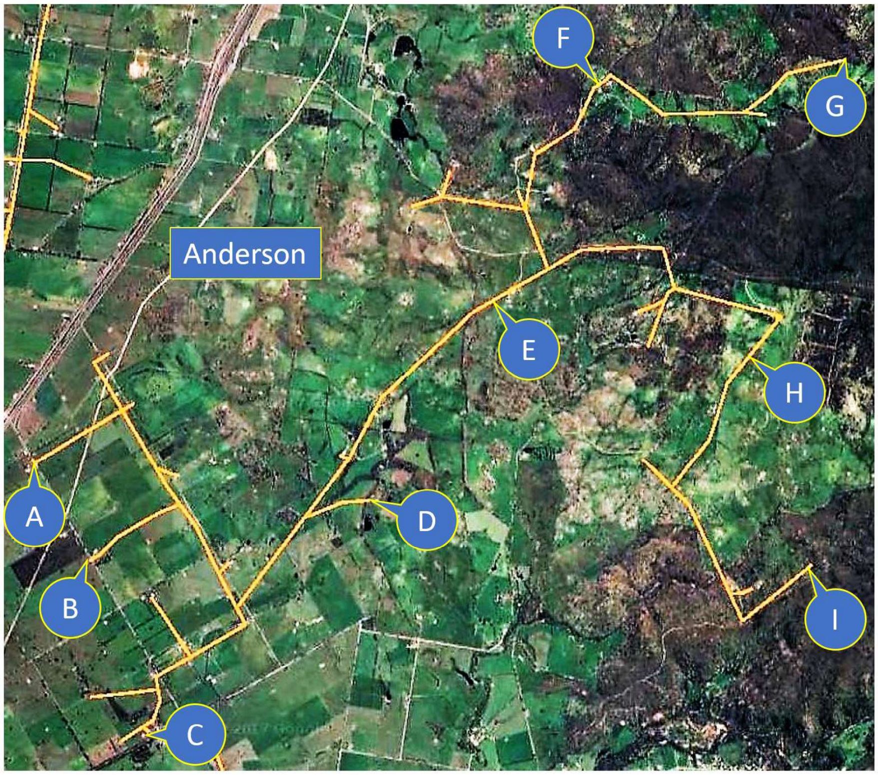
Powerline networks have a branching topology radiating from the point of supply – in a SWER network, this is the isolation transformer site where the network takes supply from a polyphase feeder. This topology usually limits available path lengths when selecting EFD unit locations. In the final design, the ratio of network route length to number of EFD units was around four kilometres per EFD unit, with 250 route kilometres of powerlines covered by 62 EFD units[3].

Figure 9: The 'as designed' allocation of EFD units to SWER networks

HNO		Network	Length (km)	Sensors	Off-path	Tee-offs
Powercor	1	Macallum	15	4	22%	10
	2	Porcupine	18	6	31%	14
	3	Hall	8	2	54%	5
	4	Ross Creek	16	4	53%	17
	5	Carween West	12	4	18%	7
	6	Doran South	12	3	37%	10
AusNet	7	Homestead	31	8	17%	12
	8	Beechworth Rd	47	11	16%	17
	9	Bryce	29	6	32%	16
	10	Carlyle	21	5	25%	11
	11	Anderson	41	9	21%	12
Trial total:			249	62	26%	131

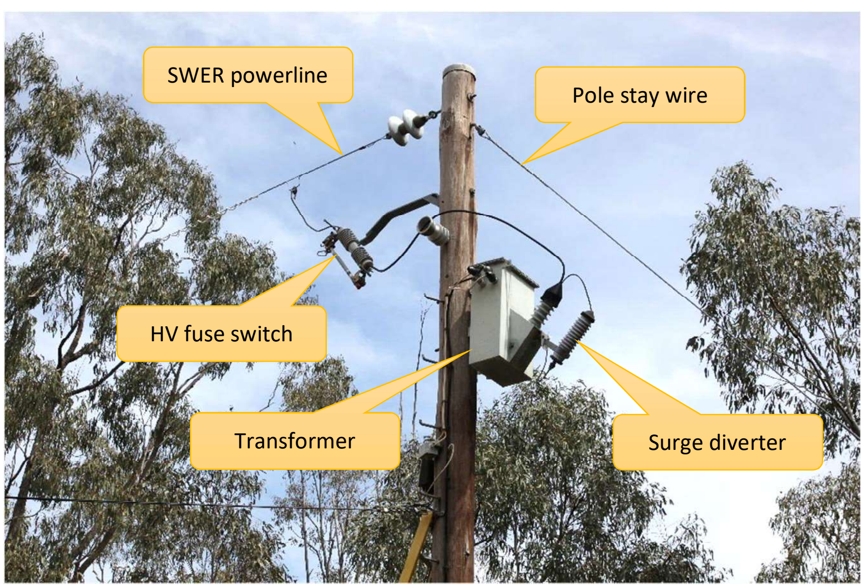
[3] For a number of reasons, an EFD unit planned for a SWER kiosk substation in the Porcupine network was not installed for the Trial, although laboratory tests confirmed it would work successfully.

Figure 10: An example of EFD unit site selection – AusNet Services' Anderson SWER network, preliminary design concept



During the design stage, it was recognised the standard powerline termination substation design precluded EFD units at termination substations - the stick-operated fuse switch supplying the transformer was directly under the powerline where the EFD sensor would have to be mounted.

Figure 11: Typical older termination pole with transformer (Thieke 3 substation)



It was decided not to modify the standard termination substation design, but instead to relocate EFD units from termination poles to the nearest unencumbered pole. With an average SWER span length of 300 metres, this reduced the length of many paths by about 600 metres (and sometime, much more) and consequently reduced the monitored paths from 74% of total route length in the original design to 66% 'as built'.

The 'as built' parameters of the Trial were as shown in Table 5.

Table 5: SWER Trial parameters ('as built')[4]

Network	Sensors	Spans	Path km	Poles	Route km	Path %	Path km/unit	Route km/unit
Anderson	9	93	29.7	94	41	73	3.30	4.6
Beechworth Rd	11	129	34.4	129	47	73	3.13	4.3
Bryce	6	61	17.7	62	29	61	2.94	4.8
Carlyle	5	53	14.3	54	21	68	2.87	4.2
Homestead	8	80	23.1	81	31	75	2.89	3.9
Carween West	4	28	6.0	29	12	50	1.49	3.0
Doran South	3	31	6.3	32	12	53	2.11	4.0
Hall	2	14	3.4	15	8	42	1.70	4.0
Macallum	4	38	11.0	39	15	73	2.74	3.8
Porcupine	5	40	11.3	41	18	63	2.26	3.6
Ross Creek	4	33	7.0	34	16	44	1.75	4.0
Total	61	600	164.2	610	250	66	2.69	4.1

The decision to not mount EFD units on powerline termination poles also meant all EFD units were fitted with solar power supplies rather than drawing on 230V supply from the termination substation. This had a budget impact that constrained the number of EFD units somewhat.

The precise number of substations was counted for the three largest networks and this number was used to estimate the total number of substations in the Trial, both on-path and off-path. Based on the three networks analysed, on average there was a substation for every 5.4 poles along inter-sensor paths and a substation for every 1.5 poles on off-path portions of the networks. This was consistent with most off-path substations being located at the end of short spur lines. Of the substations in the Trial, 58% of them were located off-path, mostly on spur line terminations.

6.2 Final Trial scope

The final scope of the Trial was as shown in Table 6:

Table 6: EFD SWER Trial key scope parameters

EFD SWER Trial Parameter	Value
Route kilometres of powerlines	250
Poles	924
Substations	311
EFD Sensors	61
Duration (months)	18

It is estimated Victoria has about 30,000 kilometres of SWER powerlines in rural areas, so the Trial scope covered a little less than one per cent of the total SWER powerlines in the State.

The number of customers supplied by each network and the maximum estimated fire consequence[5] is shown in Table 7.

[4] The parameters 'Spans', 'Path km', 'Poles' are data on the inter-sensor paths derived from the EFD web portal. The route kilometres data was supplied by the network owner.

[5] This is the estimate of the value (2018 dollars) of houses that might be destroyed by a fire on a Code Red day started in locations served by the network, i.e. in worst-case fire risk conditions similar to those on Black Saturday (2009) or Ash Wednesday (1983), assuming no effective response by fire services.

Table 7: customers supplied by each network, annualised fire risk and estimated maximum fire consequence

Network	Customers	Estimated annual fire-risk ($000s/yr)	Estimated worst-case fire consequence[6]
Anderson	60	$23.8	$690 M
Beechworth Rd	87	$36.2	$1,300 M
Bryce	51	$95.9	$3,100 M
Carlyle	34	$38.8	$980 M
Homestead	54	$4.1	$108 M
Carween West	51	$2.5	$28 M
Doran South	46	$1.5	$32 M
Hall	58	$2.2	$22 M
Macallum	37	$4.8	$64 M
Porcupine	90	$8.0	$43 M
Ross Creek	79	$5.3	$60 M
Total	**647**	**$223,100 per year**	**$22 million to $3.1 billion per event**

The total customers supplied by the eleven SWER Trial networks was about 0.3 per cent of the total rural electricity customers in the State. The risk values in Table 7 indicatively illustrate the likely order of magnitude of the value to the Victorian community of annualised and worst-case fire-risk addressed in the EFD SWER Trial.

6.3 Installation and commissioning

Training sessions were held for installation crews to discuss and agree the easiest way to mount the three items (control box, solar panel, and sensor bracket) of EFD equipment on both wooden and concrete poles. During the sessions, crews were able to inspect and handle the EFD equipment items and make suggestions about the best way to install them. IND.T oversaw the installations, initially to refine the installation procedure but later simply to commission the unit once it was on the pole. This consisted of switching the unit on and waiting a few minutes to confirm the secure cloud server was receiving data from it.

The EFD units were designed for installation without any requirement for a supply outage or special techniques (glove and barrier, or live-line); the sensor-to-conductor distance was set at 1.2 metres, so all work was performed outside Green Book standard Safe Approach Distance (SAD) for 12.7kV powerlines. Installation also included provision of a single-stake earth at the base of the pole.

The installation procedure worked well, with up to four installations per day per crew after initial crew familiarisation on the first day. Only two sites proved unsuitable at the installation stage – one site was in the middle of a ripening grain crop; and one had zero 3G signal level. Relocation of both

[6] Annual fire risk and worst-case fire consequence figures in Table 7 have been derived by IND.T from data provided by HNOs on different bases and should be treated with caution. AusNet consequence data was based on the number of residential properties estimated to be destroyed by a catastrophic fire occurring at that location in worst case conditions (Code Red), based on 2016 modelling. These numbers assume there is no effective response by fire services, e.g. the highest numbers assume complete destruction of substantial towns. They have been indicatively valued for the purposes of this report at an average of $400,000 rebuild cost per property and all other costs (agricultural losses, infrastructure losses) ignored. Powercor data included costs of stock and agricultural losses (plantations, etc.) as well as residential properties but were a weighted average of the cost of all major fires, not just catastrophic fires on Code Red days and so are lower than worst-case. The figures in Table 7 do not include broader economic costs to the community. The annual risk and consequence figures shown in this table should be regarded as illustrative order-of-magnitude only. Stakeholders including network businesses should rely on their own risk models if they need data on average annual and worst-case fire-risk.

sensors was agreed after IND.T planners checked the impact on monitored path lengths. The first installation (in NE Victoria) is shown in Figure 12.

Figure 12: Installation of the first EFD unit (of 61)

7 The EFD system was optimised to eliminate extraneous signals

For the SWER Trial, EFD system sensitivity was maximised to ensure the high attenuation of steel conductor did not cause loss of valuable information. Such high sensitivity meant that extraneous signals had to be reliably identified and filtered out to reveal signals coming from network assets.

Over the course of the Trial, major gains were made in the sensitivity of the EFD system and in the elimination of unwanted extraneous noise. These gains were expressed as a combination of high sensitivity and high signal-to-noise ratio. A simple filter based on a signal magnitude threshold was used in earlier EFD designs. This was replaced with a sophisticated blend of techniques that dealt with specific classes of noise: AM radio stations, rain, lightning, electric fences, and random coincidences of background noise impulses. This approach preserved maximum sensitivity and provided much higher signal-to-noise ratio – to a level more than adequate for network operations and asset management purposes.

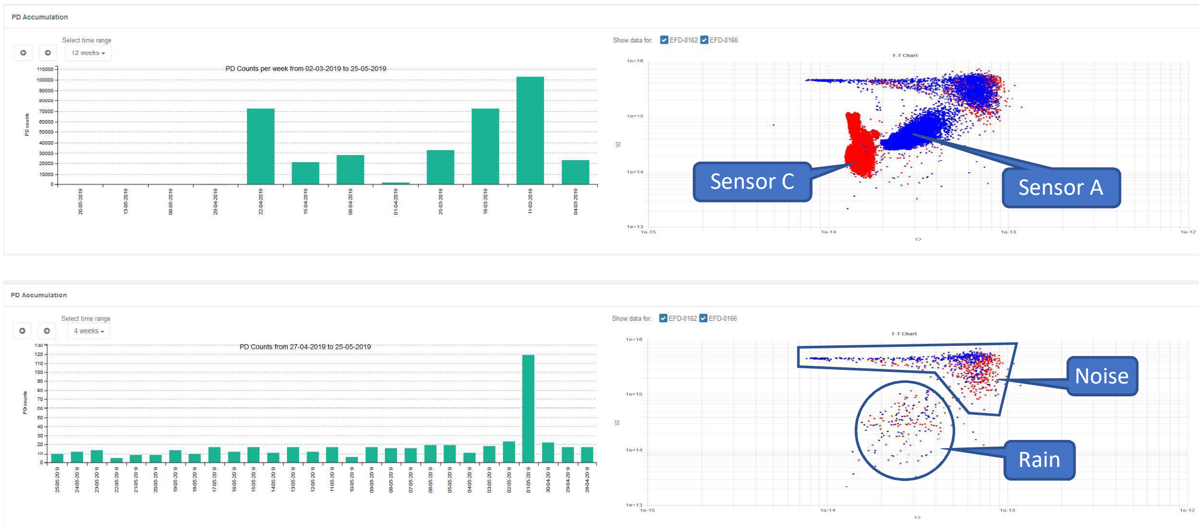
7.1 The EFD location algorithm is a powerful noise filter

For a signal to be recognised by the EFD system as coming from a source located on the inter-sensor path, the times of arrival at two sensors must be separated by no more than the time it takes for a signal to travel the whole length of the path between them, typically less than fifteen microseconds. In the data processing performed by the secure cloud server, signals that do not have a match within this narrow time window are not recorded as coming from a network location. This generally eliminates more than 99 per cent of the recorded signals. The signals that remain are those that may have emanated from a network asset. These are further filtered but the first and primary mechanism for eliminating extraneous signals remains the location algorithm.

For example, the most prolific signal source detected in the EFD SWER Trial was Pole 13105 on the Carween West network path between Sensors A and C. This source, thought to be in-tank partial discharge in the pole-mounted transformer at that site, produced 103,000 signals per week[7] at its peak in mid-March 2019, all of which were located in the 'transformer partial discharge' zone on the FT chart. This is still only six per cent of the signals recorded by the two sensors during that week – the other 94 per cent were rejected as not coming from locations on the network path between the two sensors. In its quiescent periods, only 10-20 signals per week were recorded from Pole 13105, which is 0.0008 per cent of the signals recorded by each sensor for the week, i.e. 99.9992 per cent were rejected. These signals were all in the 'random noise' and 'rain' zones of the FT chart as shown in the portal screen shots of Figure 13. The rain signals were all recorded between 5:00pm and 9:00pm on the 1st of May 2019.

[7] The peak rate during that week was 45,000 signals per day (17% of all signals recorded during that day) and 6,640 per hour (61% of all signals recorded during that hour).

Figure 13: Signals from Carween West network path A-C Pole 13105 during active and quiescent periods



The EFD SWER Trial confirmed that the basic concept of the EFD technology, location of network signal sources by time-of-flight calculations, was sound. It not only provided vital information to the network manager (the location of an active source on the network), but it filtered out the great majority of extraneous signals coming from non-network sources.

7.2 Random noise was filtered out

The EFD system identifies signal sources by correlating high-frequency signals received by two or more EFD units separated by distances of up to five kilometres. On a network carrying high-frequency random signals from multiple extraneous sources, occasional false correlations occur that were termed ‘phantom’ signal sources, i.e. two EFD units detect signals spaced close enough in time to be coming from a source on the inter-sensor path, but the two matched detections are not from a single source; the match is a random coincidence of background noise seen by the two EFD units.

The Trial enabled development of sophisticated algorithms to minimise ‘phantom’ detections. The most effective of these was a ‘detection quality’ score which discriminated between detections that could be considered reliable and those that were assessed as more likely to be caused by random noise. The ‘detection quality’ scores from each of the two EFD units were combined in logical functions to select signals that could be taken as coming from partial discharge in a network asset or another ‘real’ phenomenon located on the inter-sensor network path (e.g. rain), while ignoring those that could not be confidently associated with a real source.

Given the severe attenuation experienced when high-frequency signals travel over five kilometres of steel SWER conductor with multiple branching points, settings that ensured all ‘phantom’ events were eliminated would also have eliminated some valuable information on real signal sources, so a trade-off was struck based on experience. The final setting allowed a measured amount of random noise to appear in the network charts so that no ‘real’ sources were missed.

Figure 14 and Figure 15 show the benefit of noise filtering using the ‘detection quality’ scores. These two charts show the EFD system noise filtering performance improvement over the first 12 months of the Trial. In Figure 15 with random noise greatly reduced, the intermittent hot-spot at Pole 5111862 on the Anderson network path between Sensors F and G (the horizontal line of spots at 2,445 metres from Sensor F) is much easier to see, even at a much lower level of activity at that pole than one year earlier as shown in Figure 14.

Figure 14: Unfiltered EFD detections on the Anderson Path F-G (random noise, rain events and Pole 5111862 hot-spot)

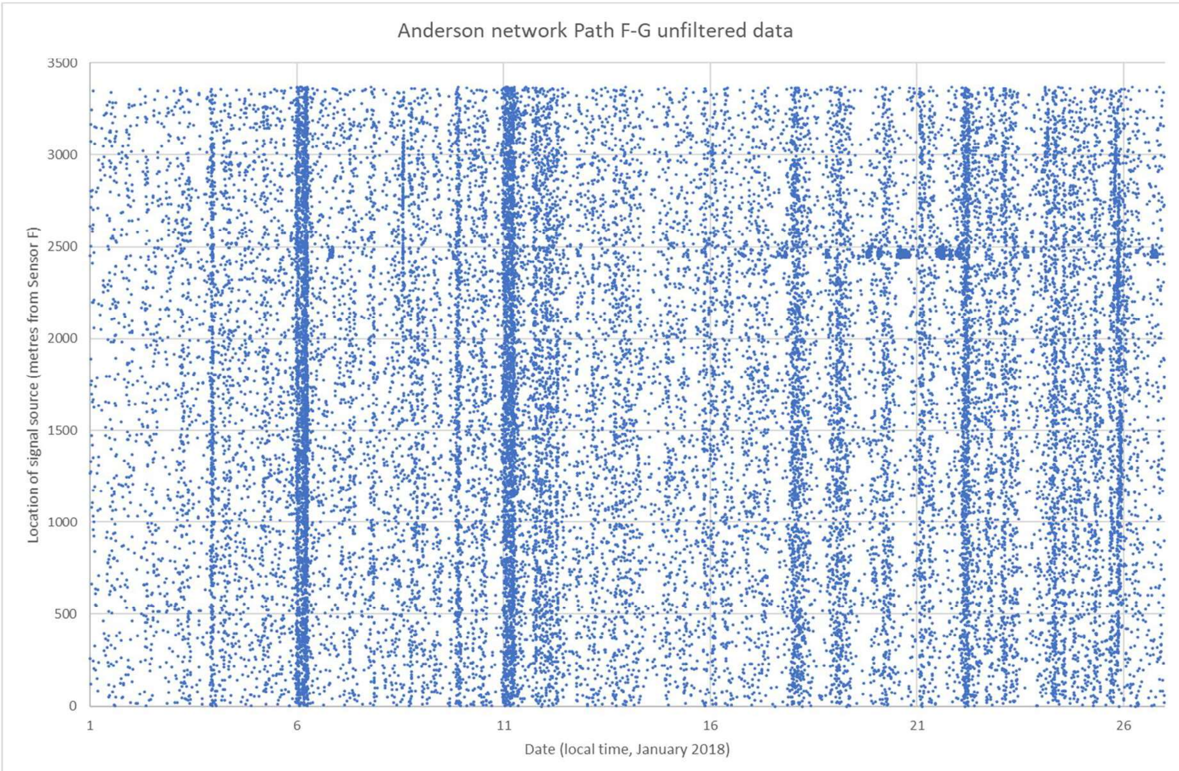
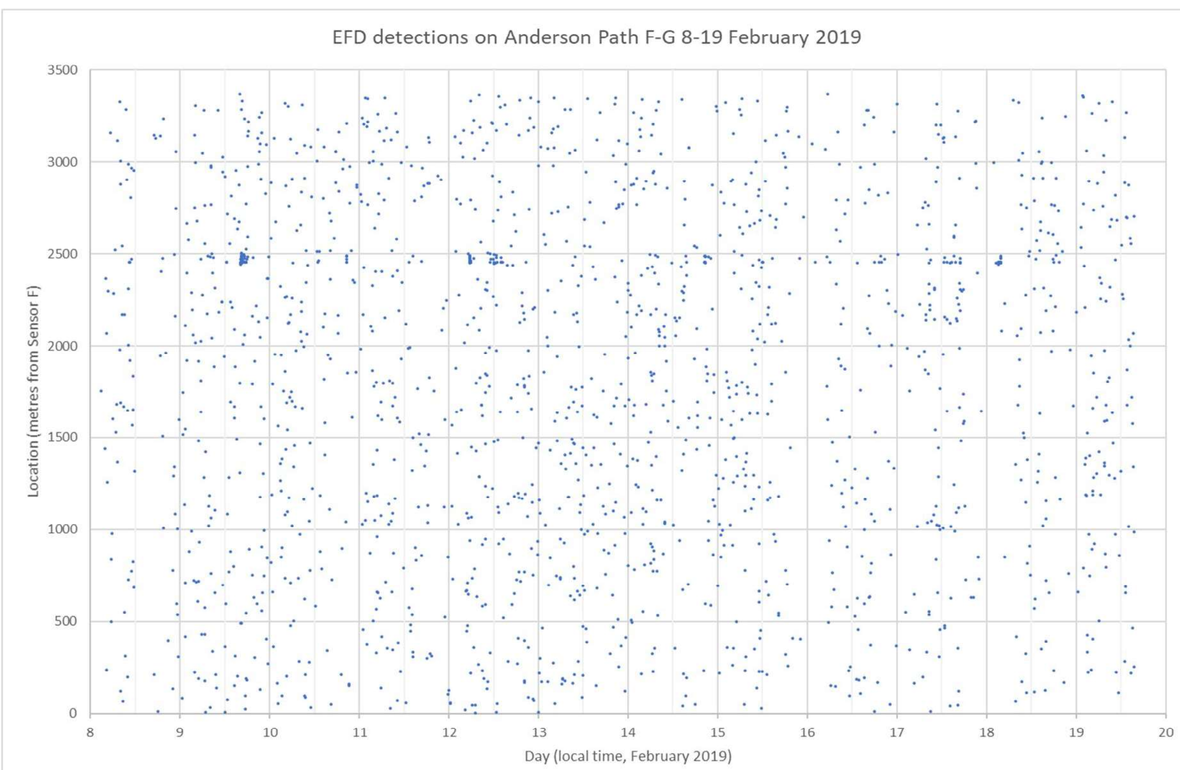
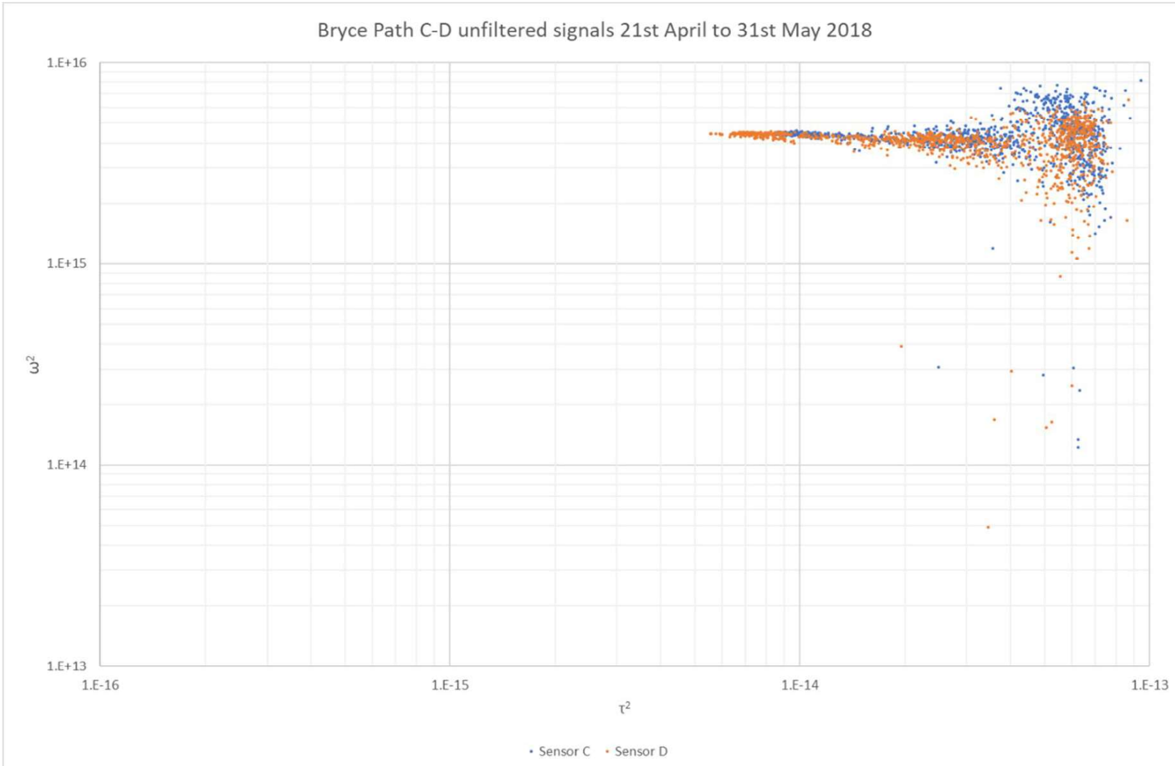


Figure 15: Anderson path F-G signals with noise filter based on detection quality, showing Pole 5111862 hot-spot



It was discovered that random noise signals tend to fall into a well-defined zone on the FT Chart as shown by Figure 16 which shows the FT Chart zone for random noise signals on the 'quiet' Bryce network.

Figure 16: FT Chart location of random noise – Bryce signals April, May 2018



Even higher system signal-to-noise ratios might be achievable if the filtering algorithm used data from the FT chart position of a signal, but this additional step was not required for the Trial objectives to be met. It was noted as a possible future development opportunity.

Experiments with different levels of noise filtering indicated that once 'random coincidence' noise was eliminated, residual network noise had low signal magnitude (typically less than 1-2% of the system full scale measurement capability) and occurred mainly during daylight hours. It was considered likely this baseline noise was created by local human activity, including electrical noise emanating from connected equipment and possibly entering the SWER network from the source polyphase network.

7.3 Rain events were filtered out

Early EFD SWER Trial experience revealed that EFD units were sensitive enough to detect the impact of individual raindrops on live powerline conductors along the inter-sensor network path. Such impacts appear to involve a brief charge-equalisation current between the powerline conductor and the raindrop, both of which are likely to carry electric charge prior to the instant of impact. This current spike creates high-frequency electrical impulses that emanate from the point of impact. These are detected by EFD units and the impact is accurately located on the network path by the algorithms running on the secure cloud server.

Raindrop impacts were real events but they did not indicate powerline asset deterioration or faults so they were not considered useful in the context of the primary function of the EFD system. Under heavy rainfall conditions, rain-induced signals could easily outnumber signals from other network sources and distort asset risk scores, so effective filtering techniques to identify and remove them from risk scores and visualisations were developed and deployed late in the Trial.

Figure 17 shows on-path source detections for Homestead network Path E-G in November and December 2017 after noise filtering. A number of rain events are visible as near-vertical lines, including two episodes of heavy rain on the 26th and 27th of November which are shown in more detail in Figure 18. After automated identification and removal of rain impact detections, the underlying 'dry' data was as shown in Figure 19.

Figure 17: EFD detections on Homestead E-G showing effects of heavy rainfall on26th and 27th November 2017

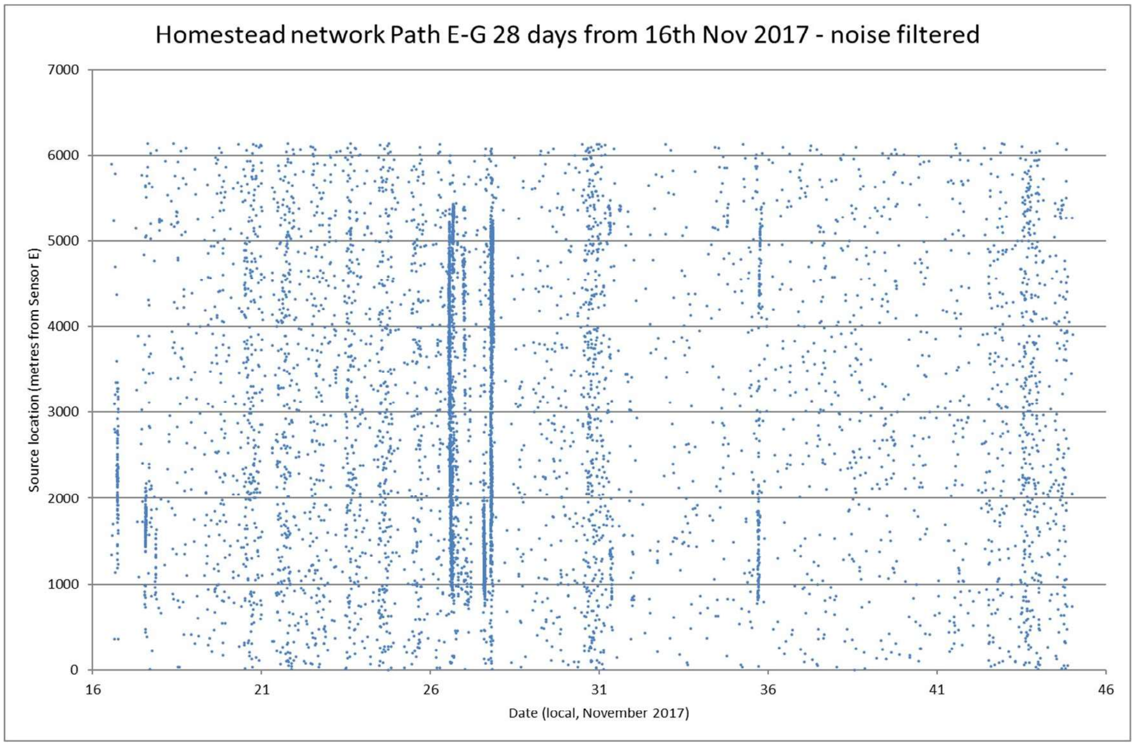


Figure 18: EFD detections on the Homestead Path E-G on the 26th and 27th November 2017 showing moving rain showers

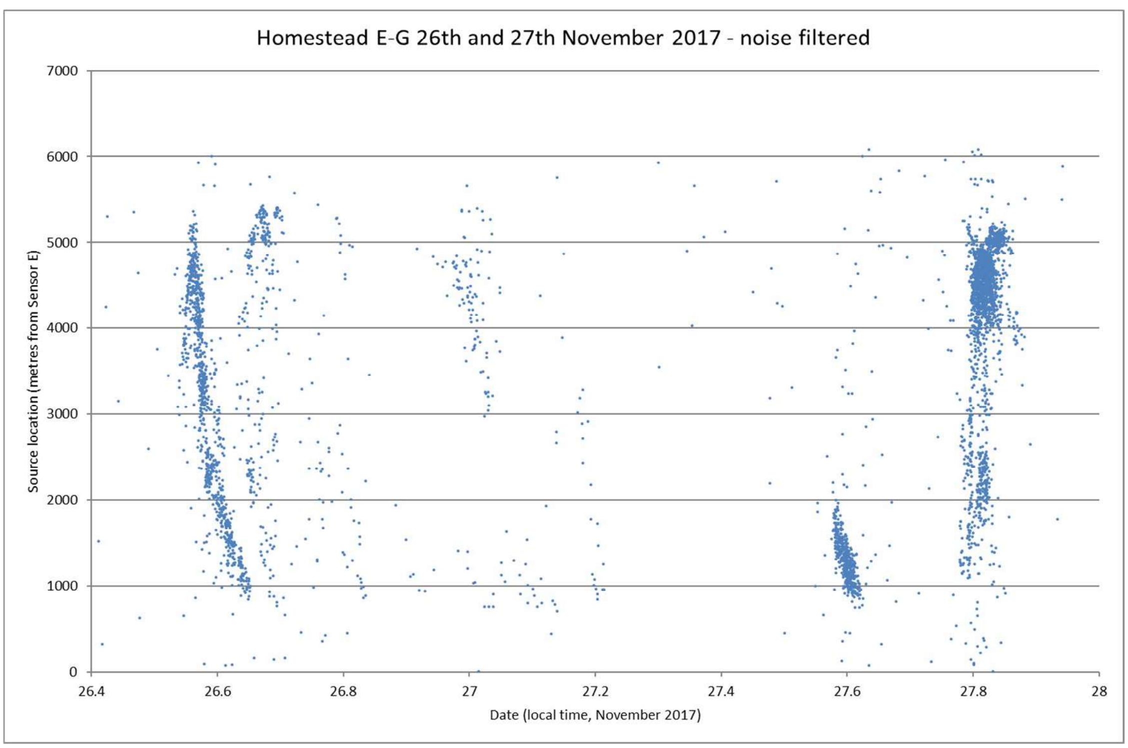
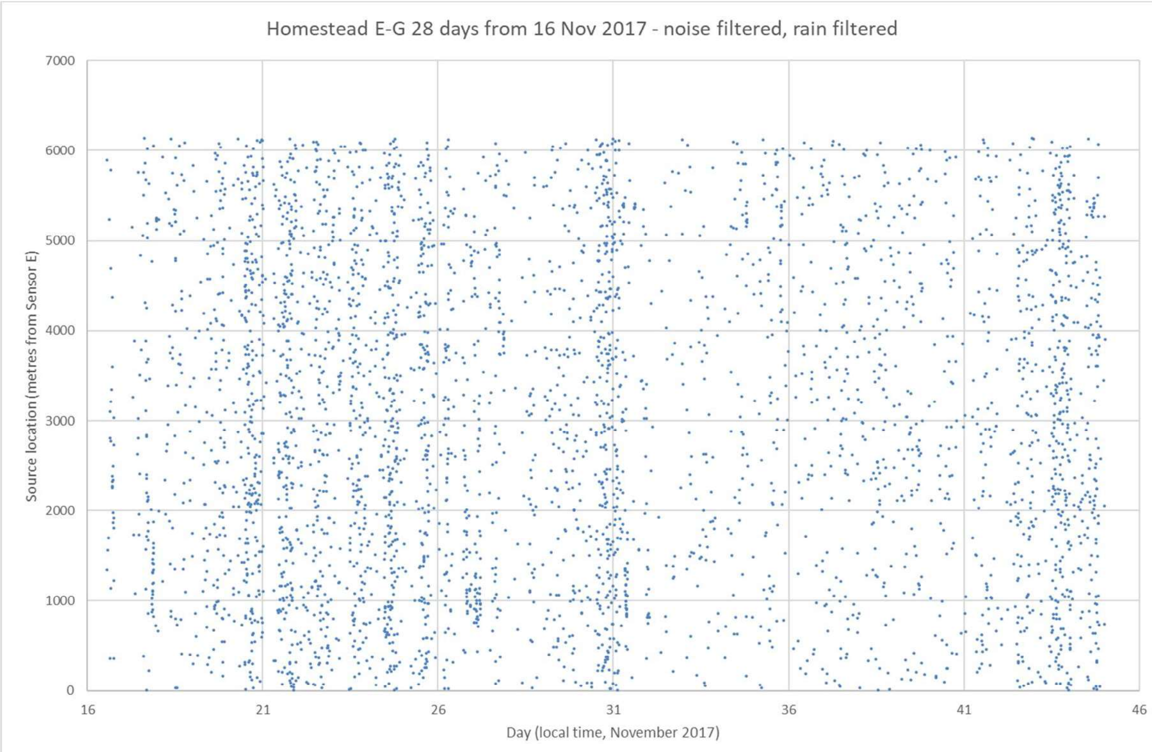


Figure 19: EFD path record after rain events have been removed



The rain filter algorithm was implemented late in the Trial. It identified the great majority of detections due to rain and eliminated them from asset risk scores and visualisations.

7.4 Radio stations were filtered out

In some networks, the dominant sources of network background noise were local radio stations, both AM and FM. These modulated the detection of random noise to create concentrations of 'phantom detections' along the monitored inter-sensor network path. Radio transmitters at Wangaratta, Benalla and Wodonga could be clearly seen in unfiltered EFD data from networks in NE Victoria in the form of horizontal bands on the signal source location chart, as shown in Figure 20. They were also clear in the statistical distribution of signal source locations as shown in Figure 21.

Filtering to reduce detection of random noise and improve signal-to-noise ratio removed radio station interference at the same time (see Figure 22), so no further special measures were needed to deal with this effect. Radio signals continued to be evident in the spectra of signal waveforms captured by EFD units as illustrated in Figure 23. The typical amplitude of radio signals was a few tens of microvolts.

Figure 20: unfiltered EFD path record showing horizontal noise bands caused by a local AM radio station

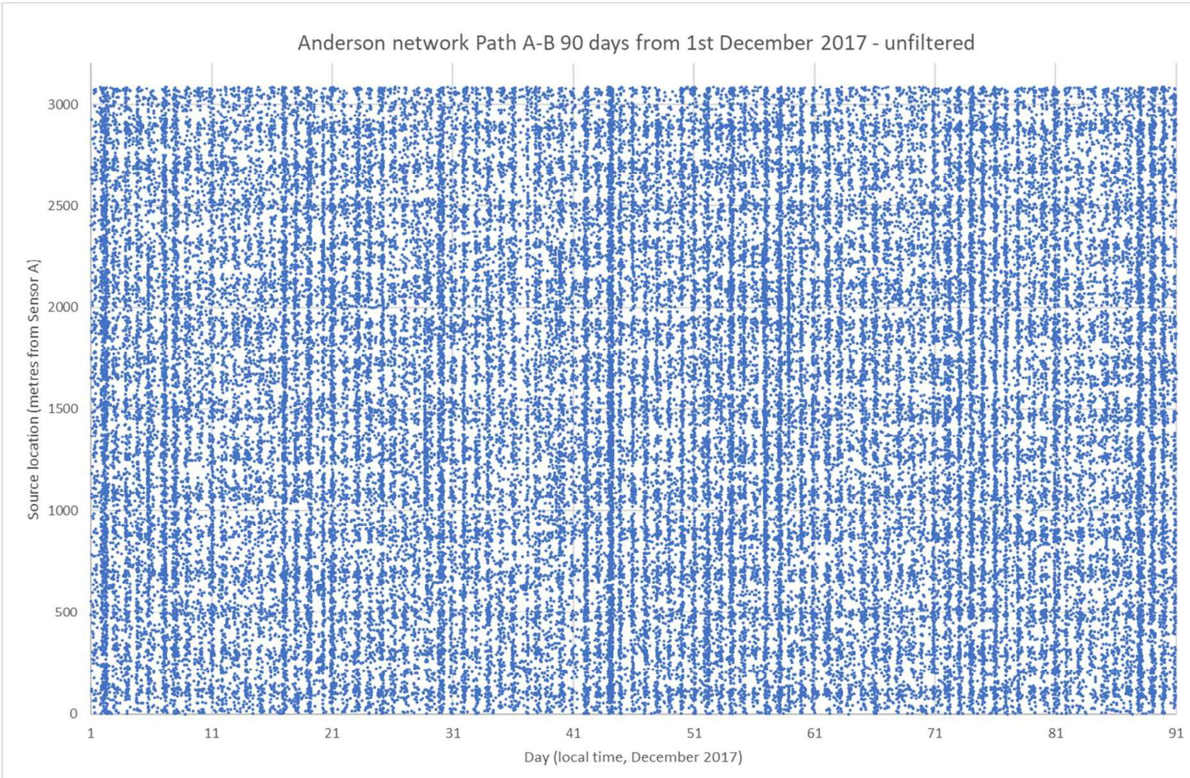


Figure 21: distribution of source location unfiltered (signal-to-noise ratio <2:1, hot-spot at Pole 5104680/629 metres)

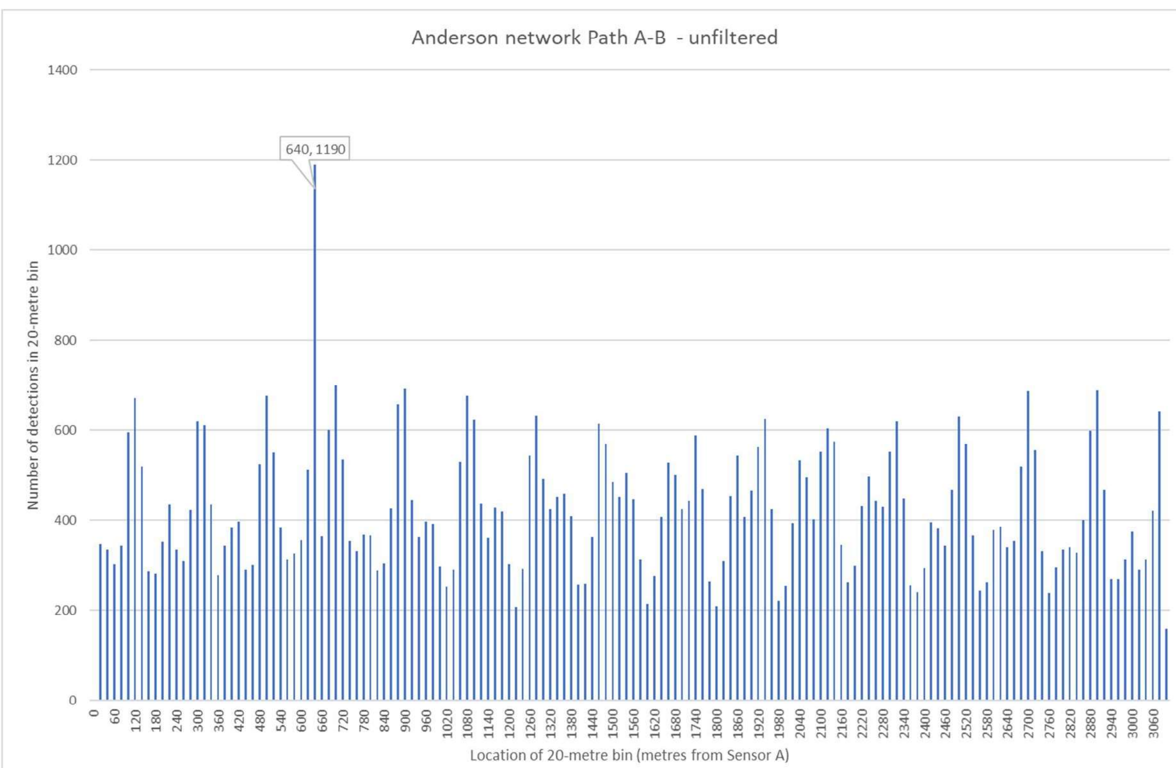


Figure 22: distribution of source locations with noise removed – improved 10:1 signal-to-noise ratio

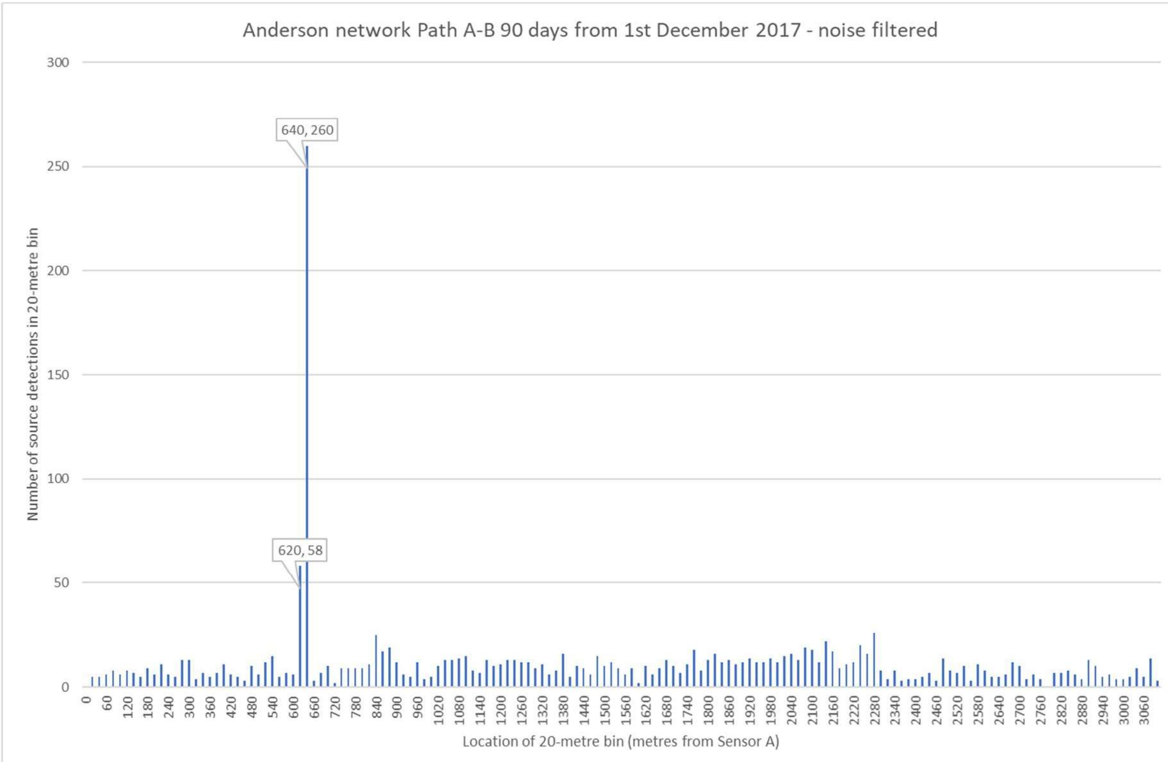
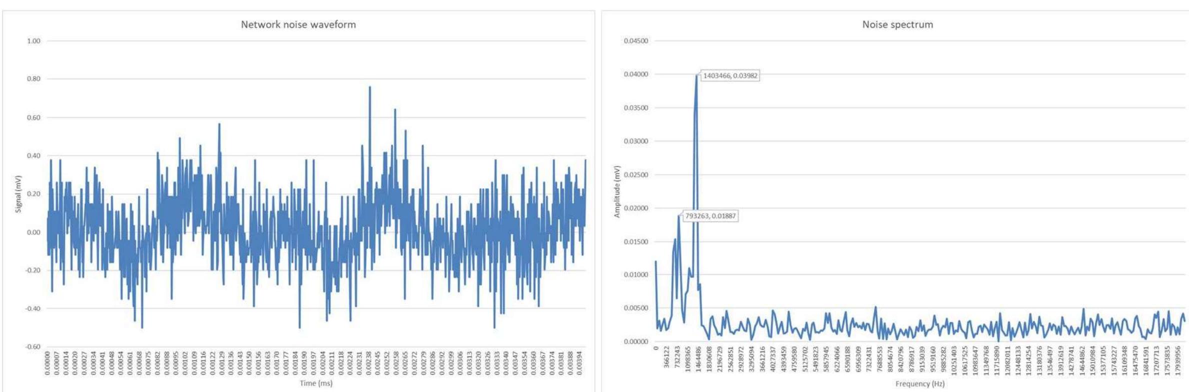


Figure 23:Network noise waveform and spectrum (the two peaks are Radio 3NE and ABC Radio National, Wangaratta)



While radio signals were constantly present in nearly all SWER Trial networks, their effect on the Trial was immaterial once noise filtering was introduced.

7.5 Lightning and network switching were identified in triage processes

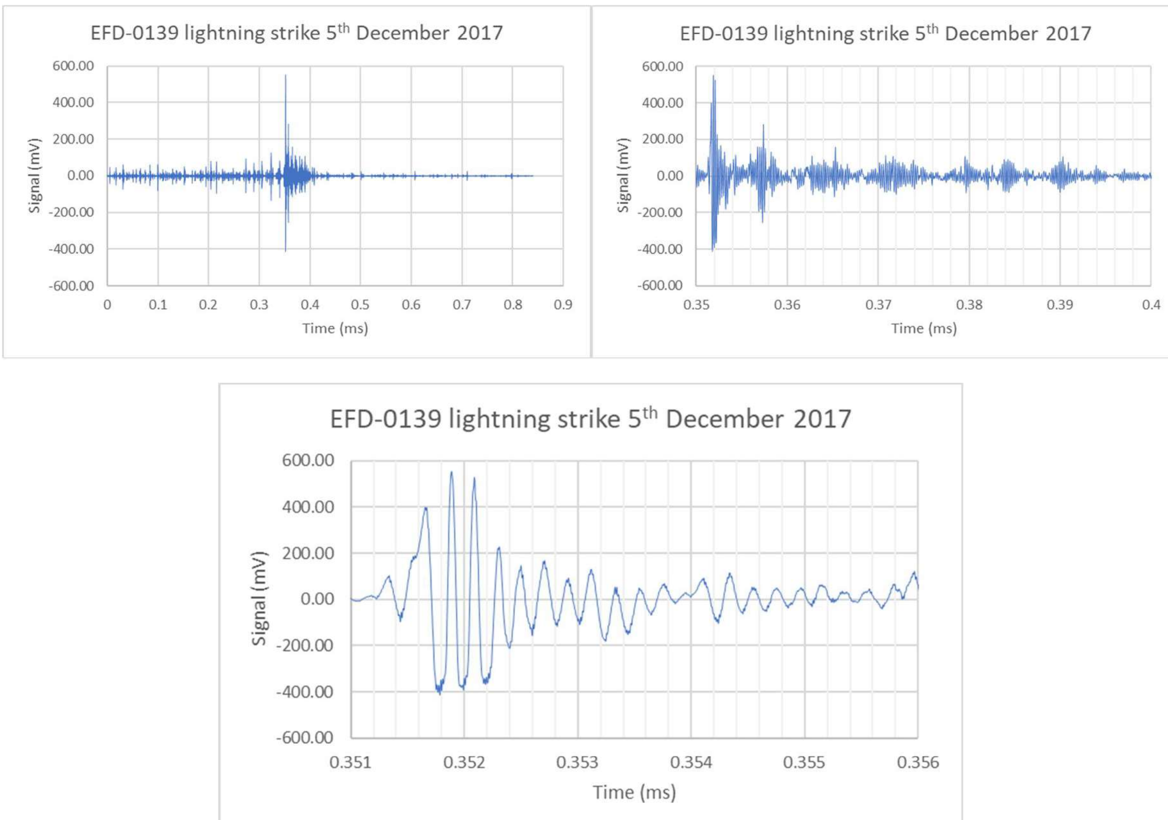
Over the Summer period, many of the monitored networks experienced frequent intense lightning storms, especially those in north-east Victoria. Lightning strikes would occasionally produce single EFD detections of a magnitude well in excess of the system alert threshold so procedures were developed to check for the presence of lightning when single system alerts were received[8]. Lightning-induced alerts could also be distinguished from real network problems because they were usually single isolated events, whereas the latter tended to produce a continuous stream of system alerts.

[8] The public website www.lightningmaps.org was found to be useful for this purpose. Most network owners subscribe to private lightning monitoring services that perform a similar role.

Lightning strikes provided a useful check of system operation in that they were single events that affected multiple EFD sensors. They were generally located well off the monitored path so while they could generate an alert, an on-path location was not recorded. Arrival timestamp data from three or more EFD sensors could be used to locate the strike by triangulation.

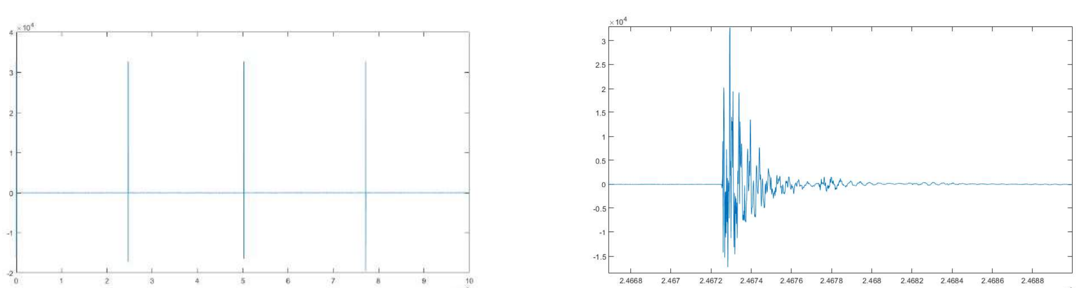
Waveforms recorded by EFD units showed lightning strikes were generally preceded (and sometimes followed) by a period of a millisecond or two of high-frequency signals similar to those produced by partial discharge in network assets.

Figure 24: EFD signal waveforms generated by a lightning strike (Sensor B Homestead network)



Operation of network high-voltage switches occasionally produced EFD system alerts similar to lightning – a single alert, rather than a stream of alerts. However, the waveforms were similar to partial discharge rather than lightning, comprising spikes synchronised to the 50Hz waveform as shown in Figure 25. The time of occurrence often coincided with 'start of task' and 'end of task' times for field crews.

Figure 25: EFD signal waveforms generated by network switching (Beechworth Road Sensor C, 08:58:52 7th March 2019)



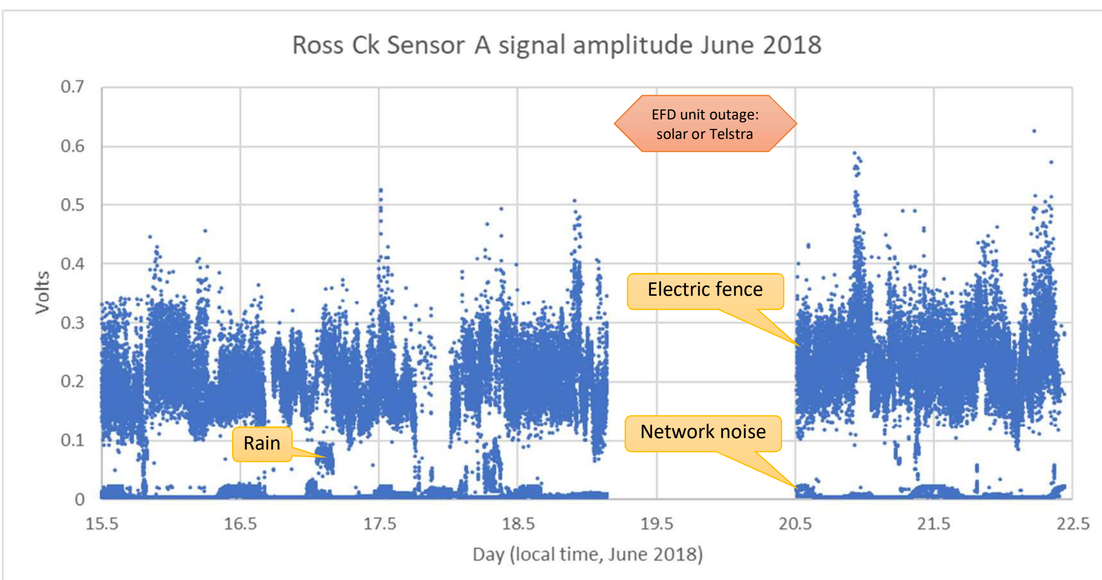
A check with network operators usually quickly confirmed these alerts could safely be ignored.

7.6 Electric fence signals were distinguished from real network signal sources

The Trial provided an opportunity to study the effect of electric fences on the EFD system – on Powercor's Ross Creek network, a farmer had run an active electric fence directly under Sensor A (actually attaching it to the pole on which the sensor was mounted). Over the course of the Trial (supported by field experiments using an electric fence generator purchased for the purpose) the following tentative conclusions were formed about this particular source of extraneous signals:

- Electric fence interference can be high-magnitude and high-volume (typically, one pulse every 2-10 seconds). Real (network) signals were recorded 80-90% of the time;
- Electric fence interference did not travel along the powerlines – it appeared to be directly radiated to any nearby sensor;
- It is possible the EFD sensor was not recording the electric fence impulse itself (which is thought likely to be at a frequency below the operational band of the EFD system) but was detecting micro-arcs between the fence and for example, nearby vegetation;
- Laboratory tests indicated that simple modification of the sensor design to increase its directionality (by providing a larger earth plane at the base of the sensor) should suffice to reduce electric fence interference to acceptable levels if it proved to be a problem;
- Alternatively (or in addition), algorithms could be developed to identify and remove records created by electric fence impulses; and
- Two fire risk situations detected in the Trial were detected by Ross Creek Sensor A despite the presence of strong interference from the electric fence directly below it.

Figure 26: signal magnitude at Ross Creek Sensor A showing electric fence interference



Despite their widespread use, only one electric fence was detected by the 61 EFD units deployed in the Trial, so any potential problem appears to be at most a second order effect on EFD system operation.

8 EFD system reliability was optimised

Deployment of sensitive electronic technology on power poles in remote rural locations subject to extremes of weather and difficulty of access required careful design. The design had to be such that any requirement for site visits was minimised. The EFD SWER Trial provided a real test of the design. Progressive optimisation via firmware upgrades and one or two hardware changes over the 18-month period of system operation addressed the few minor residual issues identified.

The new EFD secure cloud infrastructure and web portal also faced the challenges posed by large, rapidly growing data volumes and volatile processing load. Enhancements during the period of the Trial greatly improved the stability and scalability of the cloud infrastructure, while reducing its operating cost per EFD unit per month

8.1 Immunity to lightning

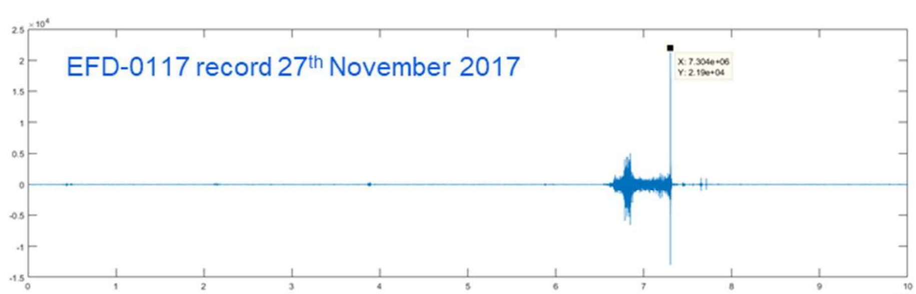
All eleven networks experienced occasional lightning storms during the EFD SWER Trial - those in northeast Victoria were subject to almost daily intense storms over two Summers. However, the number of EFD system alerts due to lightning was tiny compared with the number of strikes in the vicinity of EFD units. Though system alerts due to lightning were rare, examination of raw EFD data revealed many strikes were recorded but correctly eliminated by the EFD system's matching process (the source location algorithm) because the strike location was not on the inter-sensor network path. Lightning strikes that caused system alerts probably did so by direct radiation to an EFD sensor of a signal large enough to exceed the EFD system alert threshold.

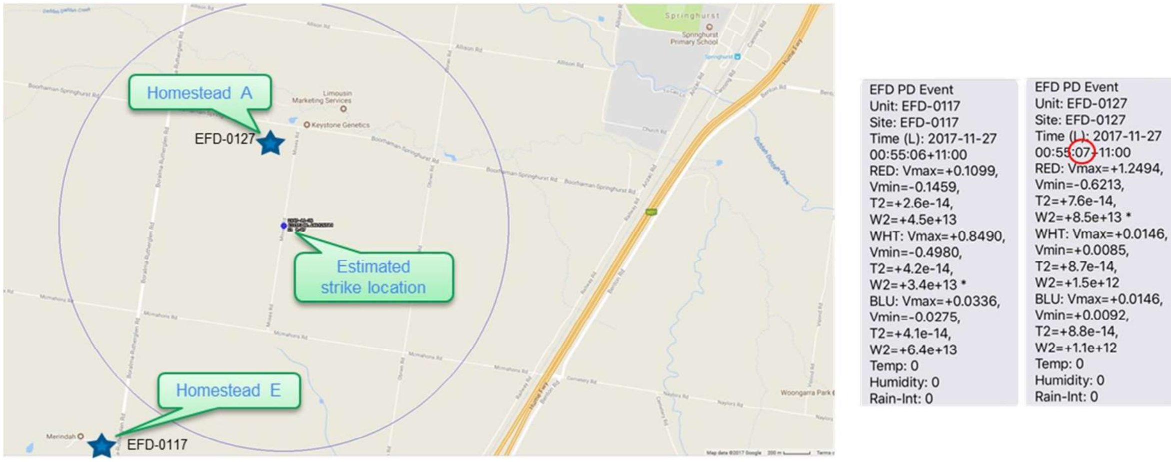
Lightning caused some minor EFD system malfunctions. Late in the Trial, it damaged one EFD unit more seriously and site attendance was necessary to restore operation.

Incorrect recorded data due to nearby strike: 27th November 20197

A minor EFD unit maloperation was observed due to an intense lightning strike at 12:55:06 am on the 27th of November 2017. The strike caused alerts to be issued by two EFD units in NE Victoria and the timestamp on one alert was found to be incorrect by one second. All EFD sensor data before and after the alert was reviewed and found to be correct. Later examination of records of other strikes revealed rare occurrences of similar incorrect data records. In such cases, there was no damage to the EFD unit which recovered to correct operation within two seconds. The impact of the incorrect data on EFD system visualisations and risk scores was immaterial.

Figure 27: Lightning strike near Homestead network Sensors A and E (40ms of signal waveform shown)

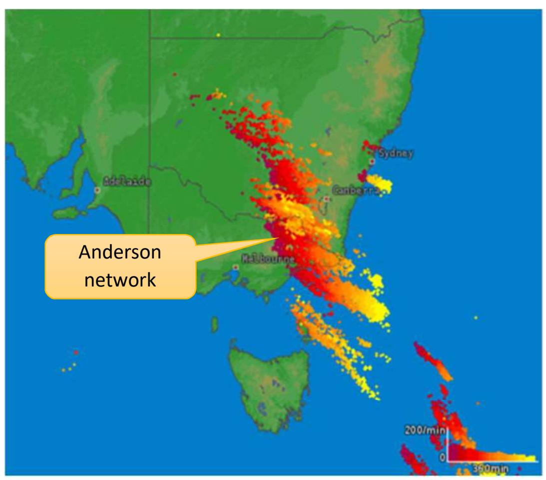




EFD unit severely damaged by lightning: 5th March 2019

Just before 5:16pm on the 5th of March 2019, an intense lightning strike caused Sensor H (EFD-0142) on the Anderson network to stop functioning. Lightning intensity in the area was extreme:

Figure 28: Lightning intensity (strikes per minute) at 6:00pm on 5th March 2019



The strike caused high-voltage to enter the EFD control unit via the sensor cable, damaging two circuit boards. These boards were swapped with spares during an on-site visit to return the unit to service. A post-event review identified design modifications to reduce the probability and extent of similar damage in future.

8.2 Solar supply adequacy

All 61 EFD units in the SWER Trial used solar power. Even though EFD units only draw five watts, the Trial revealed the challenges of this option, especially solar adequacy issues due to prolonged cloudy weather and panel shading by high trees:

- Only one or two of the 39 EFD units in NE Victoria (i.e. North of the ranges) suffered significant solar adequacy issues; both had tall trees on the North side of the Sensor pole.
- Several EFD units on networks near Ballarat (i.e. South of the ranges) were significantly affected by solar adequacy issues, the worst one having tall dense trees on its North side.
- On two days in winter, almost all 61 EFD units were offline for a few hours due to early morning fog after multiple days of heavy cloud.

EFD units were designed for orderly shutdown and restart if battery voltage fell below a set threshold due to poor solar conditions. The shutdown and restart thresholds were optimised early in the Trial. Over Summer, all 61 EFD units were available with only very rare shut-downs of one or two near Ballarat caused by solar issues. Based on experience in the EFD SWER Trial, a higher capacity solar supply was designed for use in future solar-powered EFD units.

Figure 29: EFD unit battery voltage – daily cycle in a healthy solar location

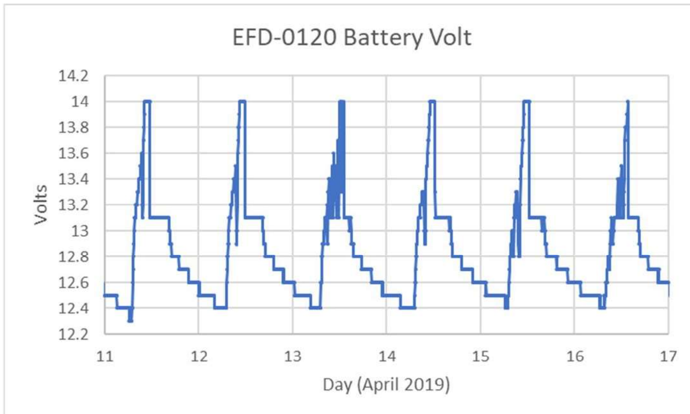
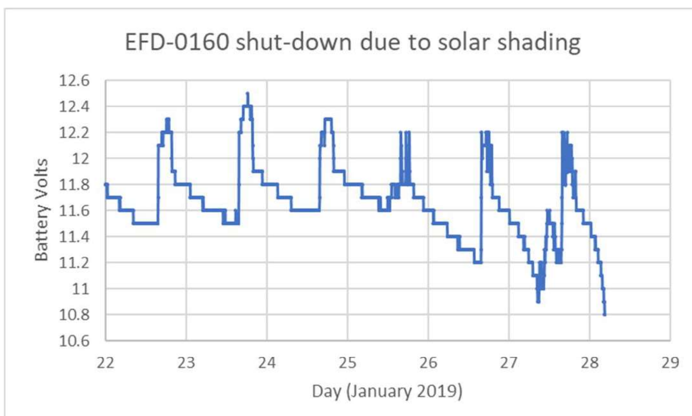


Figure 30: EFD unit battery voltage showing controlled shut-down due to cloudy weather and panel shading



The EFD SWER Trail provided a valuable test-bed to develop a robust solar power solution for future EFD systems.

8.3 3G communications service

All EFD units in the SWER Trial used Telstra's 3G data service to upload data to the secure cloud server. In some areas of the State, particularly in the networks around Ballarat, 3G coverage proved to be poor; at one site it was completely absent and although alternatives[9] were available, the EFD unit planned for that site was relocated.

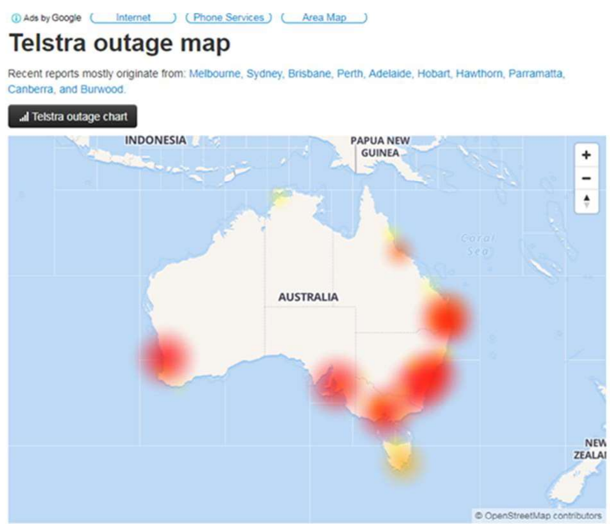
Coverage issues in the form of poor signal levels were not the main challenge as experience showed EFD units could operate down to 3G signal levels of 10% or less. Service outages where signal strength was adequate but the EFD modem could not connect to the 3G network proved to be a bigger problem. In some sensor locations, outages of Telstra 3G service were common and could sometimes last for hours or days. It was found that Telstra rarely issued any public reports of 3G

[9] Point-to-point radio links are available that can link a unit in a zero-coverage area to one with adequate coverage that can act as a data relay to pass messages to the secure cloud server.

service outages in rural areas. Volunteer websites that monitor Telstra services are more effective in urban areas where a larger number of customers are affected and are prepared to use them to report outages. Even when EFD units were unable to connect to the 3G service for extended periods, any enquiry to Telstra typically elicited the response of “Our systems show no outage in that area”.

State-wide 3G service problems occurred on a few occasions (e.g. 21st of May 2018), disabling communications from a large number of EFD units for an extended period. The cause of the EFD system problems in such incidents was not evident for some hours until the 3G service problems attracted media attention, mainly due to the impact on retail EFTPOS terminals.

Figure 31: Telstra outage map 21st May 2018 (Source: downdetector.com.au)



EFD unit firmware was modified to provide defence-in-depth against 3G service outages. This included multiple levels of modem restart/reconnect followed by upload of a limited amount of stored records when connection was re-established. Higher-gain antennas were fitted to units where it was considered low signal level might be a contributing factor.

Once these remedial actions were in place, though Telstra’s 3G service continued to prove less reliable than desired, EFD system data communications proved adequate to meet project objectives.

8.4 GPS service

All EFD units in the SWER Trial used the GPS system for precision time-synchronisation across all units. The availability of GPS service is widely assumed to be 100% as typically, ten or more independent satellites are contributing to the pulse-per-second (PPS) signal used by the EFD units. The only single point of potential failure was the GPS receiver/antenna combination in the EFD unit itself. Internal system logs indicated failures of the GPS receiver to produce a PPS signal were rare but did occasionally happen. Firmware modifications were developed to protect against the possibility of loss of EFD function caused by intermittent PPS signals.

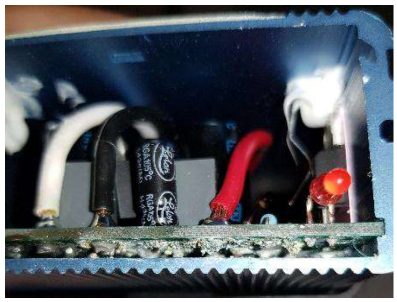
8.5 Hardware reliability

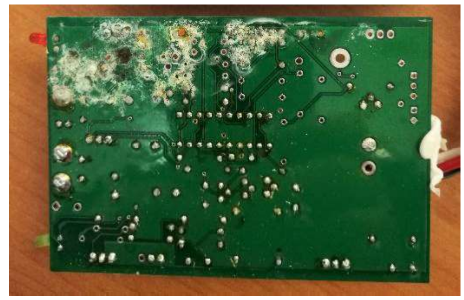
Hardware reliability was good. Each EFD unit contains complex circuit boards with thousands of individual components – in essence, it is a customised computer with a set of specialised peripheral devices. In the 1,093 unit-months of operation in the Trial, only a few failures were encountered. These included:

- A failed SD card, assumed to be due to a manufacturing defect;

- A broken 3G antenna (the wire whip was broken off at about four centimetres height) due to unknown causes; and
- Three instances of failed solar chargers (the internal PCB showed evidence of corrosion from an unknown cause).

Figure 32: Broken 3G antenna, corroded solar charger PCBs





These failures were carefully investigated and it was concluded the root cause in each case was defects in components purchased for manufacture of the EFD units. Discussions with the supplier of the solar chargers did not identify the cause of the corrosion that led to the three failures.

8.6 Firmware reliability

Many EFD units operated continuously for months without a restart (either a cold or warm reboot); the main cause of a shutdown/restart cycle was low battery volts due to local solar adequacy issues or a loss of 3G communications. Nevertheless, late in the Trial it was decided to include capability for a scheduled regular reboot to ensure latent problems did not accumulate to a level that might interrupt normal EFD service.

Three major software/firmware updates were deployed in the course of the Trial, addressing:

1. Compensation of analogue-to-digital converter input offset to ensure correct FT Chart data;
2. Introduction of the ‘detection quality’ score for noise filtering; and
3. Enhanced resilience against 3G service failures and other causes of loss of EFD unit service.

Monitoring of EFD unit performance in the course of the Trial revealed a series of firmware bugs of progressively increasing subtlety, each of which was addressed by software/firmware updates delivered remotely ‘over the wire’. Visits to sites to ‘cold boot’ a unit were very rarely required after these updates.

8.7 Cloud infrastructure performance

The size of the databases used to hold EFD data from the Trial grew rapidly and continuously. By the end of the Trial billions of data records had been accumulated. Backup and re-indexing processes were regularly re-optimised and the database structure updated to preserve performance and control costs during this rapid growth.

Less than 1% of raw EFD data produces a match to identify the location of a signal source on the inter-sensor network path and consideration was given to the option of deleting the other 99%. However, it progressively became clear that raw (unmatched) data had value in its own right as an indicator of abnormal signal levels regardless of whether these could be associated with a particular path location. The value of the non-located raw data was evident in three circumstances:

1. **‘Behind the sensor’ sources:** Often a signal source was at a termination substation one span beyond the sensor, and the raw data was the primary source of information on the situation.

2. **High intensity, high volume signals:** Sometimes even when the source was on the network path, a strong signal could overwhelm the location algorithm so the location was not clear. Manual analysis of downloaded raw data was used to investigate the problem.
3. **AI-assisted analysis:** Late in the Trial when a large amount of data had been accumulated, investigations commenced into information extraction using AI tools such as deep learning. The non-located raw data proved to be a valuable feed-stock for such analysis.

In view of these additional sources of value, it was decided for the time being to retain all data, progressively moving it to cheaper, slower-response storage as it aged. The databases on the secure cloud server were extensively indexed to preserved acceptable response times across a very diverse range of user queries.

The cloud services provider (Amazon Web Services) reviewed the design and provided expert advice on database performance improvement and cost reduction options as well as on cyber security.

8.8 Web portal performance

The web portal application pulled EFD data from the secure cloud server databases and presented it to users in a range of visualisations designed to convey in simple intuitive terms the state of the network as seen by the EFD system. Over the course of the Trial, the portal presentation was continuously improved as experience was gained. Changes to the portal over the course of the Trial included:

- A 'quality release' after commissioning to align site terminology with industry norms;
- Major enhancements to the Back-Office download pages;
- Enhancements to risk score calculations to better suit SWER networks;
- Implementation of noise filtering based on detection quality;
- Implementation of a filter to remove rain-induced signals from visualisations[10]; and
- Implementation of an 'at a glance' network status visualisation.

Throughout this active development program, portal performance was continuously optimised to limit the impact of changes on user response times.

8.9 Cyber security

The EFD system is essentially a passive monitoring tool. Direct risk to a network business and its customers from potential subversion of the EFD system is low. Nevertheless, the EFD system was progressively hardened against cyber-attack over the course of the Trial. The main enhancements were:

- Encryption and authentication of data communications using VPN channels[11] and SSH/SSL technology;
- 'Hiding' the IP address of the cloud server interface used to receive data from EFD units;
- Increased redundancy and enhanced backup functions in the cloud server; and
- Stronger passwords to control remote access to EFD units.

No cyber-attacks on the EFD system were detected during the Trial.

[10] In final test at the time of writing this report.
[11] Proof-of-concept successfully completed.

8.10 EFD system operation during fire seasons

The first EFD units were installed immediately before the summer of 2017/18 and for some months thereafter the focus was on completion of the rollout of the remaining EFD units in the Trial, creation of an understanding of the initial data the system was providing, development of methods to reduce the effect of random noise, and full operation of the EFD web portal. With all this activity, it was not feasible to take special measures for the 2017/18 fire season.

Later in 2018, when the EFD system in the SWER Trial was in full operation and the immediate post-commissioning development phase was complete, the operation of the EFD system and associated procedures were modified to make the most of the opportunity for the EFD system to contribute to network owners' fire mitigation activities.

The following steps were taken for the 2018/19 fire season:

- **A new EFD System Health monitor:** The monitor automatically interrogated every EFD unit at midnight, 6:00am, noon and 6:00pm and provided a consolidated report via email on the status of each unit, including the signal strengths for both 3G and GPS reception. This meant that if an EFD unit stopped communicating for any reason (solar inadequacy, loss of 3G service), this situation would not go un-noticed for longer than six hours. This health monitor operated independently of the portal which also displayed the dataflow status of each unit on the home page.
- **Lower EFD system alert thresholds:** The default alert threshold was reduced from 300-500mV to 200mV. This meant any material increase in signal level would generate an alert well before signal levels were reached that might indicate an imminent fault (with associated fire risk). In just one or two situations, the alert threshold was set higher where a source of repeated alerts was assessed as having low fire risk. In such cases, it was set just above the level of the 'usual' signal so any further increase would generate an alert.
- **Triage procedures for alerts:** A formal procedure for triage of EFD system alerts was defined, including escalation processes into the two network owner organisations. The triage filtered out alerts due to lightning and network switching and ranked the seriousness of each alert to guide escalation decisions. The ranking took into account a range of risk factors, including the current level of fire risk (weather conditions) and the estimated maximum fire consequence near the location of the alert. In practice, if a situation was assessed as having material risk of a fire start in high fire risk weather, liaison with the network owner was immediate and continuous.

A potentially serious situation addressed by these changes during the 2018/19 fire season was that described in Section 10.3 below – the replacement of a substation transformer located in a situation of extreme fire risk.

9 EFD system sensitivity and location accuracy were optimised

SWER networks generally use steel conductor which has a relatively high electrical resistivity and they have a branched topology with multiple tee-off spur lines. High levels of signal attenuation were expected (and observed). To ensure it remained fully effective in this situation, the EFD system was designed for maximum sensitivity with the highest possible signal-to-noise ratio. This challenge was heightened by design trade-offs to cut manufacturing costs and enable a larger scale trial.

The Trial confirmed the EFD system is sensitive enough to ‘see’ all parts of the network’s high-voltage assets and through substation transformers to some low-voltage assets, possibly even extending into customer wiring and appliances inside buildings.

The accuracy of location of individual signal sources on the network is determined by the GPS time synchronisation between units and the accuracy and consistency with which the units measure the time of arrival of signals. New algorithms were developed to compensate for known sources of location error to achieve unprecedented accuracy: nominally, ten metres anywhere along a five-kilometre inter-sensor network path.

9.1 System sensitivity

The EFD system proved to be extremely sensitive. Signal levels were measured in millivolts (mV) at the input to the analogue-to-digital converter. The following list of signal levels illustrates the ability of the system to detect partial discharge at a distance:

- ‘Phantom’ (random coincidence) events: <5mV
- Background network noise (associated with human activity): <15mV
- Impact of rain droplets: 15-50mV
- Partial discharge in substation transformers: 100-400mV
- Electric fence (directly below sensor): 100-600mV
- Broken conductor strand: 480-580mV
- Arcing fault in low voltage service line: 470-650mV
- Lightning strikes and network switching: 500-1000mV
- Full-scale of input measurement: ±1,250mV
- EFD system alert threshold: 200mV (fire season), 300-500mV (other times)

With the single exception of the electric fence signal, all of the above levels were recorded for sources located between hundreds of metres and one or two kilometres away from the sensor.

In summary, the EFD SWER Trial demonstrated that the EFD system sensitivity is more than adequate to monitor rural powerline networks.

9.2 Location accuracy

A detailed assessment of the location accuracy of the EFD system was conducted once it had reached operational maturity. The assessment was performed using EFD data from January, February and March 2019. The data related to five previously-identified representative sources of signals. All of these sources had been identified with assets on particular poles so their locations were known.

The results show that in all five cases analysed, EFD system performance exceeded all the normal requirements of network operational practices. In summary:

1. The accuracy of signal source location was generally ±10 metres or better along path lengths up to the system limit of five kilometres. EFD system accuracy was of the same order as the

accuracy of the network map used in the web portal which was derived from GIS data supplied by the network owner.

2. Discrimination (the ability to separate closely spaced sources) was generally about three metres, ranging up to ten metres depending on the nature of the signal.

3. If the signal was oscillatory and the two end-of-path sensors measured different peaks of the waveform, this could slightly degrade location accuracy to ±15-20 metres.

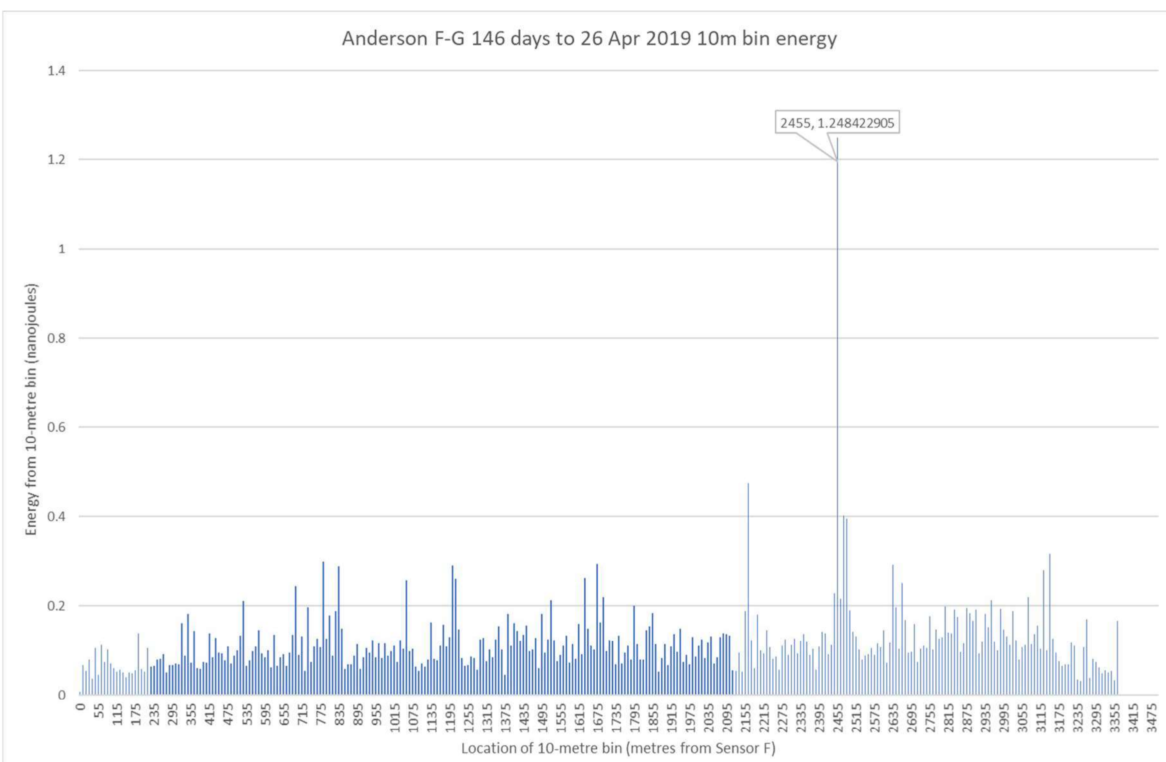
4. Based on analysis of one example of a path longer than the nominal system limit of five kilometres, location error on a 6.2-kilometre path was 30 metres. The same signal source had a location error of 0.4 metres on an overlapping 4.1-kilometre path.

5. Based on further analysis of the 'overlapping paths' case, a signal source located on a spur line 1.4-kilometres from a 3.1-kilometre monitored inter-sensor network path was identified with the tee-off pole where the spur line left the monitored path to an accuracy of 16 metres.

These results confirmed error compensation had delivered about a tenfold improvement in location accuracy compared to previous generations of the EFD system.

Figure 33 shows an extreme case with signal magnitudes less than two per cent of the maximum signal level the EFD system could handle. The energy captured by the EFD system from the ten-metre network path segment that included Pole 5111862 was only 1.25 nanojoules over 146 days, but the location of the source at the pole was quite clear. The location error compared with the pole location on Google Earth was 4.25 metres.

Figure 33: location of low-energy intermittent hot-spot on Anderson network Path F-G



The location accuracy demonstrated in the EFD SWER Trial was more than adequate for operation of normal electricity distribution networks and good enough to support a range of potential new work practices that could deliver benefits over and above fire-risk reduction.

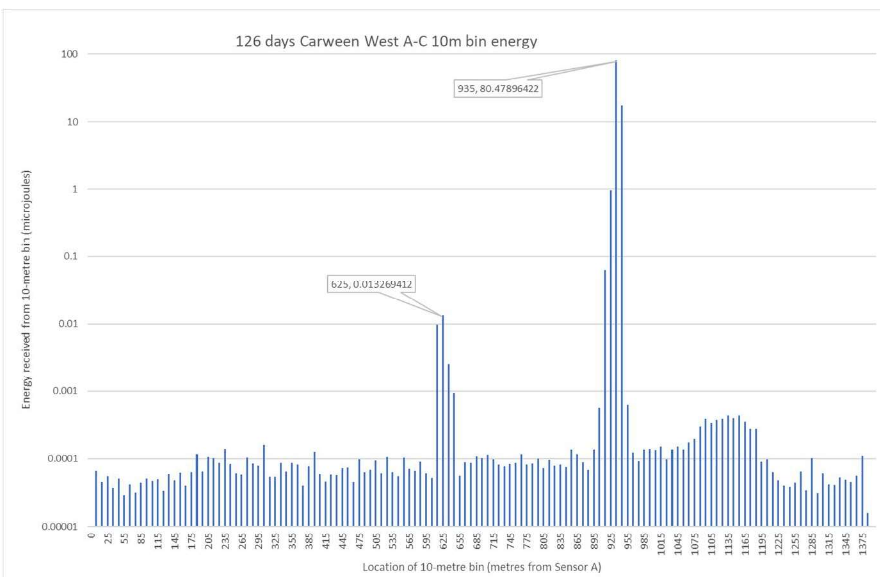
9.3 Signal-to-noise ratio exceeded expectations

Sensitivity is important but the key EFD performance parameter is the ability to separate signals emanating from network assets from the background noise caused by other processes. The ratio of signal to noise was greatly improved by changes to both EFD unit firmware and portal algorithm software. In summary, the signal-to-noise ratio (using fifty-metre location measurement bins) was eight at low signal levels about two per cent of the system alert threshold[12] and ranged up to twelve hundred[13] at medium signal levels around seventy per cent of the threshold.

The EFD SWER Trail revealed the value of moving to energy measurement rather than separate measures of signal counts and signal magnitudes. Figure 34 shows the energy profile of Carween West network path A-C which includes a higher energy source at Pole 13105. Over a 126-day period, the EFD system captured 80 microjoules of energy from the ten metres of powerline that included Pole 13105[14]. It has also detected a much lower energy source at Pole 836911 which has only generated 28 nanojoules over the same period. Despite the difference in energy by a factor of nearly three thousand, both pole locations are clearly defined within ten metres of their map locations.

The average noise energy generated by a ten-metre length of this path over the period was about one-tenth of a nanojoule, which illustrates the excellent signal-to-noise ratio in EFD system results. For Pole 13105, the ratio of signal to noise shown in Figure 34 approached one million.

Figure 34: energy captured from each 10-metre length of Carween West path A-C over 126 days (NB: log scale)



The levels of sensitivity and signal-to-noise ratio delivered by the EFD system after the enhancements made in the EFD SWER Trial exceeded all stakeholder expectations.

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[12] The nominal system alert threshold for detected signals is 200mV, so a signal level of 2% is 4mV and a signal level of 70% is 140mV. EFD units can accurately measure signals up to a 'full scale' value of 1,250mV.

[13] This study preceded the move to use captured energy as the basis of source detection which increased signal-to-noise ratio even further.

[14] This is about eighty thousand times more than the energy captured from Pole 5111862 on the Anderson network (Figure 33) over a similar period.

9.4 Identification of the type of fault

The EFD system offers the possibility of identifying the type of incipient fault that has been detected. A number of information elements provided by the EFD system can be combined to distinguish different types of incipient faults:

- **Signal magnitude:** Is it high or low? Is it increasing or fading? High signal means lightning and network switching must be ruled out first - if not those, high signal means high risk.
- **Signal energy:** Is it high or low? (High energy implies faster asset deterioration).
- **Signal intermittency[15]:** Is it intermittent or steady? Is it correlated with time-of-day, season, day-of-week, hour-of-day, etc.? Some sources are active for hours and then absent for days or weeks. Others come and go all the time. Some are single bursts that don't reappear.
- **Signal source location:** Is its location clearly separated from other sources? Is it at a pole or is it mid-span? If at a pole, the assets on the pole are suspect; if mid-span, conductor damage or vegetation encroachment must be considered. Is it stationary? If moving, heavy rain or similar must be suspected.
- **Signal waveform:** if magnitude exceeds the alert threshold, the EFD unit will have captured the signal waveform which can be examined for clues.
- **FT Chart zone:** the position and pattern of the signal on the Frequency-Time (FT) chart can provide valuable clues to its origin.

Each of these has been explored during the EFD SWER Trail to better understand their strengths and weaknesses. The fault detections outlined in Sections 10 and 11 all involved manual analysis of the above parameters. This type of analysis has not yet been automated as the best combinations of parameters are yet to be finalised. It is likely that the current AI investigation will define an approach that can be embodied in an algorithm. This algorithm can be expected to evolve rapidly as further experience is gained.

Two of the above-listed parameters are briefly explored here: signal waveform and signal pattern on the FT Chart.

9.4.1 Signal waveforms

If the signal magnitude exceeded the alert threshold, the EFD unit not only issued an alert by SMS, it stored the forty milliseconds of waveform (ten million sample values) containing the signal peak that caused the alert. The waveform could be downloaded over the Internet and examined.

Manual examination of the signal waveform when an alert was received would often provide valuable confirmation of the type of signal source involved, especially when signals overlapped on the FT Chart.

Some examples of waveforms captured in the EFD SWER Trial are shown here:

[15] The SWER Trial revealed for the first time the valuable fact that all partial discharge in network assets appears to be intermittent.

Figure 35: Typical 40ms waveform for a lightning strike (Homestead network Sensor G EFD-0119 5th February 2019)

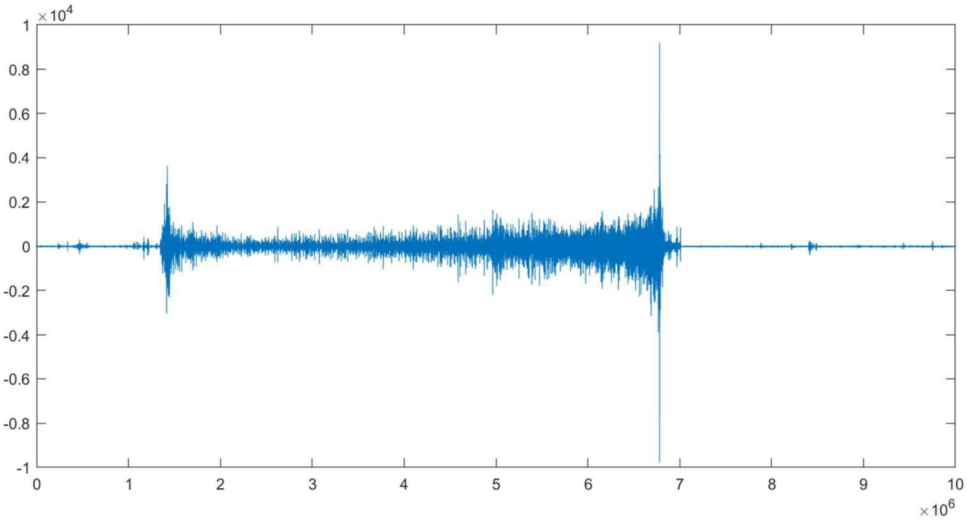


Figure 36: Signal bursts at 10ms intervals from transformer partial discharge (Beechworth Rd network sensor K)

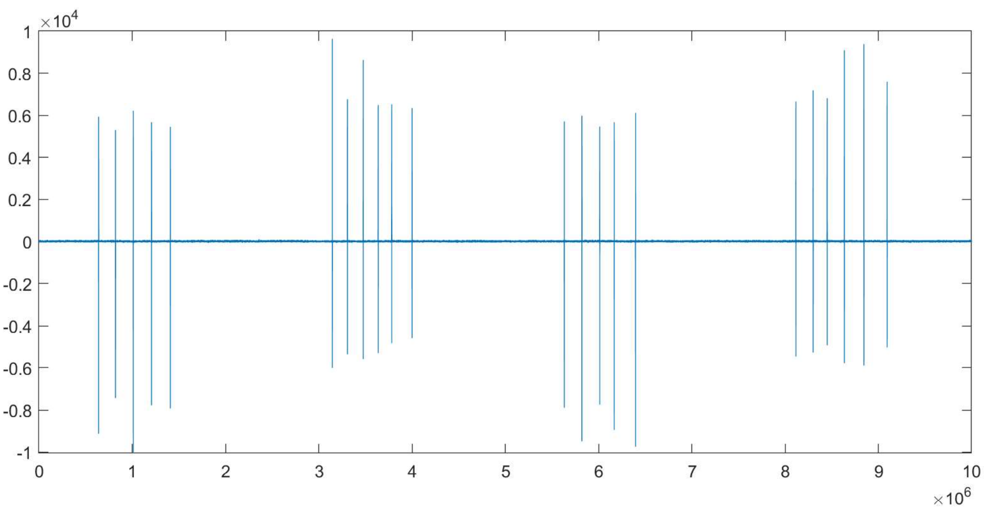


Figure 37: A single partial discharge impulse (Beechworth Rd network sensor K, about 2µs shown)

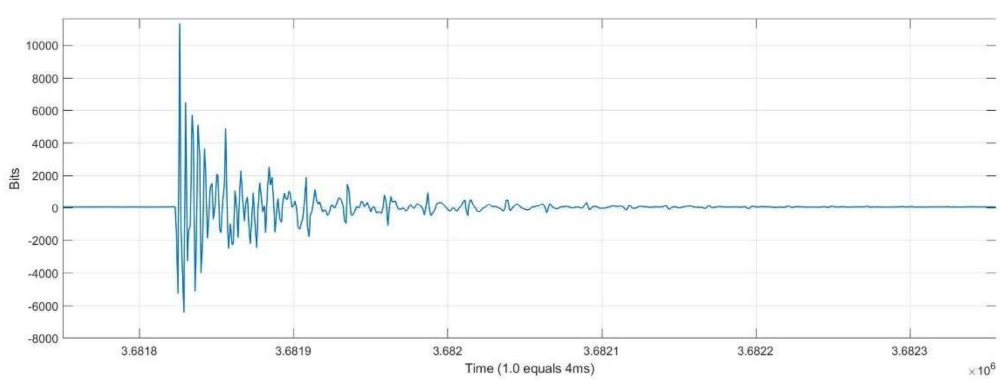


Figure 38: Typical electric fence signal waveform (40ms of waveform shown)

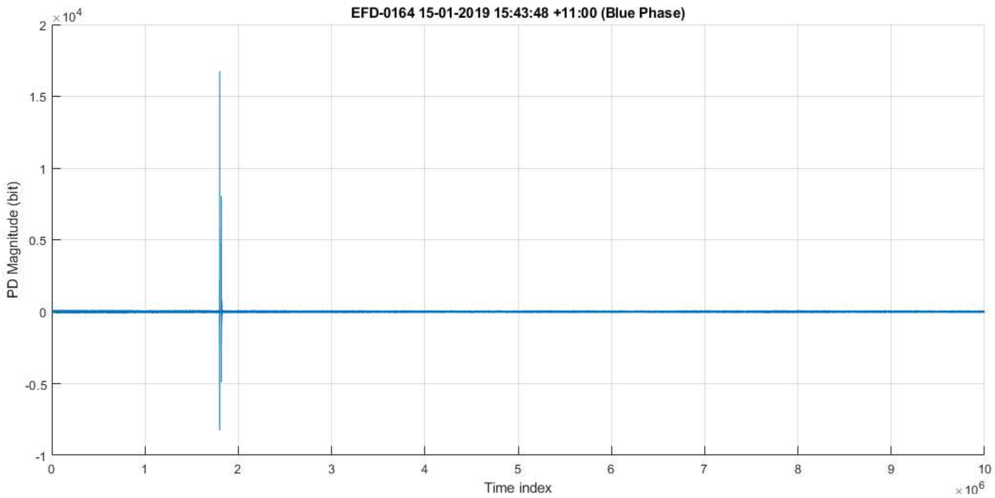
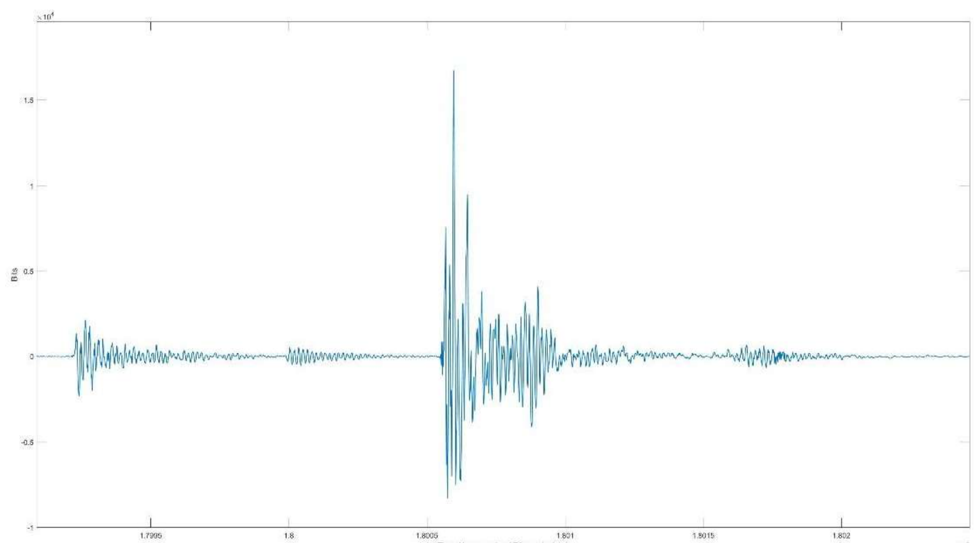


Figure 39: Typical electric fence impulse (Ross Creek Sensor A EFD-0164, about 15µs shown)



The signature of partial discharge was repeated bursts of signal at intervals of ten milliseconds as shown in Figure 36. This could be taken as a reliable indicator of insulation deterioration within a network asset of insulation breakdown or electricity tracking across the surface of an insulator.

9.4.2 FT Chart patterns

The Frequency-Time (FT) Chart[16], was used extensively in the Trial and has been automated into the portal visualisation of site activity. It was found that:

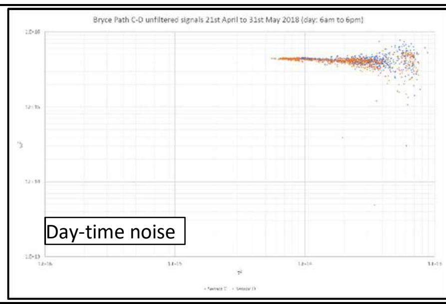
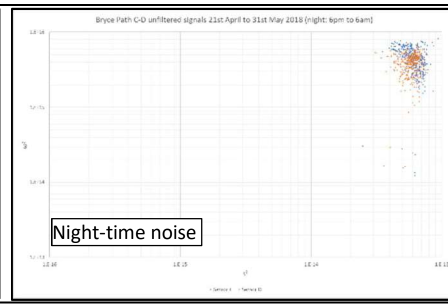
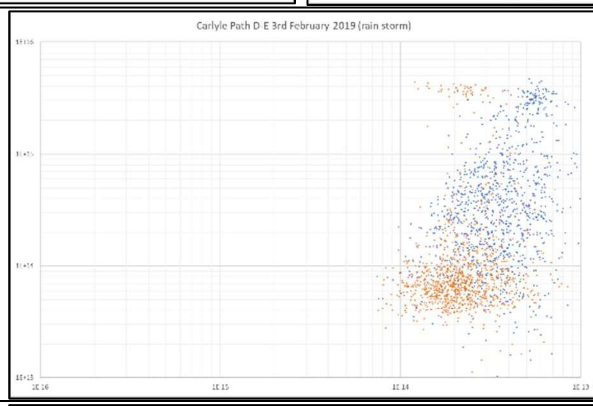
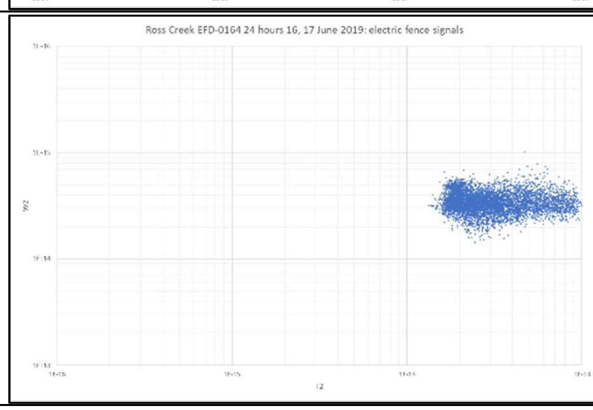
[16] Time-frequency analysis is a method for distinguishing between multiple partial discharge locations within an electrical asset undergoing laboratory tests. See: *Digital Detection and Fuzzy Classification of Partial Discharge Signals*, Contin et al, IEEE Transactions on Dielectrics and Electrical Insulation, Vol 9 No 2, June 2002. EFD technology uses it to classify different signal sources on in-service high-voltage networks.

1. FT chart clustering became visible at signal levels around one or two per cent of the EFD system alert threshold and was very clearly defined at higher signal levels.

2. FT chart cluster patterns varied from source to source indicating the sources varied in nature and from sensor to sensor, reflecting signal convolution[17] over distance. Both these features were as expected (and desired) for the EFD system to support network asset management.

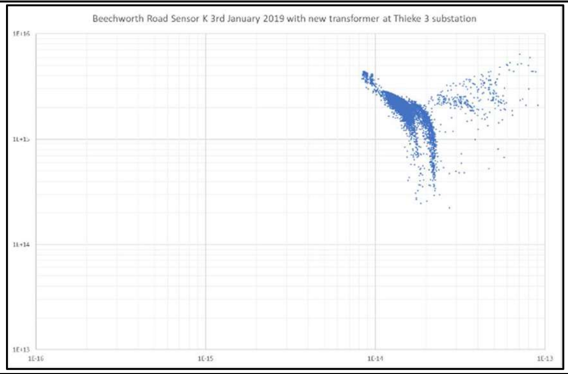
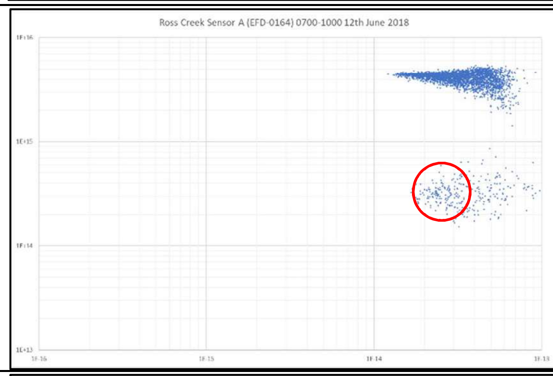
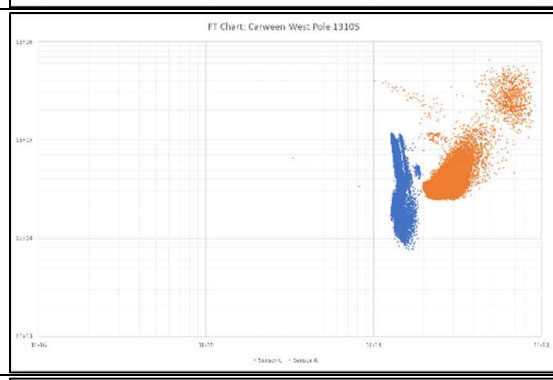
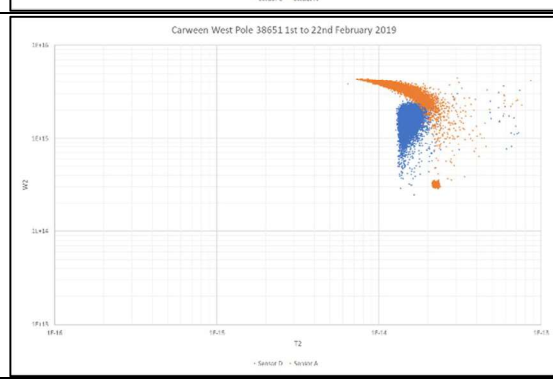
A sample of some FT Chart zones seen in the EFD SWER Trial is shown in Figure 40:

Figure 40: FT Chart zones seen in EFD SWER Trial[18]

Background noise: Bryce network path C-D April/May 2018. Bryce was one of the quietest networks in the SWER Trial. The FT noise zone is very different by day and by night. Noise is very low energy.		
Rain: all networks exhibited rain patterns in heavy rain storms. These showed clearly on location charts where storm movement was obvious. The FT chart showed diffuse clouds of signals caused by rain.		
Electric fence: a dense pattern that overlaps some network asset fault zones on the chart.		

[17] The change in signal waveform as it travels along the powerline. Different frequencies are attenuated at different rates causing the waveform shape to change with distance travelled.

[18] The use of FT Charts in the EFD SWER Trial converged to a standard set of logarithmic axes: Vertical (ω^2) from 1E13 to 1E16; and horizontal (τ^2) from 1E-16 to 1E-13. The vertical position may be loosely thought of as an indication of the signal impulse bandwidth, while the vertical position may be loosely thought of as signal impulse duration. However, the sole purpose of the FT Chart is to separately identify multiple signal sources.

Transformer internal partial discharge: the 'double crescent' pattern first appeared in EFD field tests on a polyphase network, but has been seen again in the EFD SWER Trial in the first three hours of service of a new transformer.		
Broken conductor strand and arcing on low-voltage service line: In both cases, the signal was hidden in electric fence noise.		
Unidentified 1: the hypothesis is that this is likely to be internal partial discharge in the transformer on Pole 13105. The two sensor patterns are different due to signal convolution.		
Unidentified 2: the pattern for Pole 38651 is different to that of signals from other substation poles. The only obvious difference in the source is that Pole 38651 is concrete and all the others are wood.		

The compilation of an 'FT Chart album' of patterns identified with specific types of incipient fault will take time and investment in forensic examination of network assets removed from the field. After eighteen months of EFD SWER Trial experience, three source types can already be confidently identified from FT Chart patterns: network noise, rain and in-tank transformer partial discharge. This early experience confirmed the value of the FT Chart to network operators and it was automated and presented on site pages of the EFD portal.

10 EFD technology successfully identified fire risks

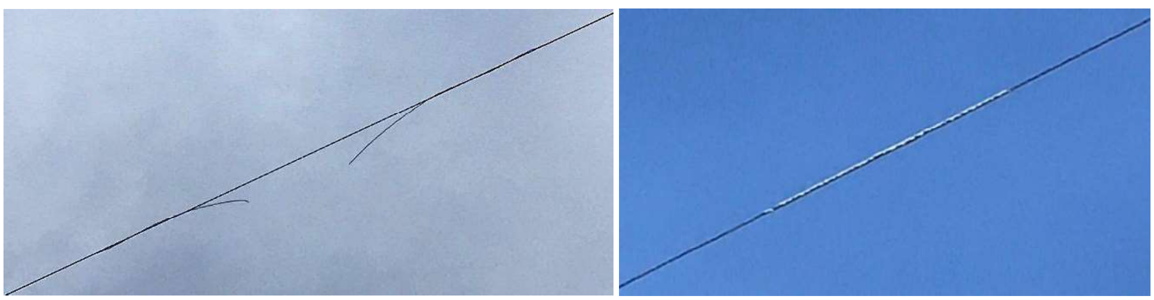
The EFD technology deployed for the Trial covered less than one per cent of Victoria's total 30,000 kilometres of SWER networks for 18 months. Despite this limited scale and duration, the Trial's EFD technology identified two network faults (a broken strand on a powerline conductor, and arcing in a low-voltage private overhead service line) that posed direct fire risk and a third situation (a failing asset in a location of extreme fire consequence) where indirect fire risk was unacceptably high at a time of high fire danger.

If this rate of identification of fire-risk applied to all of Victoria's SWER powerline networks, EFD technology would offer material fire-risk reduction benefits for all rural areas of the State.

10.1 Broken conductor strand at Ross Creek

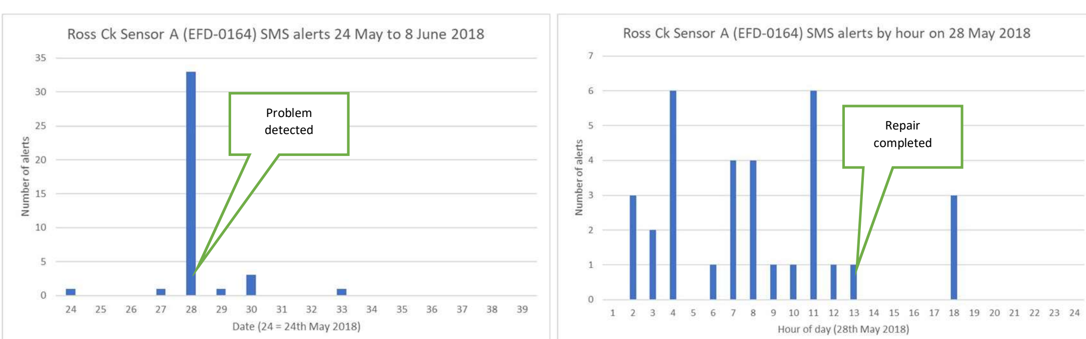
On 28th of May 2018, multiple SMS alerts were received from Sensor EFD-0164 (Ross Creek Sensor A) starting at 2:09:33am. IND contacted Powercor at first light suggesting an immediate patrol. A Powercor crew attended and found a broken conductor strand between pole 4 (LIS15878) and Pole 5 (LIS18206), roughly mid-span about 300 metres from Sensor A. The line was de-energised from 11:48am to 12:39pm while a splice was applied.

Figure 41: Broken conductor strand detected at Ross Creek, before and after repair



The first SMS alert was received from EFD Sensor A at 7:08pm on the 24th of May, four days before the defect was found. The second was received at 9:38pm on the 27th of May, i.e. one day before. On the 28th of May there were 30 alerts between 02:09am and 12:39pm when repairs were completed. Occasional alerts (five over six days, followed by none for six days) were received after the repair was complete. These stopped within a week.

Figure 42: EFD system alerts from Ross Creek Sensor A in May and June 2018 before and after repair



There were no alerts around that time from other Sensors on the Ross Creek network. The Ross Creek network is small with relatively short path lengths: Path A-D is 3.26 kilometres long. The location of the fault was not as clearly defined as expected, though prompt manual analysis of data downloaded from the EFD portal allowed the repair crew to be correctly instructed it was likely to be within a span or two downstream of Sensor A.

Electric fences operate extensively in the area, including one running directly under the line and actually mounted on the pole supporting Sensor A. The characteristics of electric fences as a noise source in EFD data was further investigated following this incident with the results described in Section 7.6 on Page 34.

The physical mechanism which created the signals picked up by EFD-0164 was not identified with certainty. Of the various hypotheses considered after the event, the one that appears to best fit the known facts was that once the strand broke, the two broken ends slid back away from the break over a period of hours or days or even longer – at the time of discovery the gap in the broken strand was of the order of a quarter of a metre. As this movement happened (possibly in fits and starts), the electric current transferring between strands on each side of the break (from three strands to two and then back to three) was subject to sudden discontinuities that created high-frequency signals. Powercor advised a repair splice can take some time to re-distribute tension equally across the three strands, so it was to be expected the signals might not stop immediately after the repair because the sliding movement might continue for a time until this equalisation was achieved.

The detection of the broken strand had particular significance for stakeholders as it was precisely this failure that led to the disastrous Kilmore East Kinglake fire on Black Saturday which killed more than one hundred people. Until now there has been no way to detect broken strands apart from visual inspection patrols every few years.

10.2 Arcing failure of a privately owned low-voltage service line

Ross Creek EFD Sensor A (EFD-0164) started issuing SMS alerts at 2am on Saturday the 9th of June 2018 at a rate of about six per day. Initially, there was a possibility the alerts were an after-effect of the broken strand fault detected 12 days earlier by the same sensor, so they were monitored but no immediate action taken. As they continued to arrive, the possibility of a new fault on the Ross Creek network became more and more likely.

At 8:39pm on Sunday 10th June, IND advised Powercor that the continuing alerts suggested a new patrol of the Ross Creek network was warranted. Given the cold wet weather with very low fire-risk and the public holiday on the following day, it was agreed there was no compelling justification for an after-hours crew callout.

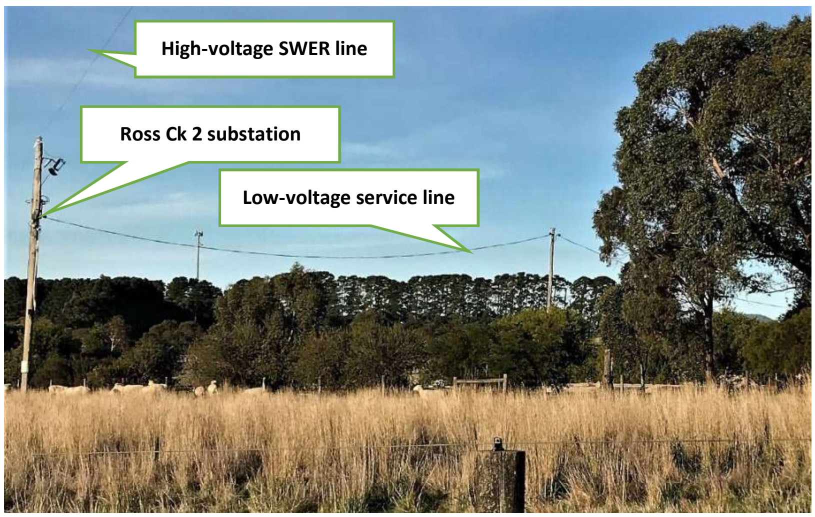
The rate of alerts increased to 15 alerts on Tuesday 12th June and then suddenly ceased at around 6pm. A crew was on their way to carry out the requested patrol on Tuesday morning when they received a work order at around 11:30am to attend a supply outage at Post Office Road Ross Creek. They discovered a failed private low-voltage service line supplied by Ross Creek 2 substation.

The service line was a black-rubber flat-format cable (informally known as ‘liquorice’) comprising three multi-strand copper wires as shown in Figure 43. The insulation between the active and the neutral wires had failed part way across the first span from the substation. There was evidence of arcing over a period of days or weeks. The fault had progressed to flashover on Tuesday morning which had blown the service fuse interrupting supply to the house. Apart from a 600mm length that had failed, the remainder of the service line was intact.

The crew’s 11:30am Tuesday work order was triggered by the smart meter at the address which reported a supply outage lasting more than the set threshold, automatically generating a work order for attendance and investigation.

Figure 43: Damaged section of low-voltage service line due to insulation breakdown and arcing

Figure 44: Private low-voltage service line from Ross Creek 2 substation (photo taken 1 June 2018)

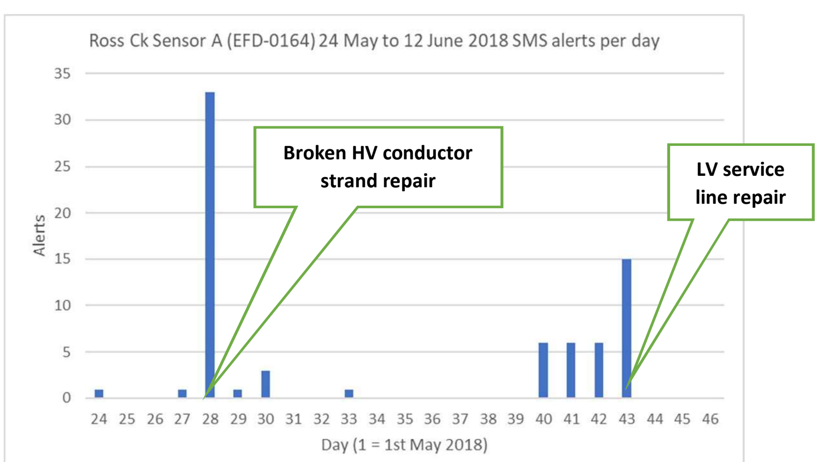


Repairs to faulty overhead low-voltage service lines in high fire-risk areas of Victoria are subject to Energy Safe Victoria regulatory procedures that mandate undergrounding if the line requires major reconstruction. Under these procedures, the customer must seek approval of a temporary interim repair to restore supply and an extension of time to underground the service line.

Powercor records indicate the supply was restored at about 7pm which is consistent with the last EFD alert being received at 6:12pm. No alerts were received from EFD-0164 for the next five days.

The pattern of alerts from Ross Creek Sensor A over the three weeks was as shown in Figure 45:

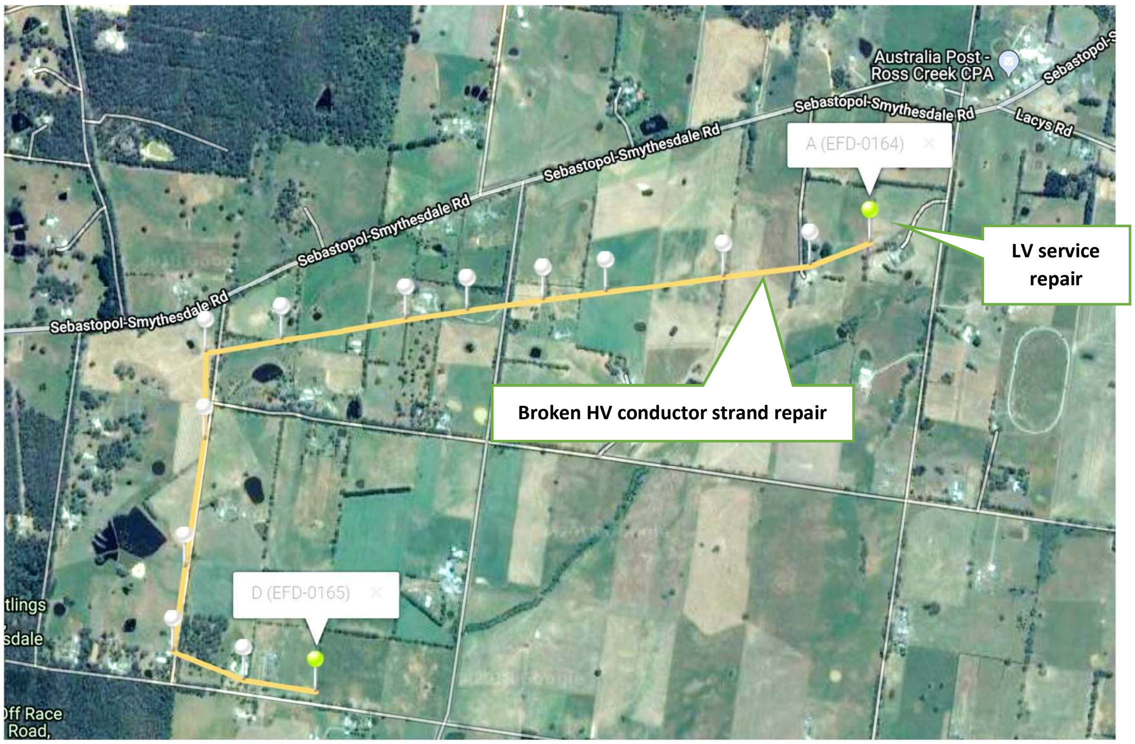
Figure 45: Alerts from Ross Creek Sensor A (EFD-0164) in May and June 2018



There were indications in the four-day pattern of alerts associated with the low-voltage line failure that the problem was at its worst during periods of high customer load (grouped around morning and evening demand peaks). This was consistent with a residential customer-side fault. Similar correlation was not observed in the alerts for the broken strand detection, indicating the problem was independent of load level.

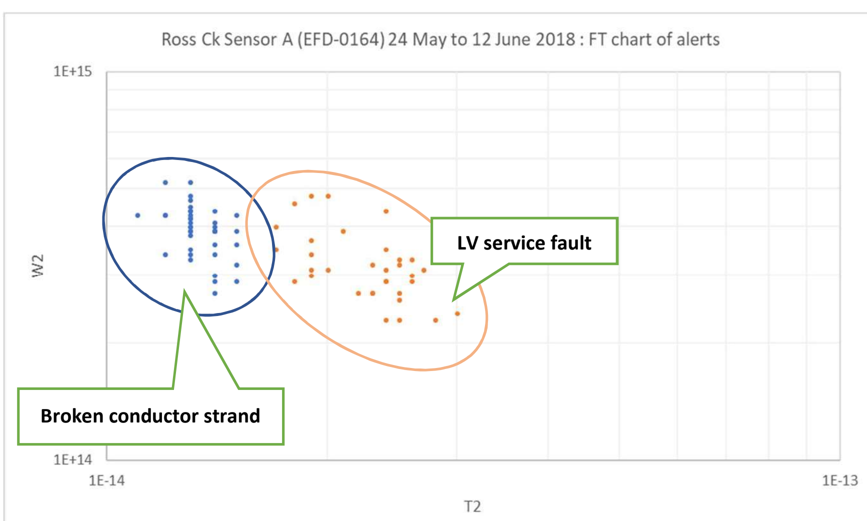
The location of the low-voltage service line failure was just beyond the Ross Creek EFD-monitored path and the EFD system was not able to locate the fault except to indicate it was close to Sensor A.

Figure 46: layout of Ross Creek path between Sensor A and Sensor D showing incipient fault locations



Time-frequency analysis of the alerts show the low-voltage failure created a different pattern of partial discharge signals to that created two weeks earlier by the broken conductor strand:

Figure 47: FT chart patterns of broken strand alerts and low-voltage service line alerts



Lessons taken from this incident included:

- EFD technology detected the low-voltage fault three days before the smart meter detected a supply outage;
- EFD technology which monitors SWER powerlines can 'see through the transformer' to detect low-voltage faults; and,
- EFD time-frequency analysis and 'time-of-day' analysis can help indicate the type of fault.

10.3 Media coverage

The significance of EFD incipient fault detection demonstrated in the two events at Ross Creek was not lost on local regional media. The following is typical of the stories they ran:

Ballarat Courier July 11 2018 - 3:19PM

Potentially disastrous fire prevented by new power line technology

Greg Gliddon

The simple box that may have prevented a bushfire at Ross Creek. Picture: Greg Gliddon

NEW power line conductor technology being trialled in Ross Creek may have already prevented a bushfire.

The technology, which is being tested across the western district and the north east of the state has uncovered a potentially disastrous fault, which, while unlikely to cause anything more than a power outage in winter, could have been disastrous had the line collapsed in summer.

The Early Fault Detection System has been placed on 61 power poles throughout the state by Victorian company IND.T in a state government funded trial of new technology aimed at reducing fire risk.

The technology is placed on power poles where it can detect faults as they develop.

Minister for Environment, Energy and Climate Change Lily D'Ambrosio said the government had committed $650,000 to the trial.

"We never want to see the repeat of the 2009 Black Saturday bushfires," Ms D'Ambrosio said.

"Many of the bushfires that came from Black Saturday came from faults on single wire electricity lines, such as the ones these trials are being conducted on. Importantly, there was an event in May this year where two faults were detected which gave early warning signals to Powercor that there were faults in the line.

"We know that one of the faults detected was a similar fault to what caused the fires in Kilmore on Black Saturday. That is really a sobering reminder of how important these technologies and research into products like this is."

The frayed wire discovered at Ross Creek, which had it have fallen could have caused a bushfire. Picture: Greg Gliddon

IND.T chairman Tony Marxsen said the technology was a world first.

"The box on the pole is sending data up to the cloud for processing every second and that is combined with data from other boxes up to 5km away," Dr Marxsen said

"Any fault along that path at any time, will be signalled so the owner of the network can take action to remedy the fault before it turns into a fire or outage.

"The really good thing is we had a chance to trial it in rural areas where the fire risk was highest, the single wire lines are regarded as the worst type of lines that recorded the most damage at Black Saturday."

The boxes were installed from November last year to February this year with the trial to continue until June next year.

Powercor general manager electricity networks Steven Neave said having an overhead network in a fire zone meant fires were bound to happen.

"It is our highest priority to mitigate the chance of bushfires and technology like this goes a long way to do that," Mr Neave said.

"It's relatively early stages, the trial will go until June, but what we can say is the results have been very promising and it's worked the way it's designed to.

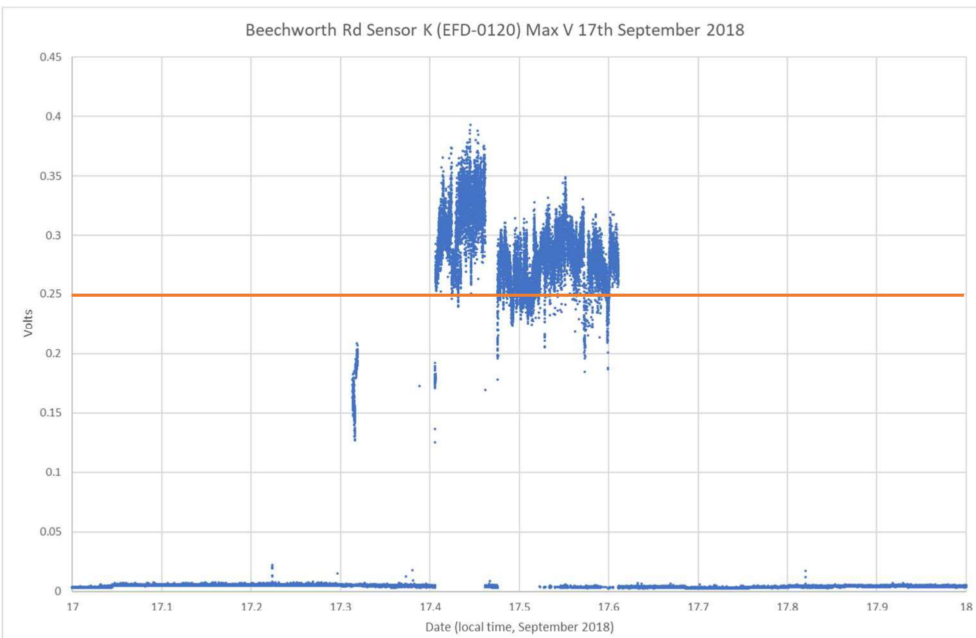
"We'll let the trial play out and then we'll look at the deployment across our network."

Similar stories were run on regional television, including supportive comments from local Country Fire Authority fire crew leaders.

10.4 Replacement of deteriorating substation transformer in high fire-risk conditions

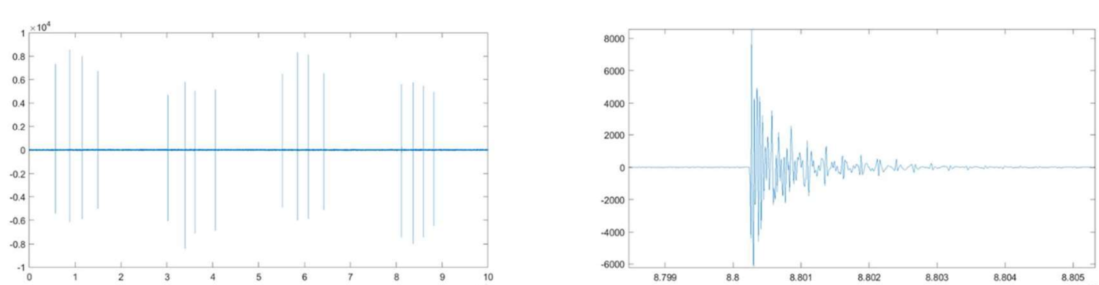
At 9:49:12 am on the 17th of September 2018, Beechworth Road Sensor K (EFD-0120) sent an SMS alert indicating PD of magnitude greater than the 300mV alert threshold. A total of 35 alerts were then received up until 2:10:41pm when they ceased. Data downloaded from the EFD portal showed almost continuous high-magnitude signal over the 4.8-hour period as shown in Figure 48. Fire risk was low.

Figure 48: burst of high signal magnitude from Beechworth Road Sensor K on 17th September 2018



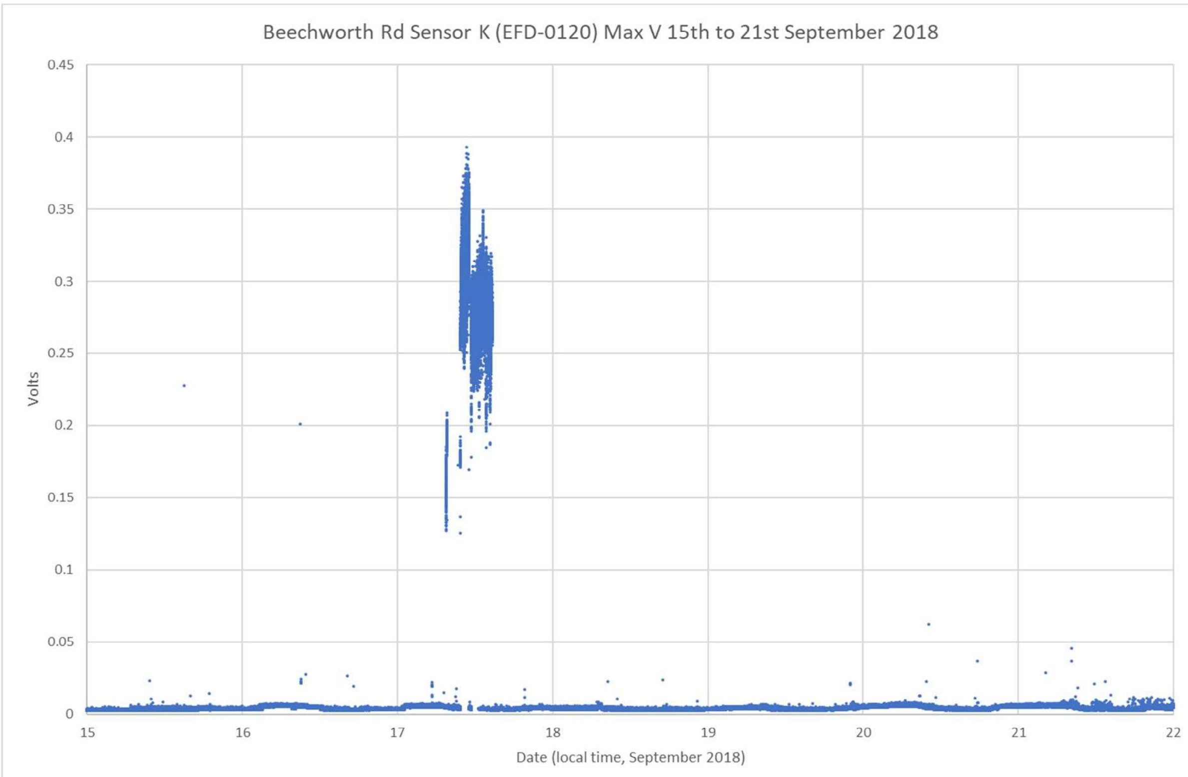
Signal waveforms captured by EFD-0120 showed classic partial discharge with groups of multiple high-magnitude peaks spaced every ten milliseconds, corresponding to the peaks or zero-crossings of a 50Hz voltage waveform. A typical example of the waveform is shown in Figure 49.

Figure 49: Signal waveforms from high-magnitude burst from EFD-0120 on 17th September 2018 (40ms, 2.7µs shown)



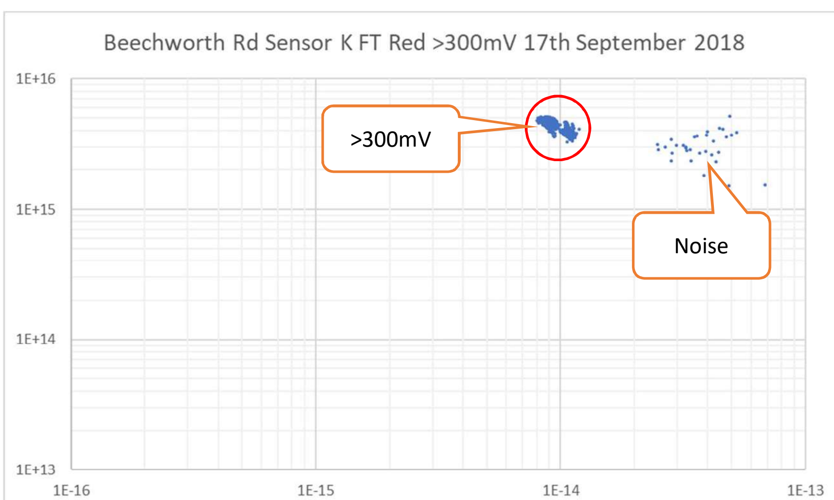
The local network was ‘quiet’ with an underlying network noise level that varied in a regular daily pattern from five to seven millivolts. Signal on other days that week was low as shown in Figure 50.

Figure 50: Beechworth Rd Sensor K signal level over the week from 15th to 21st of September 2018



The FT chart showed a clear separate cluster of high-magnitude signals.

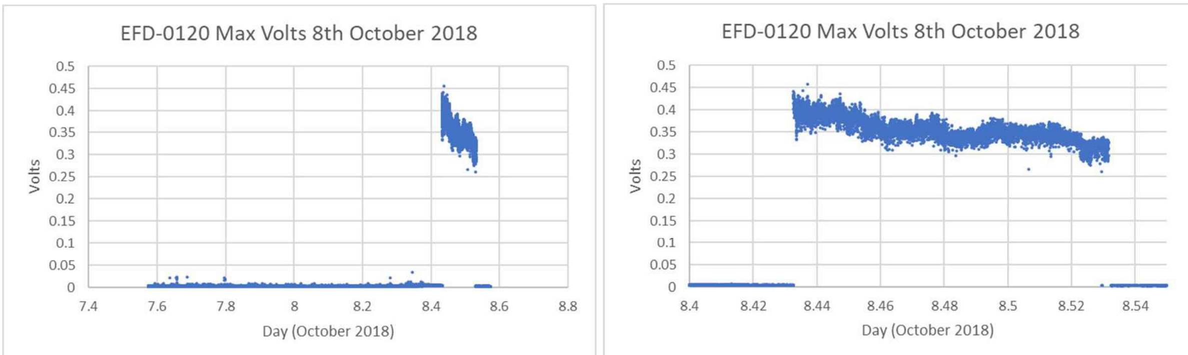
Figure 51: Beechworth Road Sensor K (EFD-0120) FT Chart of high-magnitude signals on 17th September 2018



AusNet carried out an inspection with particular attention given to the network around and beyond Sensor K. The patrol found a desiccated ring-tail possum carcase across the low-voltage terminals of Thieke 3 substation at the end of the spur, 392 metres beyond Sensor K. They removed the carcase and arranged to have insulating covers installed on the LV terminals. No supply outage was required. It was assumed the possum was the cause of the EFD detection as the signal did not recur in the next two weeks.

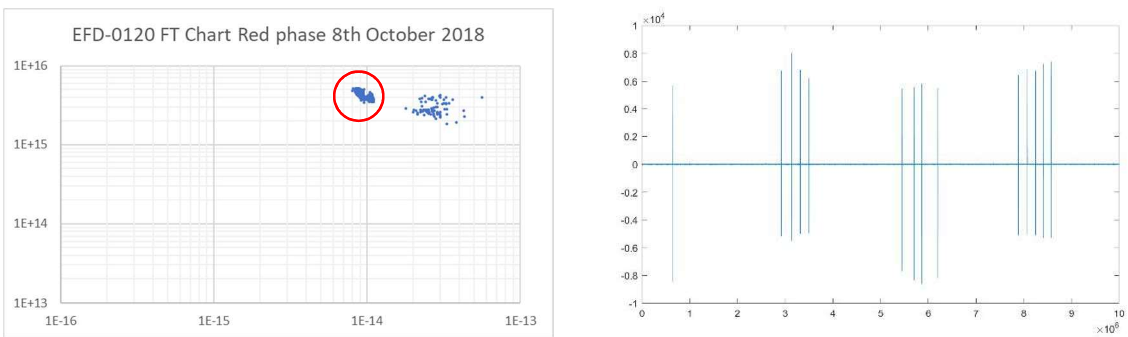
Three weeks later, on the 8th of October 2018, Beechworth Road Sensor K issued continuous alerts from 10:23am to 12:46pm. The raw data revealed a similar pattern to the 17th September event.

Figure 52: Beechworth Road Sensor K (EFD-0120) disturbance on 8th of October 2018



It was a single isolated burst with nothing significant in the days before or after. The FT Chart showed the alerts fell in the same chart zone as those on the 17th September with the same 'double-blob' shape. The alert waveforms were of the same form as those recorded on the 17th September.

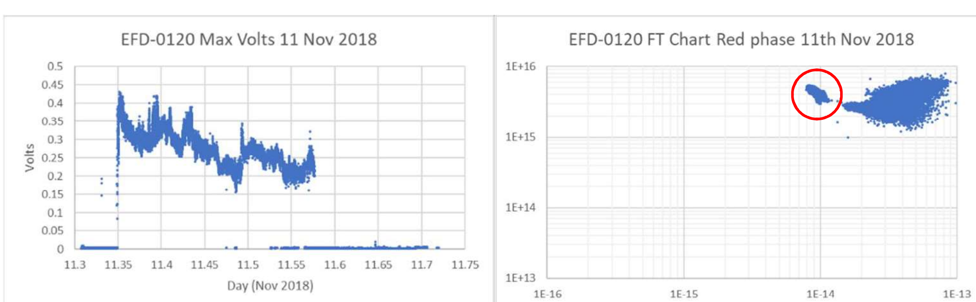
Figure 53: Beechworth Road Sensor K (EFD-0120) disturbance on 8th October 2018 - FT Chart and waveform example



The area was again patrolled but no cause was found. Metering data was examined and though supply voltages were elevated during the middle of the day due to local rooftop solar PV, they did not exceed 250V. There was some evidence of solar inverters switching on and off due to high residential voltage, but the timing did not correlate with the EFD signal. Fire risk was still low.

Four weeks later on the 11th of November 2018, the pattern repeated again as shown in Figure 54.

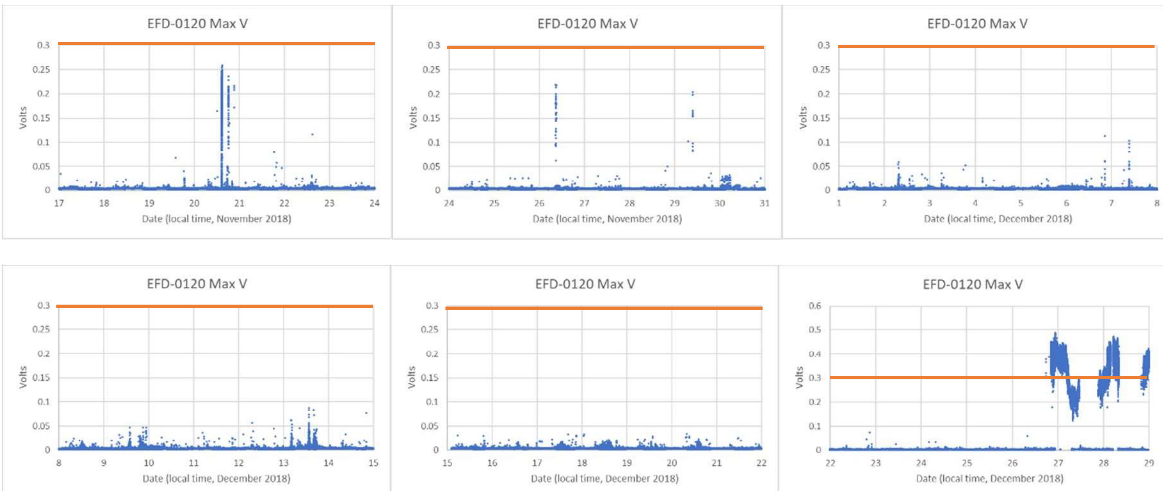
Figure 54: Beechworth Road Sensor K (EFD-0120) disturbance on 11th of November 2018 - signal magnitude and FT Chart



The area was again patrolled on the 12th of November with no cause found. An Electrical Access Permit was taken out and a new high-voltage earth fitted to the tank. This provided a second earth to back up the one provided by the metal link between the high-voltage winding return terminal and the tank. Supply to the nearby (unattended) residence was interrupted during these modifications.

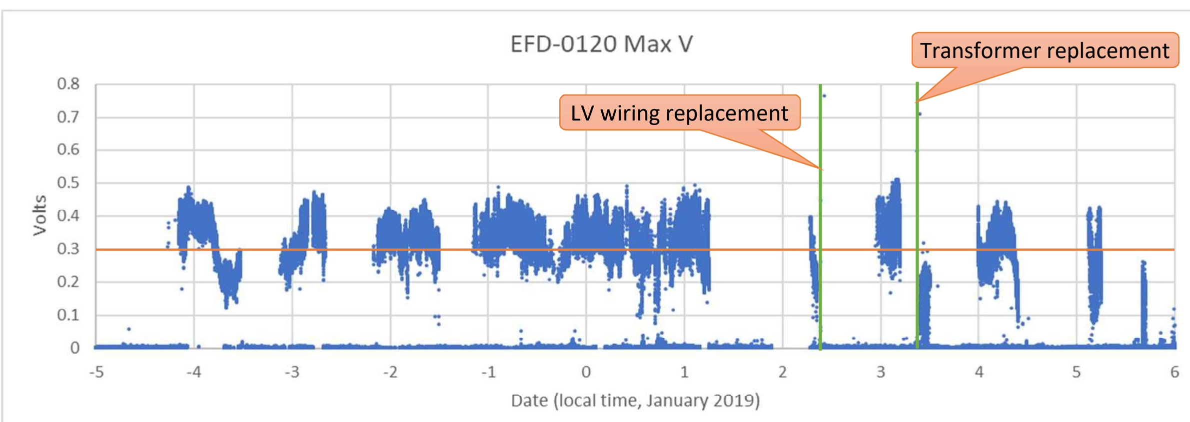
Though there were occasional short-duration signal bursts seen at Sensor K over the next eight weeks[19], none reached the alert threshold until 8:32pm on Boxing Day, the 26th of December 2018.

Figure 55: Signal magnitudes at Beechworth Road Sensor K from mid-November to late December 2018



From first alert on the 26th of December 2018, alerts were received almost continuously for long periods until the alert mechanism was disabled and the activity was monitored directly using the EFD portal. High-volume, high-intensity signals were received by Sensor K until the Thieke 3 substation transformer was replaced on the 3rd of January 2019.

Figure 56: Signal magnitude at Beechworth Road Sensor K from 26 December 2018 to 5 January 2019



The situation was viewed as potentially involving serious fire risk: fire consequence at the location was very high with partially surrounding forest, the ground under the substation littered with dry branches and grass close to a weatherboard house and a large heap of dry firewood. Repeated heat waves were forecast, the property was unoccupied, and there was a possibility (based on the EFD

[19] These and later short duration spikes in EFD signal magnitude were found to be correlated with REFCL commissioning work at Barnawartha zone substation which supplies the Beechworth Road SWER network.

detection of the low-voltage service failure at Ross Creek) that the signal source might even have been in the low-voltage wiring inside the house. Resolution of the situation was a priority.

To manage the potential risk, the following sequence of actions was taken by IND Technology and AusNet Services working in close collaboration through the seasonal holiday period:

- 26 December: downloaded and analysed EFD data from Sensor K, confirmed the source was the same as the one detected in September, October and November; AusNet Services was informed of its reappearance and an immediate site inspection recommended.
- 27 December: the site was visited (it appeared not to have been occupied for some time) and a thorough asset inspection performed by an IND Technology expert and AusNet Services crew, including a simple scan of the high-voltage earth grid integrity; noted that after 14.5 hours of continuous signal, it stopped at a time very close (within seconds) to when a ladder was first placed against the pole; low-voltage wiring hot joint(s) were then suspected; it was concluded that whatever the problem was, it was located at or very close to the Thieke 3 substation.
- 28th December: forecast maximum temperature of 40°C; agreed to monitor and analyse EFD data every 24 hours; plan agreed with AusNet Services to replace substation low-voltage wiring as soon as a crew became available (availability for outdoor work restricted by heat).
- 30th December: total number of alerts from Sensor K in the week was more than 300 (an order of magnitude greater than any previous experience across the 61 units in the Trial); reorganised internal storage of Sensor K which was filling up due to the number of waveforms being stored; set Sensor K's alert threshold higher to minimise future alerts; the agreed plan remained to inspect low-voltage wiring as soon as possible.
- 31st December: correlation analysis of signal with weather data indicated the signal was affected by the arrival of heavy rain storms (timing indicated it may have been the wind gust just before the storm front); this indicated it was an outdoor source and not inside the house; work was scheduled to address potential low-voltage wiring issues on the pole.
- 1st January: a Telstra 3G outage cut off dataflow from Sensor K at 9:14pm.
- 2nd January: Sensor K resumed operation ten hours after the Telstra 3G service outage; the AusNet crew attended the site and inspected and then replaced all low-voltage wiring on the substation pole, as well as the high-voltage surge diverter and 'wineglass' insulator between the fuse/switch and transformer; the EFD signal fell to almost zero after the work and monitoring continued.
- 3rd January: high-volume high-magnitude signal returned at 10:49pm on the 2nd January and was continuous for six hours overnight; the decision was taken to replace the transformer immediately given imminent arrival of even hotter weather; transformer replacement changed the EFD signal but did not immediately eliminate it– the new transformer exhibited in-tank 'double crescent' partial discharge pattern on the FT Chart; this was taken as confirmation that the original issue had been replaced, so it was unlikely there were issues in the low-voltage house wiring.
- 4th and 5th January and beyond: the EFD signal fell to negligible levels as the new transformer 'bedded in', checked all other sensors on the Beechworth Road network and found no signals above 50-60mV and most below 20mV (Sensor K was 450mV before replacement); monitoring and analysis continued daily for the first week, then moved to a weekly report.

The change in signal FT character with transformer replacement is shown in Figure 57 and the longer-term signal magnitude over the next twelve weeks is shown in Figure 56.

Figure 57: FT Chart of signal before and immediately after transformer replacement at Thieke 3 substation

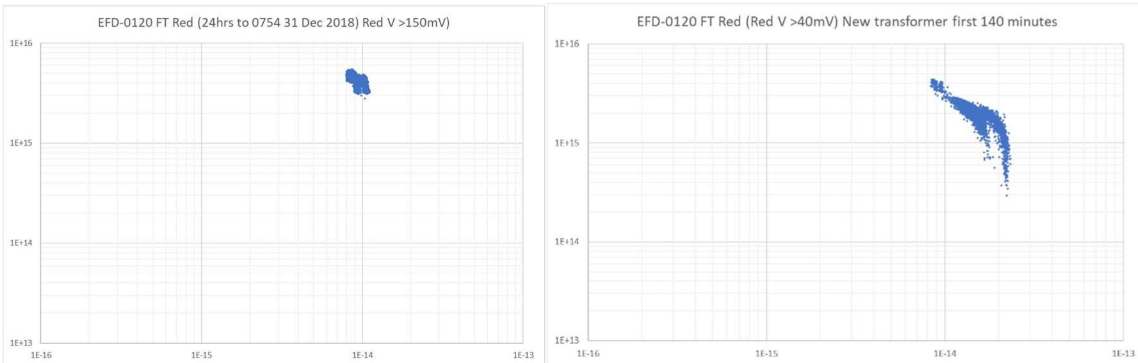
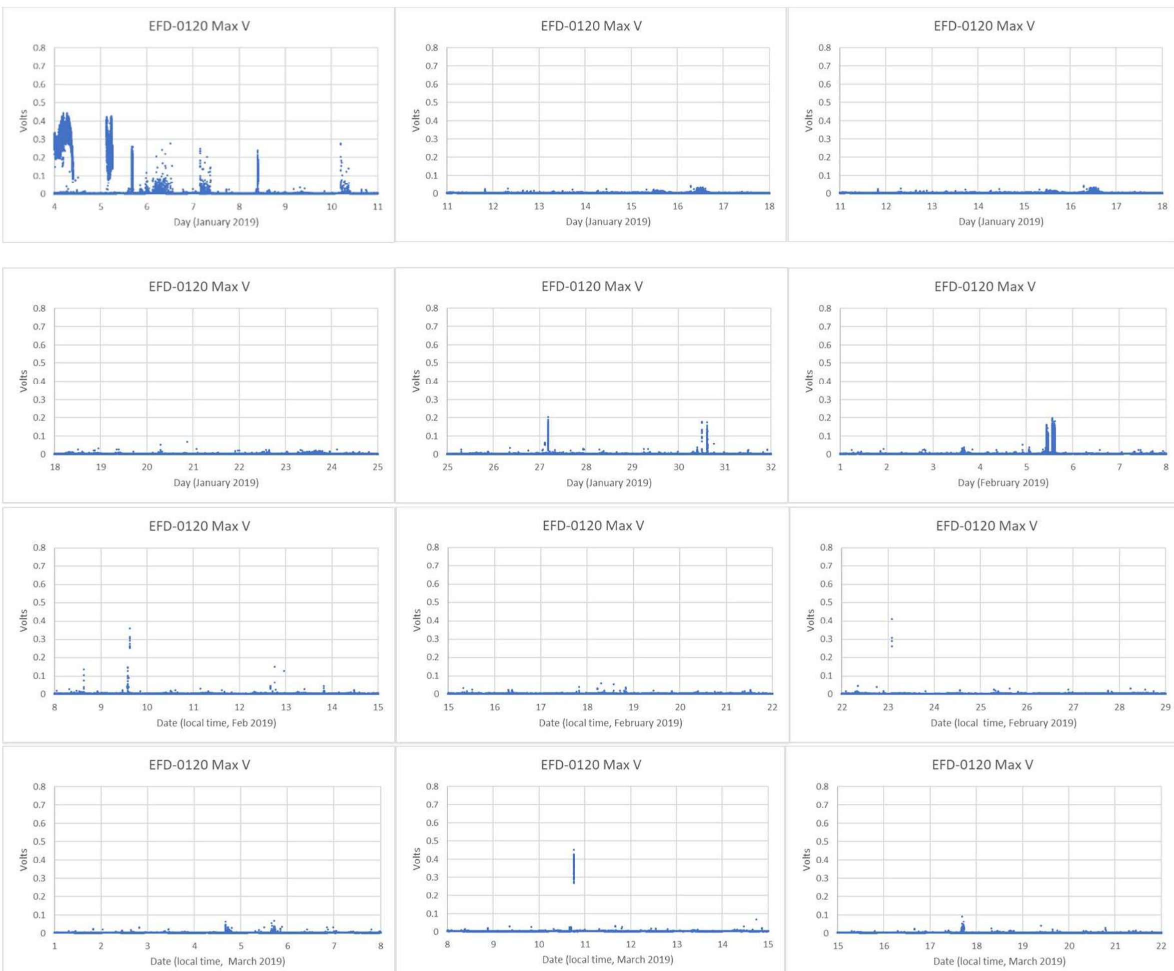


Figure 58: Beechworth Sensor K signal in the twelve weeks following transformer replacement at Thieke 3 substation



After twelve weeks of essentially zero signal from Sensor K, it was considered safe to conclude the issue was gone and transformer replacement at Thieke 3 substation had been a successful remedy. Weekly monitoring continued as a precaution against recurrence.

On the 2nd and 3rd of May 2019, the signal level at Beechworth Road Sensor K increased in a pattern very similar to that seen in the second half of 2018, as shown in Figure 59. The FT pattern of the signal (Figure 60) was very similar to that recorded just prior to transformer replacement.

Figure 59: Beechworth Road Sensor K signal 2nd and 3rd of May 2019

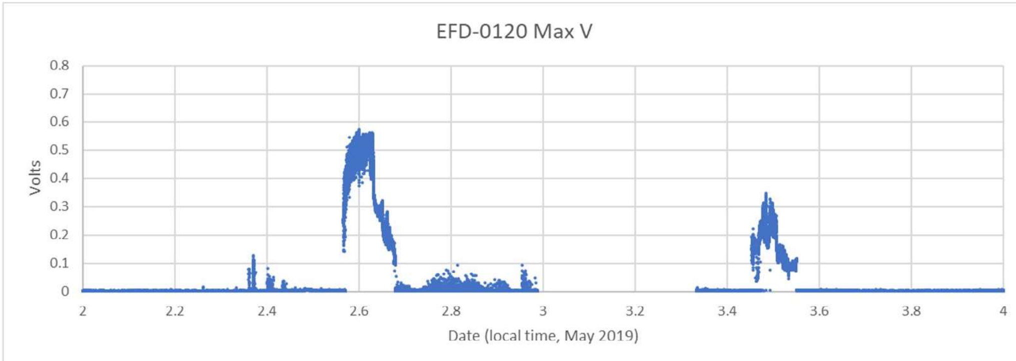
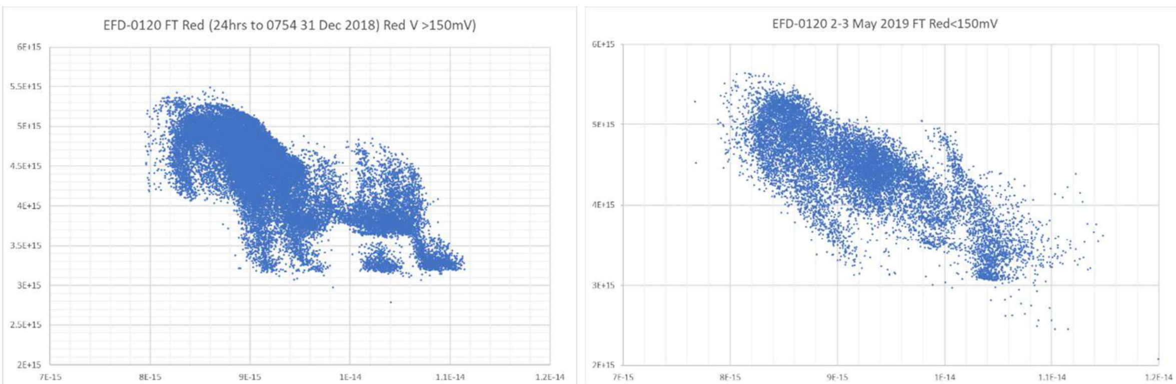


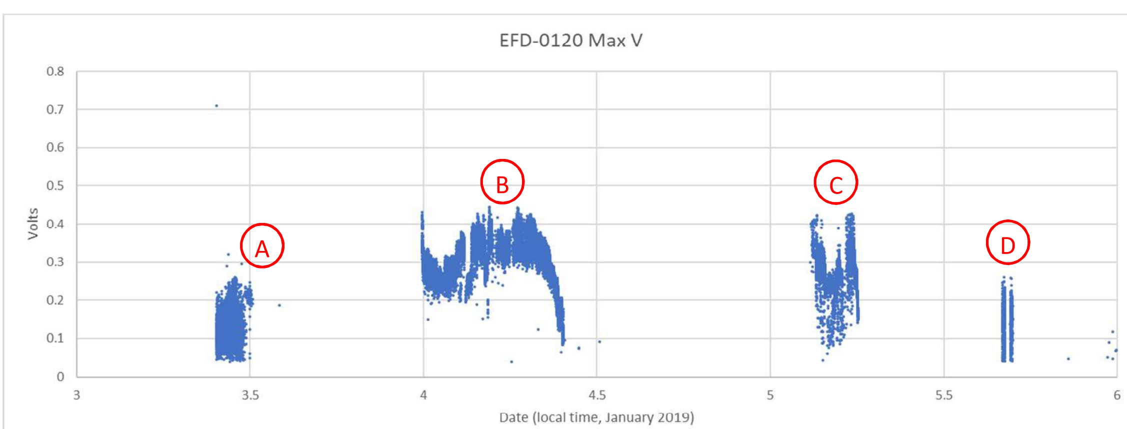
Figure 60: FT patterns (zoomed) of Sensor K signal prior to transformer replacement and on 2nd and 3rd of May 2019



Since the 3rd of May 2019 until the time of writing this report, the high-magnitude signal has not recurred. The recurrence in early May indicates the original issue may still be present but was somehow made quiescent for four months by the work performed on the pole to install new low-voltage wiring and the new transformer.

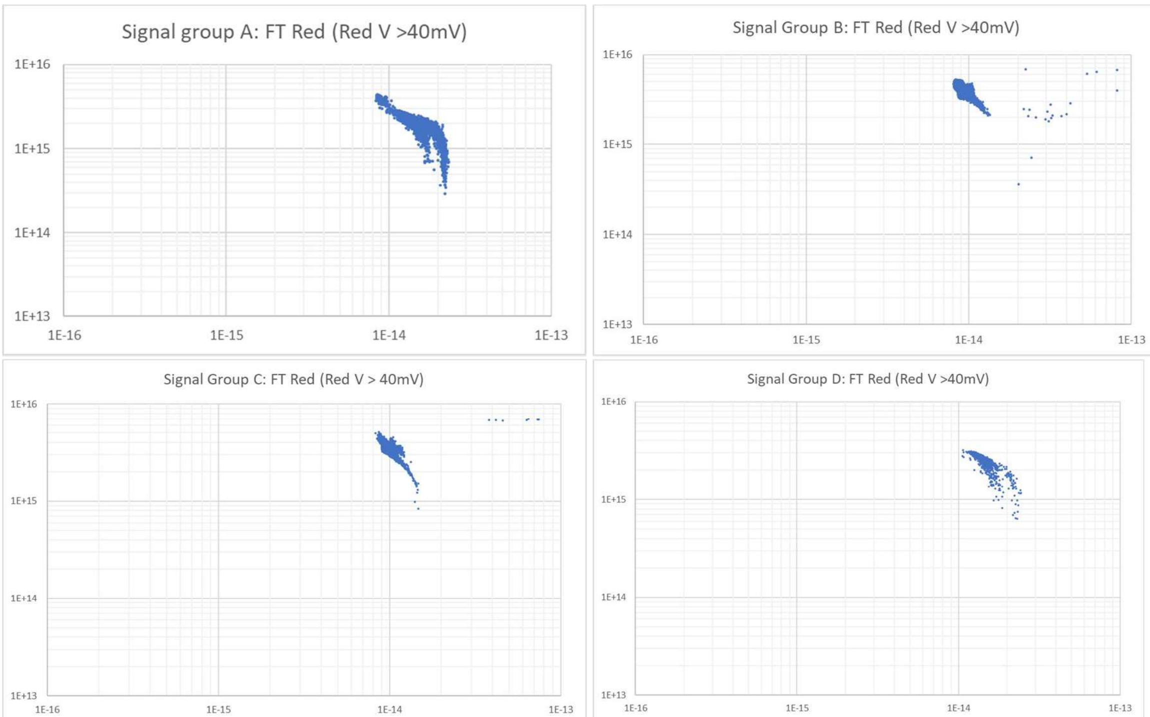
The recorded signal data for the few days immediately after the transformer replacement (Figure 61) was re-downloaded and re-examined as soon as the early May recurrence was recognised. It showed four clearly separate bursts of signal over three days. Each of these was separately analysed for its FT characteristics.

Figure 61: Beechworth Road Sensor K signal immediately after transformer replacement



The FT patterns for each signal group are shown in Figure 62. Signal group D is clearly associated with REFCL commissioning tests, being two bursts of ten minutes each, separated by a gap of twenty minutes. This pattern is the standard ‘soak’ test of network hardening prior to REFCL commissioning. The source was almost certainly an asset somewhere on the polyphase network supplied by Barnawartha zone substation where REFCL commissioning was underway. The ‘double crescent’ pattern indicates likely in-tank transformer partial discharge.

Figure 62: FT charts for Sensor K signals 3rd to 5th of January 2019



Comparing the charts in Figure 62 with the FT pattern of Sensor K signals prior to transformer replacement (Figure 51, Figure 53 and Figure 54) indicates that signal groups A, B and C all had some characteristics of the 2018 signals, particularly groups B and C which also had some of the same magnitude pattern character of earlier events (compare Figure 61 with patterns shown in the early part of Figure 56). The early May signals look very much like a recurrence of the 2018 issue.

The current status of the Thieke 3 substation site is that there may still be an incipient fault at that location which (despite all the efforts since first detection) has not been found and remedied. The work at the site appears to have caused it to become quiescent for months, but monitoring will continue in case it recurs. Monitoring will be stepped up and further site investigations schedules prior to next fire season to manage any associated fire-risk. If it is indeed still there, the fault may be revealed by further investigation or it may reveal itself (preferably during a period of low fire risk).

The lessons drawn from the incipient fault at Thieke 3 substation included three new challenges:

- Existing field procedures and test tools can be ineffective in finding signal sources that are not visible. New techniques and tools are required to find incipient faults once their location has been determined to single-pole accuracy.
- There is a possibility that a detected incipient fault may be in the wiring of the customer premises. This poses unprecedented questions about appropriate communications with a customer when information is so uncertain, as well as about obligations and liabilities.
- Nearly all signal sources detected in the Trial have been very intermittent which makes finding the source doubly difficult as it is often quiescent when a crew attends the site.

11 The EFD system can successfully prioritise network asset condition

The EFD SWER Trial constituted the first-ever large-scale continuous monitoring of high-frequency signals on real electricity distribution networks. It generated valuable new insights into the characteristics of a range of different signal sources, both at 'complex' poles with pole-mounted distribution substations and at 'simple' unencumbered poles, as well as providing valuable data on the background noise on networks. The availability of continuous real-time asset condition data has the potential to profoundly change asset management strategy within network businesses for the better.

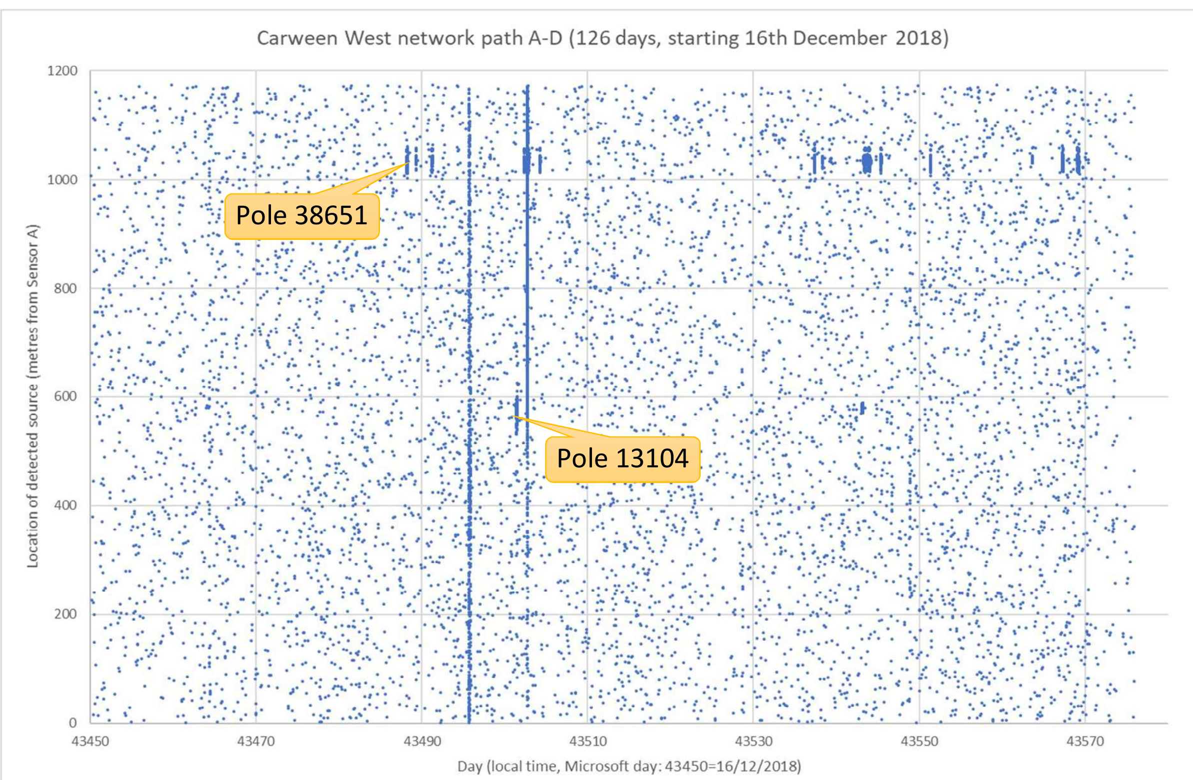
The following cases outline the only assets identified in the Trial (one out of 924 poles and four out of 311 substations) that showed abnormal levels of signal. The EFD system identified the one or two per cent of assets that warrant attention, out of the vast majority that show no sign of abnormality. The first step in this part of the Trial analysis was to understand network background noise.

11.1 Background network noise is best measured by energy

The best parameter to characterise network background noise is energy. It is reasonable to assume that the energy captured by the EFD sensors is directly related to the energy of a signal source.

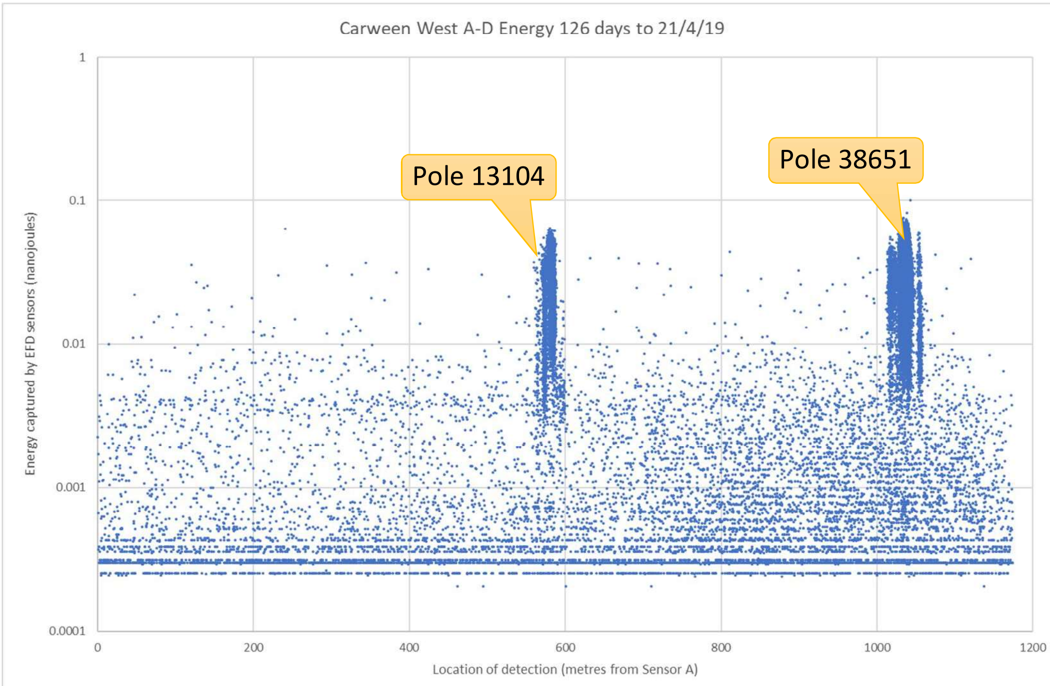
When EFD data for a particular network path was downloaded from the EFD portal, the quickest and easiest visualisation to create was the location chart which shows every detection in time (horizontal axis) and location (vertical axis). An example is shown in Figure 63. This locates shows a repeated intermittent hot-spot (Pole 38651), a second hot-spot (Pole 13104) which had a single major burst and 43 days later another briefer one, and two half-day periods of heavy rain (the vertical lines).

Figure 63: source detection location chart for 126 days of Carween West network path A-D



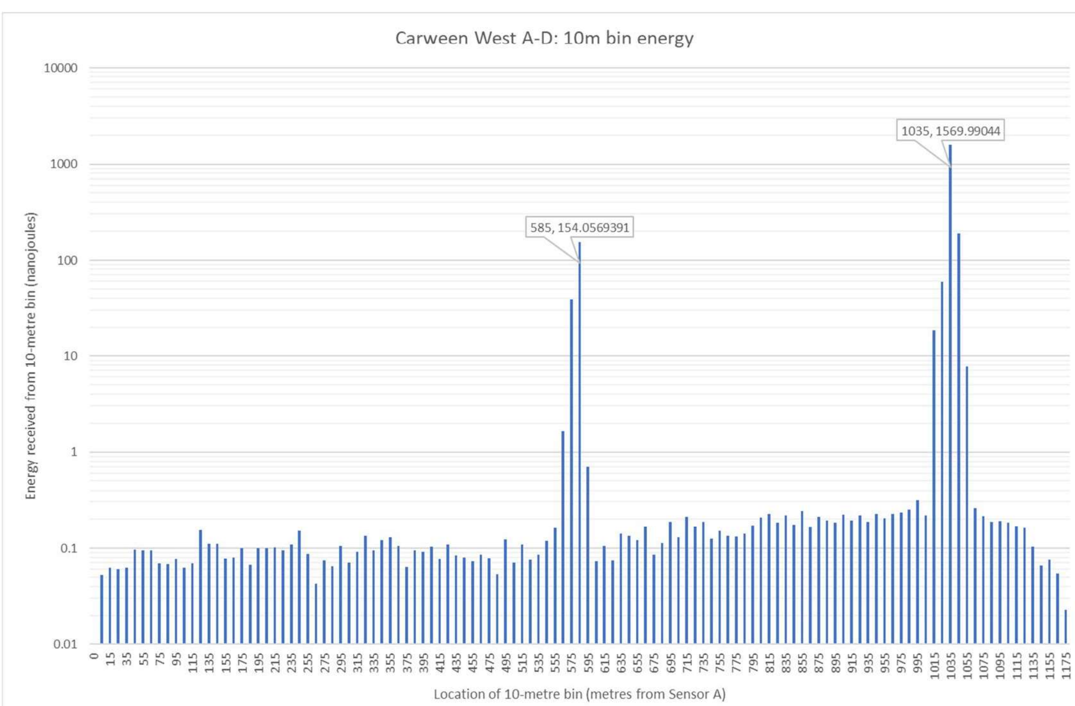
Once the concept is grasped, the location chart visualisation of EFD path data reveals at a glance everything that has happened over the period. However, it does not indicate the relative energy of the detected signals. For this, the energy-by-location visualisation shown in Figure 64 works well.

Figure 64: Carween West network path A-D energy distribution



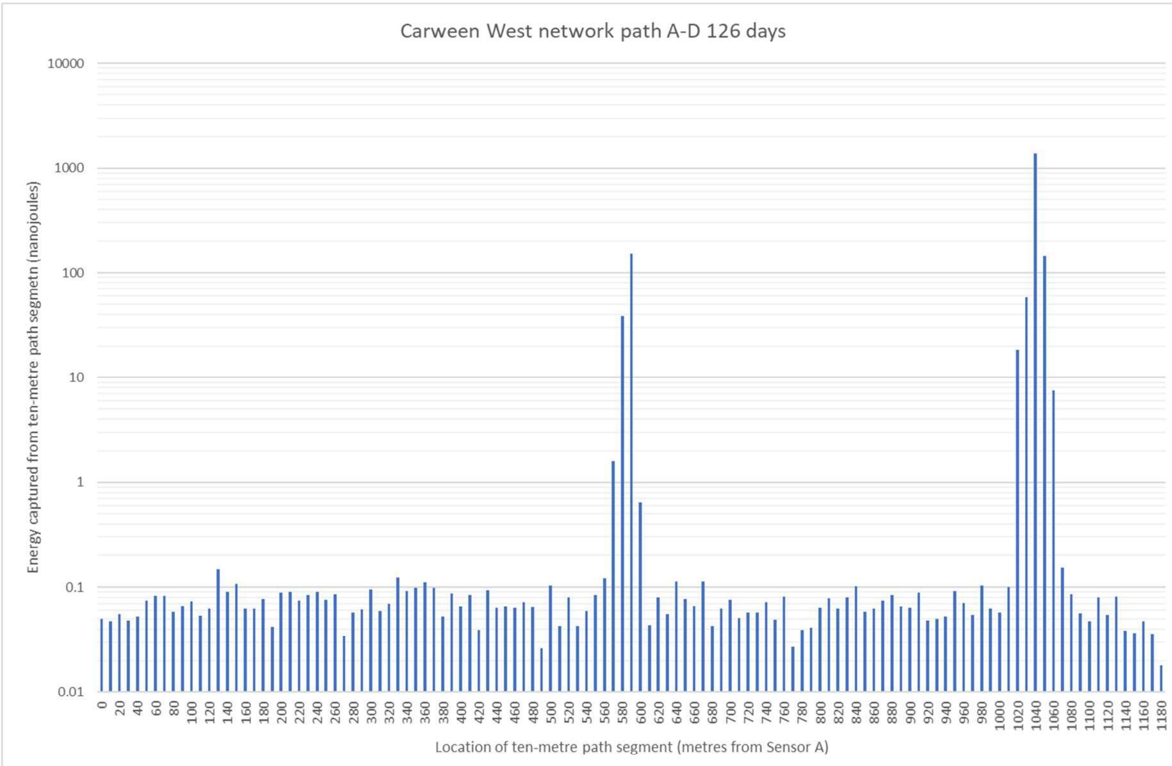
If the detected energy is totalled for each ten-metre segment of the network path, as shown in Figure 65, the relationship between the two hot-spots and background noise becomes very clear. To compare network paths across different networks in different locations, the average energy captured from a ten-metre segment of powerline per day proved useful.

Figure 65: Energy totals for ten-metre segments along Carween West network path A-D



In Figure 65 above, the background noise is only lightly filtered and rain detections have not been filtered at all. Once the rain signal is removed, the network energy picture is revealed as shown in Figure 66.

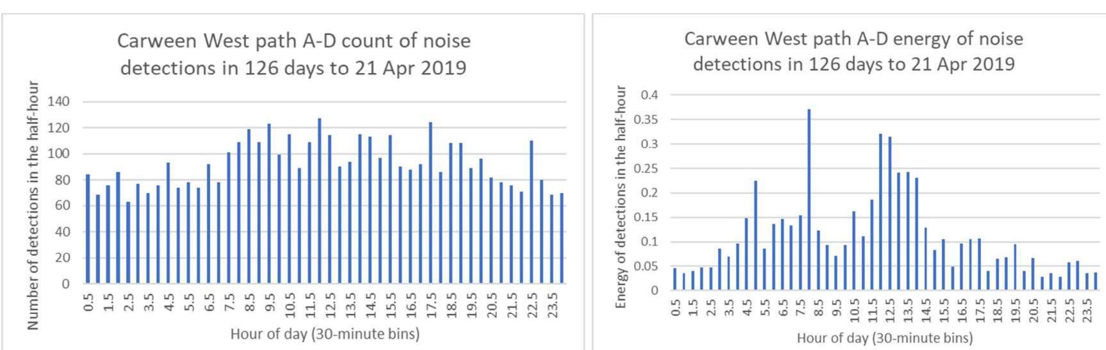
Figure 66: Carween West network path A-D 126 days with rain detections removed - energy from ten metre path segments



Each ten-metre segment of powerline path generated about 100 picojoules of energy into the two EFD sensors over 126 days, i.e. less than one picojoule per day. Sources detected at Poles 38651 and 13104 generated 1.5 microjoules and 150 nanojoules respectively which is 1.5 million times and 1.5 thousand times the background noise energy. It was clear the EFD system could pick up even the lowest energy phenomenon on the path, so long as it emitted high-frequency signals.

The daily pattern of background noise is shown in Figure 67, accumulated over the 126-day period.

Figure 67: Carween West network path A-D daily pattern of background noise (rain removed)



While the count of noise detections (left-hand chart) was relatively constant over the 24-hour daily cycle, the noise energy (right-hand chart) showed distinct peaks in the morning (5am and 8am) and a broader peak (noon to 2pm) in the early afternoon, indicating a likely correlation between noise level and human activity in the local area.

While the charts above relate to a single network path (Carween West A-D), energy reviews of other networks found similar patterns. It was concluded that background noise on monitored networks was well below any level that could potentially disturb the effective operation of the EFD system in its primary role - monitoring the health of network assets.

11.2 Intermittent activity at substation poles

During the EFD SWER Trial, four of the 311 substations on the eleven networks exhibited high-volume signal production indicating progressive insulation destruction within assets at those locations. The Thieke 3 substation case is covered at detail in Section 10.4 above. The other three cases identified in the Trial included a second termination substation (Hughes 24) and two substation poles on monitored network paths (Poles 13105 and 38651). Each is more fully outlined below.

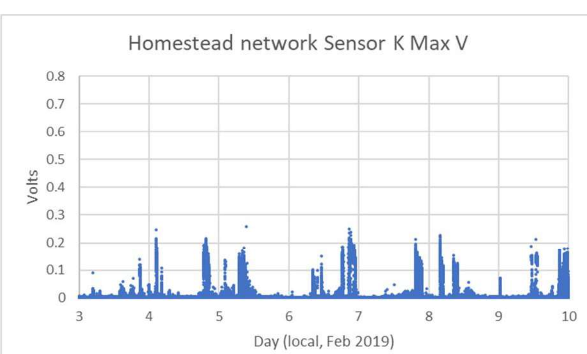
11.2.1 Hughes 24 substation (Homestead network EFD Sensor D EFD-0123)

Hughes 24 is a termination substation (at the end of a SWER powerline), one 280-metre span beyond EFD Sensor D on the Homestead network in north-east Victoria. High-volume, high-energy signal activity at Hughes 24 was first identified in a scan of networks on the 5th of January 2019 prompted by the experiences at Thieke 3 substation.

Figure 68: layout of Homestead network showing Hughes 24 substation and Sensor D

The substation supplied a complex of farm buildings via a mix of multiple underground and overhead low-voltage service lines, with a private pole supporting the overhead services. Parts of the installation looked very old but inspection by AusNet Services revealed no issues.

Figure 69: Homestead Sensor D – a typical week of signal from Hughes 24 substation



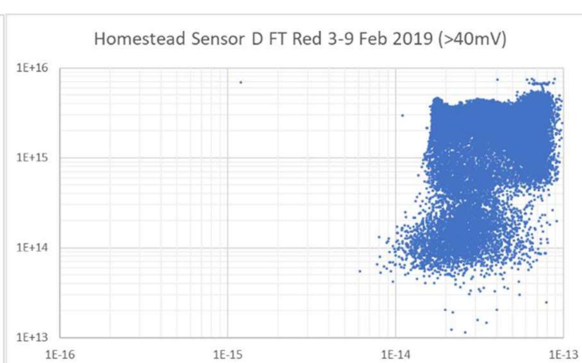


Figure 70: Hughes 24 substation assets

The fire-risk of this situation was seen as lower than the extreme levels that applied at Thieke 3. The FT Chart was very diffuse and not like any other pattern observed in the Trial. Signal energy level was four times lower than that at Thieke 3 substation and an inspection had found no cause for concern. It was decided the EFD signal from Hughes 24 would continue to be monitored but no specific action would be taken unless the situation deteriorated further.

11.2.2 Carween South 1 substation (Carween West path A-C Pole 13105)

Path A-C is 1,383 metres long and comprises six poles, three of which have substations on them.

Figure 71: Carween West network path A-C showing location of Pole 13105

EFD data for this path showed an intermittent hot-spot at Pole 13105 that had been intermittently active since the start of the Trial. The energy chart (Figure 72) and detection location chart (Figure 73) both showed a high-energy intermittent hot-spot at the Carween South 1 substation on Pole 13105. A typical signal burst from this location comprised several hours of medium magnitude (≈100mV) signal with no activity before or after - until the next burst.

The energy chart also showed a much weaker (twenty times less energy) signal from tee-off Pole 836911 one span to the North of Pole 13105 which was not easily seen on the detection location chart, though retrospective review of EFD data indicated this tee-off pole may have produced more signal in early 2018 (specifically from 3am to 8am on the 12th of April 2018), possibly from an off-path source. This source was discounted because of its low signal energy.

Figure 72:Carween West network path A-C energy chart for 126 days starting 16 December 2018

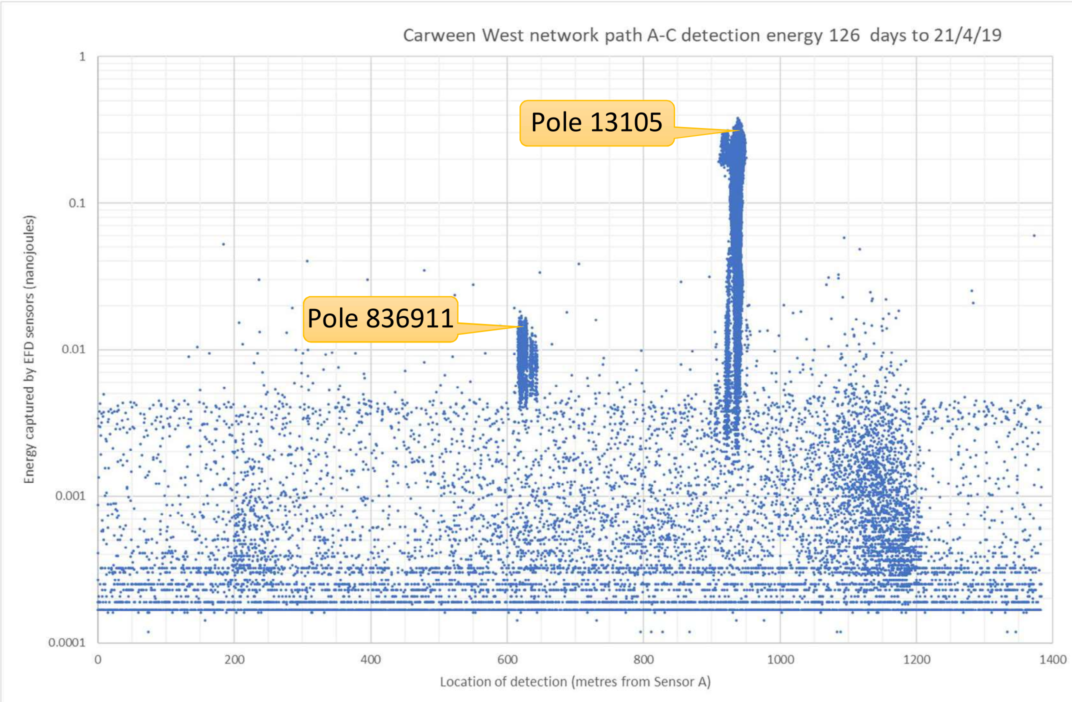
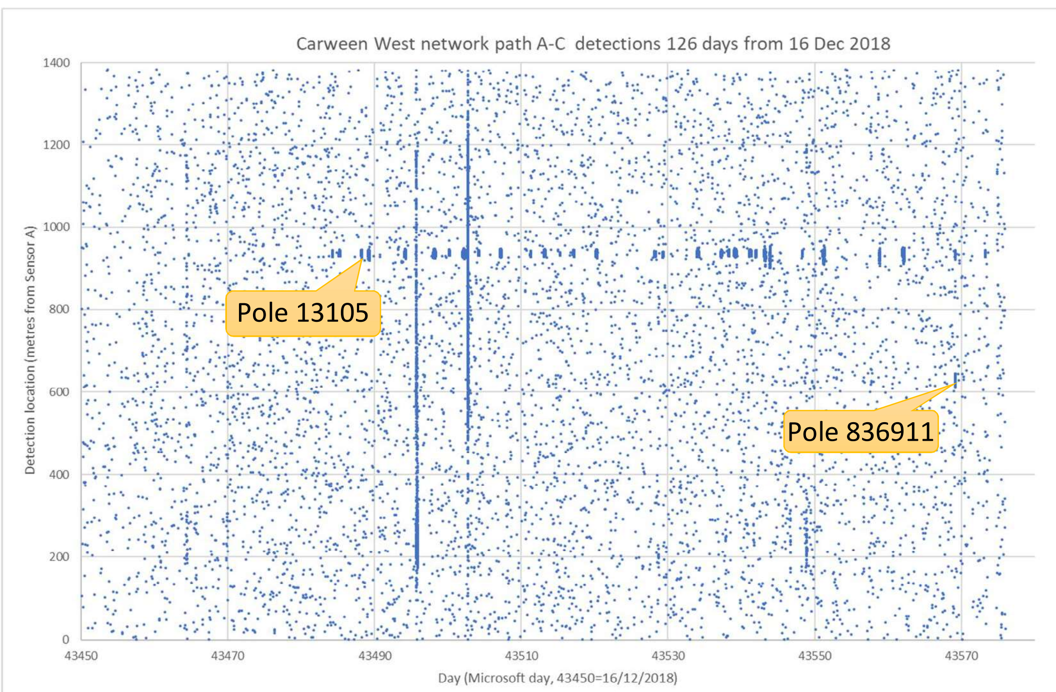


Figure 73: Carween West network path A-C for 126 days starting 16 December 2018

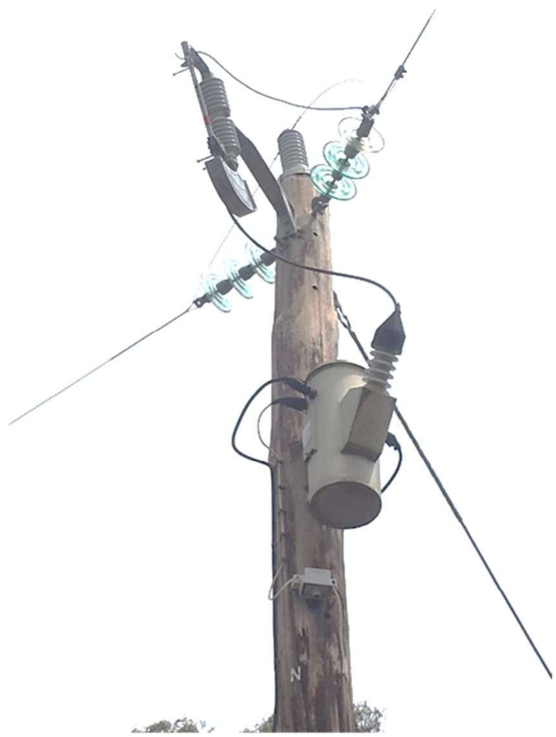


Pole 13105 signal magnitude at Sensor C was high - up to 70% of the 200mV Summer system alert threshold - and the FT Chart showed the abnormal character of the signal (not rain, noise, electric fence, etc.).

Figure 74: Detection count and FT Chart for Pole 13105 as shown on EFD portal

Pole 13105 was inspected in November 2018 with no fault found and the intermittent signal continued.

Figure 75: Assets on Pole 13105 Carween West network path A-C



The signal was observed to be less frequent over the colder winter months. IND.T has recommended Powercor replace the assets on Pole 13105 if activity is high again next Summer.

11.2.3 Veal 2 substation (Carween West path A-D Pole 38651)

Pole 38651 is one span (163m[20]) away from Carween West Sensor D (EFD-0158) on the path to Sensor A (EFD-0162). It is a substation pole located in a paddock about 50 metres from a farm residence.

[20] The span is 163m by visual pole location and distance measurement on Google Earth, but only 115m in the portal data base which is based on historical records.

Figure 76: General layout of Veal 2 substation (Pole 38651) and Sensor D on the Carween West network

High-volume signal from Pole 38651 was first noticed in November 2018. The locations chart (Figure 63 on Page 63) and energy chart (Figure 64 on Page 64) for Carween West network path A-D show Pole 38651 as a repeating intermittent source of signal, though not at the energy level of some others. The FT Chart for signals captured from Pole 38651 is again different from others seen in the Trial. The only obvious hypothesis for the difference is that Pole 38651 is a concrete pole - unlike all the other active sites identified in the Trial which are at wood poles.

Pole 38651 was inspected in November 2018 with no cause found. It is shown in Figure 77.

Figure 77: Assets on Pole 38651 Carween West network path A-D

The lower energy level and lower fire risk situation led to a decision to monitor Pole 38651 but capture further insights and take no replacement action unless the signal energy increased further.

11.3 Intermittent activity at non-substation poles

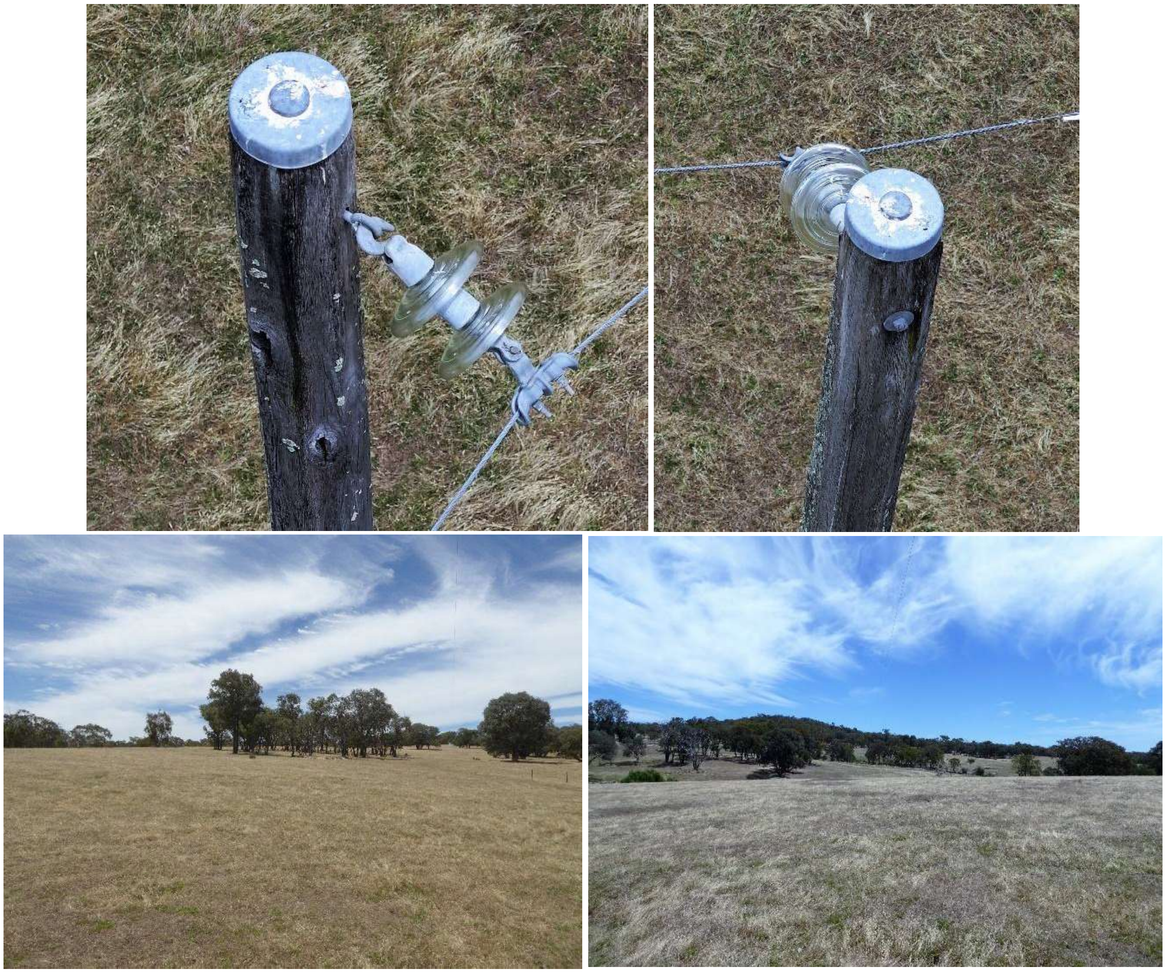
As well as signal sources at substation poles, the EFD system detected signals from two poles that did not have substation transformers mounted on them.

11.3.1 Anderson F-G Pole 5111862

Intermittent signals were captured from Pole 5111862 from the start of the Trial. Viewed in retrospect they were (and remain) low energy signals, albeit high volume. At the time, the signals attracted a lot of attention and Pole 5111862 was inspected a number of times, including with a high-resolution drone camera. The reason for this focus was the nature of the surrounding country which was considered to be a high grass-fire risk if the SWER conductor were to fall from the pole.

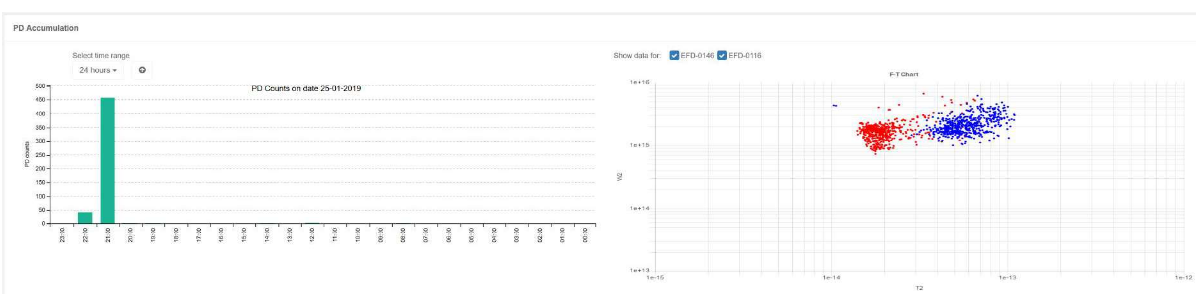
The pole had almost no assets on it as can be seen in Figure 78.

Figure 78: Pole 5111862 on Anderson network path F-G and the surrounding countryside



The signal continued to appear right through the Trial, waning in colder months and waxing stronger in Summer, but always there and always very intermittent.

Figure 79: Pole 5111862 site charts for 25th of January 2019 from EFD portal



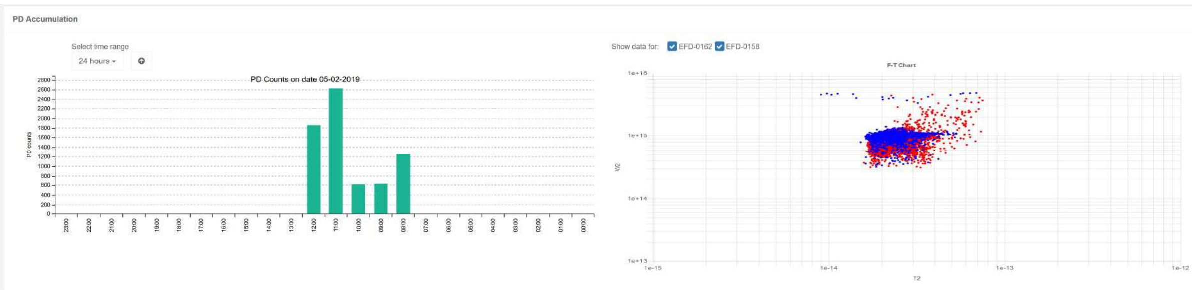
Checking with line crews and others who have been in the network industry for decades, it was learned that the type of glass disc insulator on Pole 5111862 was well known in the 1960s and 1970s as a source of television interference. The cause was thought to be discontinuities in the tiny capacitive current traversing the metal parts between the glass disks as the wind moved the conductor. The standard fix was to insert small steel 'brushes' to ensure good contact between the metal parts. With the change to digital television and FM/digital radio, the problem had faded from industry consciousness. At Pole 5111862, the EFD system may have detected an example of a very old problem that is no longer considered a serious issue.

11.3.2 Carween West A-D Pole 13104

Pole 13104 on Carween West network path A-D is two spans (480 metres) north-east of Pole 38651 described above. The locations chart (Figure 63 on Page 63) and energy chart (Figure 64 on Page 64) for Carween West network path A-D show Pole 13104 as producing signal energy at a level one order of magnitude lower than Pole 38651. Even with the much lower signal energy, this pole was still of interest because it had no substation assets on it.

The EFD portal shows the intermittent character of the signal and the FT Chart (Figure 80). In the 126-day period of the energy survey of the Carween West network, there were only two burst of signal – one lasting about five hours and one lasting less than one hour.

Figure 80: EFD portal data on Pole 13104 for the 5th of February 2019



Pole 13104 is a tee-off pole and it is thought likely that it is injecting signal into the monitored path A-D that originated from a substation about 300 metres away at the end of the spur line, i.e. the signal is not being produced by a problem at Pole 13104.

11.4 Assessment of risk using EFD data

The EFD SWER Trial has confirmed that EFD technology detects incipient faults before they occur. It also provides a rich stream of data on asset health. In the Trial, 98 per cent of network assets generated signals that did not indicate damage or deterioration. However, the last one or two per cent were emitting signals that indicated potential asset health issues. For this data to deliver maximum value to network businesses, the key question to be addressed is: how can it be used to assess the risk of asset failure in the short-term future?

Trials of EFD technology including the EFD SWER Trial have demonstrated that EFD signals emanating from deteriorating or damaged network assets come from a diverse range of physical processes: internal partial discharge, broken wires, surface tracking, vegetation encroachment, bird and animal activity, issues on low-voltage wiring, etc. As described in Section 9.4 on Page 45, the various characteristics of the EFD signal can be used to identify the cause. The EFD SWER Trial has made a start on such identification and larger scale deployments will soon create a database to support confident identification of the type of asset deterioration detected.

Some causes of asset deterioration or damage may require a quick response – for example, vegetation encroachment and broken wires or damaged insulators. Others may warrant a more measured judgement on the need for and timing of a response. A particular signal source in this category is internal partial discharge within substation transformers. The reality is that all partial discharge involves destruction of insulation, but in practice the rate of destruction may be so slow that asset replacement may not be warranted within the normal service life of the asset.

All network businesses are accustomed to making judgement calls on when to act on condition monitoring data in this situation. The essential value of EFD technology is that it provides a rich data set and continuous monitoring so sudden changes (e.g. from a lightning strike) will be brought to an asset manager's attention as soon as they happen rather than at the next scheduled routine inspection or test which may be years later.

The EFD portal provides a comparative risk score that combines signal energy level, long-term trend, medium-term trend and short-term trend in the signals from an asset. This risk score is just the first step in development of an automated guide for asset management decisions on deteriorating assets. It will develop rapidly as EFD deployments increase. AI and 'big data' methods are already being explored to accelerate this journey. Development of a simple, reliable indicator of risk will best be done through collaboration between the technology supplier and the network business in each case. Risk appetite varies and the best solution may differ from company to company, network to network and even from region to region within a network business.

12 EFD on SWER powerlines offers return on investment

Victoria's Powerline Bushfire Safety Program reflects a commitment of $750 million. The program includes the 'smart' ACR rollout to cover all SWER powerlines and the Program's Powerline Replacement Fund has also supported some undergrounding of SWER powerlines or their conversion to polyphase.

12.1 EFD would cut Victoria's estimated $40 million annual cost of powerline fires

The financial value of fire-risk is high in rural areas[21], so for EFD deployment on rural SWER powerlines, any business case must centre on fire-risk reduction.

Victoria's November 2015 Regulatory Impact Statement (RIS) estimated the average annual cost of major fires from electrical assets at $81 million[22]. The RIS also estimated that the regulatory changes proposed at that time (now being implemented) should cut the number of fires by 50% (polyphase powerlines) and 37% (SWER powerlines). The average annual cost of fires from electrical assets after completion of the rollout of polyphase REFCLs and SWER ACRs could therefore reasonably be assumed to be around $40 million. This will increase over time as the number of high fire-risk days increases due to the effects of climate change[23]. Reduction in this ongoing fire cost to the Victorian community could justify investment in rural use of EFD technology.

Experience gained in the EFD SWER Trial allows a very preliminary indicative assessment of the difference SWER EFD could make. Table 8 summarises the data on Black Saturday fires and (based on experience in the EFD SWER Trial) the effect that EFD could have had on Black Saturday:

Table 8: summary of powerline fires on Black Saturday and estimate of EFD benefit

Fire	Cause	Losses	Settlement	Potential EFD fire-risk reduction benefit
Kilmore East (SWER)	Conductor down	1,242 houses, 242 injured, 119 killed	$495 million	High - early detection of broken strand movement would have led to repair and prevented fire
Horsham (SWER)	Conductor down	13 houses lost	$40 million	Likely high but not proven – pole cap came off pole, conductor was swinging against pole and tree
Coleraine (SWER)	Conductor loose	One house, one injury	$10 million	High – early detection of broken tie wire would have led to repair and prevented fire
Pomborneit (Polyphase)	Conductor clash	No houses lost or injuries	$10 million	Low to medium – possible detection of repeated high-resistance faults
Murrindindi (Polyphase)	Conductor down	538 houses, 73 injured, 40 killed	$300 million	Uncertain – depends on cause of conductor fall (undetermined)
Beechworth (Polyphase)	Tree fall	38 houses, 12 injured, two killed	$33 million	Low or nil – fault would have been detected when it happened with too little time to act to prevent the fire

In the ensuing litigation, Black Saturday fires started by powerlines led to nearly $900 million of civil damage payouts by network owners, insurance companies and others.

12.2 EFD on all SWER could cost $40 million for $6-7 million net annual benefit

For Victoria to fully receive the fire-risk benefits of EFD technology, it must be more widely deployed on networks in high fire-risk areas of the State. Victoria has an estimated 30,000 kilometres of SWER powerlines in rural areas. Using the EFD SWER Trial benchmark of four kilometres per EFD unit, EFD coverage of all SWER networks in Victoria would require 7,500 EFD units. Assuming maximum

[21] This is in contrast to urban areas, where supply reliability risk can have higher financial value.
[22] In 2014 dollars. See Pages 37 and 38 of the 17 November 2015 ACIL Allen Regulatory Impact Statement.
[23] CSIRO: *State of the Climate 2018*, published 20th of December 2018.

possible scale economies in manufacturing, procurement and installation, such a deployment might require initial capital investment of the order of $40 million. Ongoing operational expenditure of the order of $4 million per year would be required to cover mobile broadband communication costs, secure cloud data processing infrastructure charges and the cost of support services. Unlike many other fire safety solutions, no customer supply outages would be required for installation of the EFD systems.

In the most simplistic terms, if it is conservatively assumed that full EFD SWER coverage would prevent a quarter of all major powerline fires remaining after the rollout of REFCLs and SWER ACRs, that would deliver an estimated fire-risk saving of $10 million per year to Victoria, i.e. a net saving of $6 million per year after EFD operational costs. Selective deployment to cover only networks with the highest fire consequence would increase the return on investment, though the loss of some economies of scale would increase the initial investment per kilometre required for coverage.

This macro assessment indicates EFD deployment on rural SWER powerlines warrants serious consideration.

12.3 Accurate assessment of the benefits of EFD deployment requires rich data

Victoria's electricity distribution businesses are commercial companies that require a business case as a pre-condition of any discretionary investment. EFD technology has a pattern of costs and benefits that is different to other network technologies, so a new template is required. In particular, EFD delivers multiple streams of benefits, of which fire-safety is only one. Accurate estimation of these benefits requires extensive historical data on network faults and fires. The following framework is offered as a high-level guide for those developing EFD business cases in cases where such data is available.

EFD technology offers multiple benefit streams to network businesses. The relative value of these streams varies from network to network. Rural and peri-urban networks offer very different benefit mixes to urban networks. In rural areas, fire safety benefits dominate. In urban areas, supply reliability benefits can dominate.

The benefit streams identified in the EFD SWER Trial complement those identified in earlier small-scale EFD trials in urban areas. The consolidated benefits of EFD deployment are:

1. **Fire-risk reduction:** The EFD SWER Trial has demonstrated the detection of incipient faults before they develop into faults that release energy into the environment and start fires.

   The broken conductor strand detected on the Ross Creek network would not likely have been found prior to the next few fire seasons. Mid-span conductor breaks away from roads are also very difficult for line inspectors to reliably find. A broken strand in a three-strand SWER powerline conductor places more strain on the remaining two strands, leading in time to further strand breakage and failure of the powerline in the next period of very high winds. This failure mode is likely to result in the live powerline falling into vegetation below during a period of high fire risk. If it falls it will almost certainly start a fire.

   The arcing low-voltage service line detected on the same network is a type of fault that has caused fires in the past[24]. Recent fire statistics indicate some resurgence of fires from low-

[24] Past fire incidents have led to *Regulation 220(1) of the Electricity Safety (Installations) Regulations 2009* that mandates all new customer-owned low-voltage service lines in high bushfire risk areas must now be placed underground. This applies to any 'substantial reconstruction' of old private overhead lines as well.

voltage assets. The EFD SWER Trial demonstrated that EFD technology can see 'through the transformer' to detect incipient faults in low-voltage assets, which is another strong indicator of its fire-prevention benefits.

In-tank transformer partial discharge such as that detected on the Beechworth Road, Homestead and Carween West networks is an indicator of insulation deterioration. If this deterioration is allowed to progress to internal flashover in the transformer tank, the transformer's high-voltage fuse will operate. Historically, this is associated with some risk of fire, though modern fuse types are much lower risk than earlier types.

Despite its limited powerline coverage and relatively short duration, the EFD SWER Trial demonstrated the reality of EFD technology's fire-risk benefits.

2. **Improved customer supply reliability:** Detecting faults before they occur can also prevent customer supply outages. The subsequent repair may still require an outage but customers have prior notice and the work can be scheduled for a time that minimises customer impact.

   Many SWER transformer faults and low-voltage service line faults affect only a single customer, but 'powerline-down' faults affect all customers downstream of the failure. The cost of such failures to the network owner can be high in urban and peri-urban areas where hundreds or even thousands of customers may be affected by a single failure. If the fault is detected in its incipient stage, repairs can be performed using techniques that minimise or completely eliminate the need for customer supply outages.

   Networks are investing major capital amounts in increased network switching and automated resilience schemes to reduce the duration and extent of customer supply outages when powerline faults occur. Avoiding a supply failure by detecting the cause of the fault in advance is likely to offer even greater benefits.

3. **Optimised asset management:** Electricity distribution networks comprise millions of assets of great diversity: poles, crossarms, insulators, conductors, surge diverters, fuses, transformers, cables, etc. Condition monitoring is done at routine intervals[25], most commonly by visual inspection. Sophisticated new technologies such as LIDAR[26], drone-mounted high-resolution cameras, corona cameras, thermal cameras, etc. are also used. Single-point-in-time inspection reports guide the development of pre-emptive asset replacement programs and prioritised maintenance programs.

   In the EFD SWER Trial, EFD technology revealed that just one or two per cent of assets are actively breaking down. Unlike every other technology in use, EFD technology 'sees' in-tank and in-pole (hidden) problems just as well as it does on-pole (visible) problems such as dirty insulators, broken conductors, etc. EFD's ten-metre location accuracy and three-metre discrimination provide sufficient granularity to complement or partially replace other asset monitoring methods. EFD monitors assets every second of every day continuously for years so the rate of development of problems can be accurately estimated.

[25] In high bushfire risk areas, the intervals can be mandated by regulation – e.g. 37 or 60 months.
[26] LIDAR is relatively expensive and usually reserved for vegetation clearance checks in high bushfire risk areas.

This means incipient faults are detected sometimes years in advance of the next visual inspection cycle, as in the case of the broken strand described in Section 10.1 on Page 50. EFD results are also consistent across all monitored assets, so the normal human variability between individual inspectors is no longer a risk. Maintenance and capital investment programs that incorporate EFD system results would have a material edge on traditional methods, concentrating available resources on the one or two per cent of assets that warrant close attention.

4. **Improved network operations:** The EFD SWER Trial did not directly explore this area of benefits, but the Trial results can be interpreted to indicate their nature and extent. The key drivers of such benefits would be EFD's capacity to locate very high-impedance faults (including faults on the low-voltage network) which are extremely difficult to locate through visual inspection by a patrol crew. Even if not able to immediately and precisely locate the fault, EFD can offer a reliable list of 'suspect assets' in that location for crews to check first. This class of benefits can only be speculatively estimated at this stage of EFD deployment. Getting fault crews to the fault location quickly is the goal of every operations team when customers are off supply. EFD technology has a valuable future role to play in this challenge.

5. **Vegetation management:** Maintenance of powerline-vegetation clearance is a major ongoing cost to network businesses. Powerline contact with trees is a cause of both fires and customer supply outages. EFD technology will indicate if vegetation is starting to touch powerline conductors. It can provide a safety net to alert network businesses to failures of vegetation management programs. These indications may occur in rapid-growth periods in Spring in time for remedial action to remove associated fire-risk before Summer.

   This capability was not demonstrated in the EFD SWER Trial as no vegetation encroachment was detected on the eleven monitored networks. However, it has been proven in other trials of EFD technology on urban Victorian networks. A network owner may choose to realise this benefit in terms of savings in follow-up inspections currently performed to confirm vegetation trimming has been satisfactory (in low fire risk areas) or maintain such inspections and recognise the financial benefit of fire-risk reduction (in high fire-risk areas).

Frameworks for the estimation of EFD benefit streams listed above are set out on the next few pages. The total benefits are dependent on many factors and the mix benefits will depends strongly on the characteristics of the network. Some benefits can be realised immediately (fire risk reduction) and others are realised only after business process changes.

EFD will not provide early warning of faults that occur from causes other than asset failure and vegetation encroachment. It cannot predict vehicle-pole impacts, falling 'hazard' trees, etc., though may provide immediate alerts when such things occur.

12.4 Assessment of EFD benefits can still be done when data is scarce

Good historical data on network faults and fires is a valuable resource in accurate estimation of EFD benefits. This is not always available and the framework shown in Figure 81 which relies on rich data may not be useful. Most network businesses have numbers based on long experience that can be used in a simpler framework such as that shown in Figure 82. Potential benefits to the usual business performance measures (that may not always be quantifiable) are shown in Figure 83.

Figure 81: Estimation of business benefits of EFD deployment on a network when comprehensive data is available

Business analysis of possible EFD deployment on a selected network – benefit as

Community and network owner fire-risk benefits	Customer and network owner supply reliability benefits	Network owner asset management benefits	Network owner vegetation management benefits
Major fire frequency: Route kilometres x average fires/kilometre/year on high risk days	Outages: Total customer-minutes off supply for the network	Scope: total inventory of assets on the network by type	Scope: total route length of vegetation management activity
Fire consequence: Major fire frequency x consequence of a fire in that area on a high-risk day	Reliability loss: Total customer-minutes off supply x value of outages	Asset management cost: Total cost of asset condition monitoring, maintenance and end-of-life replacement	Asset management cost: Total cost of vegetation management – inspections, regular contracts, ad hoc interventions, etc.
Potential fire savings: Fire consequence x proportion of fires due to asset failure and vegetation	Available reliability savings: Reliability loss x proportion of outages due to asset failure	Variable cost factors: variation of asset management cost by key parameters such as service life, inspection cycle, etc.	Variable cost factors: variation of total vegetation management cost by key parameters such as contractor effectiveness, growth rate estimation errors, etc.
Realisable fire savings: Potential fire savings x proportion of fires where early warning would have prevented the fire	Realisable reliability savings: Available savings x proportion of outages where early warning would have prevented the outage	Available savings: reduction in cost of asset management based on prioritisation (of up to five per cent of assets that warrant action) identified by EFD	Available savings: reduction in cost of vegetation management with real-time continuous EFD data on vegetation encroachment
Estimated EFD fire savings: Realisable fire savings x proportion of fires where EFD would provide early warning	Estimated reliability savings: Realisable savings x proportion of outages where EFD would provide early warning	Estimated savings: portion of available savings net of cost of process changes required for realisation	Estimated savings: portion of available savings net of cost of process changes required for realisation

Figure 82: Estimation of business benefits of EFD deployment when data is scarce

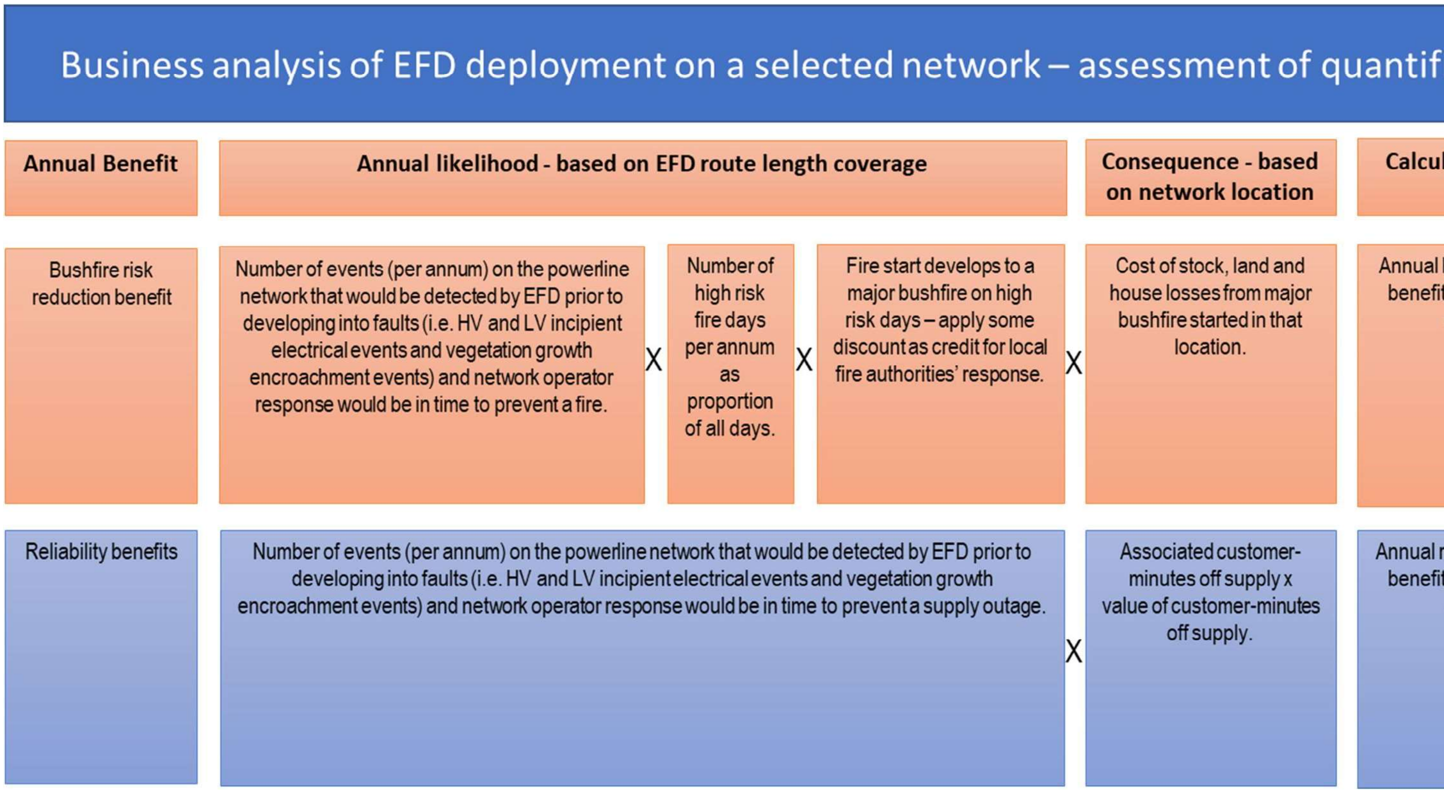


Figure 83: Assessment of EFD benefits to typical network business performance measures

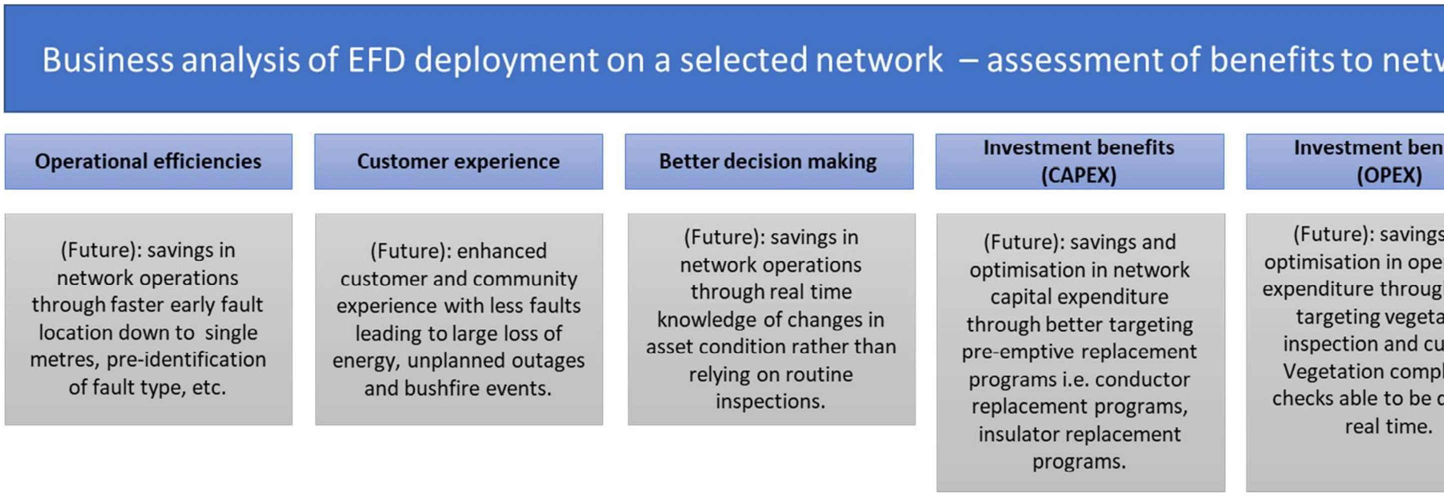
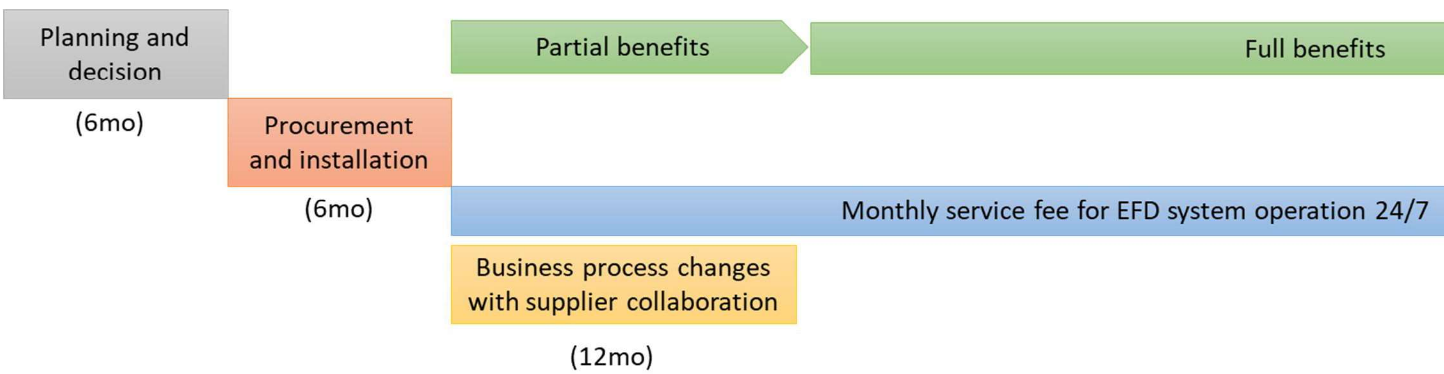


Figure 84: likely timing of costs and benefits of EFD deployment



12.5 Assessing the costs of EFD deployment

The detailed cost structure of the EFD product is commercially sensitive information but the overall high-level cost structure set out here can help those compiling business cases for potential deployments of the EFD system.

The main cost streams to be included in a business case for EFD deployment would normally include:

1. **Planning of EFD system deployment:** For a given network, planning for EFD deployment proceeds in stages:
    a. **Concept:** The approximate number of EFD units required for effective network coverage can be estimated with sufficient accuracy for budgetary purposes by laying them out on a network map at distances of about 3.5-4.5 kilometres. An allowance of five per cent additional units is made to cover requirements likely to emerge in the detailed planning stage.
    b. **Detailed plan:** This step allocates EFD units to specific poles according to two rules: inter-unit paths must not exceed five kilometres in length; and, all points on off-path spurs should be within five kilometres of two EFD units. The detailed plan accurately identifies how many EFD units are required to provide basic coverage of the network. The sites for EFD unit installation are preferred rather than absolute – the site survey stage will confirm or make changes to about five per cent of the sensor poles selected in detailed plans. The most common change is moving a sensor one span to avoid an issue, typically competition for pole real estate from other assets.
    c. **Site survey:** each preferred site is first checked using Google Street-view or aerial photography to identify any obvious obstacles to the installation of an EFD unit. Each site is then visited to confirm its suitability and identify the work required for the installation. The site survey usually confirms whether solar power supply or installation of a 230-volt junction box is required. The site survey also provides guidance on the type of communications antenna for each sensor.

2. **Procurement of EFD equipment:** the procurement cost depends on several factors:
    a. **Volume:** the manufacturing cost of the equipment is highly sensitive to the number of units being manufactured. This is in turn determined in the planning stage. The 65 units manufactured for the EFD SWER Trial allowed major cost reductions compared to previous smaller production runs.
    b. **Number of phases:** polyphase units require two or three sensor antennas, whereas SWER units require only one. Otherwise they are identical.
    c. **Sensor type:** if the coverage is to include substantial lengths of underground cable, high-frequency current transformer sensors (to be fitted on the screen-earth connections) may be required in place of the overhead wireless antenna.
    d. **Power supply:** solar power supply is more expensive and potentially troublesome, so 230-volt AC supply is preferred if available. In the EFD SWER Trial, the design of SWER substations precluded installation of EFD units on substation poles (refer Figure 11 on page 21) so all units in the Trial had solar power.
    e. **Communications:** units with whip antennas can function successfully in most rural and urban areas. In areas with strong 4G signal a low-profile (flat) antenna can be used. In areas with poor signal strength, a special directional antenna (Yagi) may be needed. In locations with zero signal, point-to-point radio-frequency links can be used to relay signals to another sensor with better signal.

f. **Packaging of data communications and processing:** EFD equipment comes with a two-year warranty period. Purchasers may choose to pre-purchase extended warranty as well as the data processing and communications services rather than pay them annually.

3. **EFD unit installation:** The cost of installation of EFD units can be a large portion of total deployment cost. In the EFD SWER Trial this cost was low because:
   a. All units were installed on unencumbered poles.
   b. There was only one type of sensor to install and it came ready to mount with its own bracket. In deployments of polyphase units, a crossarm is usually required to support the three sensors below the three separate phase conductors.
   c. All units were solar powered. While this increased the procurement cost and involved solar adequacy issues at some sites, it greatly simplified the installation process.

   These factors meant the SWER deployment could be done at rates of up to four installations per crew per day. Installations on polyphase networks generally require more effort with between two and three units installed per crew-day. The experience of the SWER Trial would imply that development of lower cost installation methods should be a priority. This will require collaboration between the EFD supplier and network businesses.

4. **EFD system operation:** the costs of data communications (the SIM in the EFD unit and the associated VPN data communications plan), data processing (the cloud infrastructure and web portal) and associated support activities (firmware updates, problem resolution, portal user administration, expert interpretation of results, incremental improvement of portal functionality) are all normally packaged into a single annual service fee for each EFD unit.

5. **Business process change:** for some classes of benefit, especially asset management and operations benefits, full benefit realisation may require changes to business processes. The cost of such changes will vary depending upon the sophistication of the existing process and the network company's history of successful business process change. This cost may extend over the first year or two of the EFD system operation. As with most emerging 'Internet of things' technology, business change to get maximum benefit from EFD technology will involve collaboration with the supplier to identify and develop those product features that will deliver the greatest safety, supply reliability and business benefit. The essence of the change will be an increase in pre-emptive maintenance or replacement of assets and a decrease of fault response activity, i.e. less forced/breakdown outages and more planned/programmed outages. New standards for assessing risk based on EFD data will be needed and better tools and techniques for finding incipient faults that offer no visible sign of their presence. The challenge of finding faults that are not visible will be frustrating for crews, asset inspectors and the control room operators in the early stages.

6. **Long term refresh of EFD components:** some components in the EFD unit have a shorter life and provision may be made for replacement. The main one is the battery included in the solar power supply which has a ten-year service life. The electronic components in the EFD unit are designed for regular firmware updates via the Internet connection. The service life of the EFD unit is at this time unknown but should be similar to that of other digital electronic components installed on the network, e.g. 15-20 years.

7. **Potential consequential costs – the strategic challenge:** Implementation of EFD technology on a network is likely to reveal latent faults in existing network assets, some of which may pose potential public safety risks, either through fire starts or public/worker exposure to high voltage electricity. There will be pressure to remedy such risks as soon as possible. Network businesses are resource-constrained and business managers will face a strategic choice between two possible scenarios: rationed implementation to keep costs within current business plan targets, or acceptance of short-term increases in resource levels to fix revealed safety problems with returns on this investment delivered through longer-term cost reductions. The economic regulatory environment under which network businesses operate is likely to be a key consideration in this choice.

The timing of the costs of EFD deployment might be represented in a business case analysis as shown in Figure 84 on Page 79. Benefits commence with EFD system operation and are continuous into the long term. Benefits from business process change commence a little later depending on the extent of the changes required.

12.6 EFD should also be assessed under the precautionary principle

The traditional engineering approach to business case analysis values risk by multiplying likelihood and impact. This approach is inherent in the frameworks presented in Figure 81 and Figure 82. In recent years, businesses are increasingly viewing safety investments using what is termed the precautionary principle. This approach has grown out of litigation experience where likelihood is irrelevant since the risk has already been realised – the loss-causing event has actually happened. It also reflects company obligations under Australia's reformed health and safety legislation. The precautionary principle was adopted by the Victorian Government Powerline Bushfire Safety Taskforce[27] and is consistent with Victoria's electrical safety legislation[28].

The net effect of adoption of the precautionary principle in decisions on safety investments is to ensure low-probability high-impact events are properly considered and that low-cost mitigation options are implemented if consequence is high, regardless of likelihood. It is relevant to EFD deployment decisions on SWER networks because these address low-probability (Code Red days), high-impact (Maximum bushfire consequence) risks.

From a precautionary view, the case for EFD deployment can be summarised as:

- **Consequence:** $22 million to $3.1 billion[29] for a worst-case fire started by failure of a SWER powerline asset.
- **Precaution:** EFD deployment at a cost of $350 per SWER network asset[30] plus annual cost of $35 per asset.

Given its status in legislation and legal precedent, this type of assessment is an appropriate complement to the usual engineering business case approach based on likelihood/impact thinking. Board Risk and Audit Committees are increasingly requesting this type of analysis for significant investments in safety.

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[27] 2011 PBST final report Section 3.6 pages 52-55.

[28] Section 98 of the *Electricity Safety Act 1998*

[29] Refer Table 7 on Page 22. This cost range is for the networks in the EFD SWER Trial. Other networks are likely to have lower and higher consequence costs than these. This cost assumes ineffective fire response.

[30] Assumes major scale economies through deployment of 7,500 EFD units to cover 30,000 route kilometres of SWER powerlines and an average of four network assets (poles) per kilometre of SWER powerline (derived from Table 6 on Page 21).

13 The EFD SWER Trial generated valuable insights and findings

The EFD SWER Trial has generated experience and evidence to support the following findings:

13.1 The EFD SWER Trial met its objectives

The two objectives set for the EFD SWER Trial were fully met:

Objective 1: Gain experience of IND.T's EFD technology operation on real SWER networks

The EFD SWER Trial covered a wider range of rural SWER networks than originally contemplated, it revealed many issues and identified the critical success factors for EFD technology to deliver rich streams of benefits to network owners, their customers and the wider community.

The two major operators of rural networks in Victoria remained strongly engaged as active contributors throughout the Trial. This included line crews, asset inspectors and faults crews as well as network planners, designers and senior engineering management.

Incipient faults were found, assets at risk were identified and the discussions between IND.T and network owners on these occasions generated valuable lessons on the realities of continuous monitoring of asset health in real networks. These lessons were used to accelerate the development of EFD technology to increase its applicability and value in rural networks.

Objective 2: Measure the potential of the technology for fire risk reduction in rural Victoria.

The EFD SWER Trial identified a small number of instances of network deterioration that posed serious potential fire-risk. Although extrapolation is always challenging and inherently involves uncertainty, these few cases indicate the potential of EFD technology to deliver material fire-risk reduction benefits across rural Victoria.

13.2 EFD systems can cut fire risk on rural SWER powerlines

In this very limited Trial (coverage of less than one per cent of Victoria's 30,000 kilometres of SWER powerlines for 18 months), two faults were found that were capable of creating serious fire risk and both were identified well before that fire risk was realised. In a third case, a substation transformer was replaced in an extreme fire risk area after the EFD system reported a serious and worsening issue at the site.

A simplistic extrapolation of this experience indicated that EFD technology may be capable over a similar period of revealing up to the order of 200-300 latent SWER network situations that could pose serious fire risk. Though there are many uncertainties to be considered in attempting such an extreme extrapolation, it remains the only estimate on the best available data and is a striking indication of the potential value of EFD technology in cutting fire risk from rural SWER powerlines.

The incipient faults identified in the EFD SWER Trial are of types that also occur on polyphase powerlines, so the benefits may be even greater if EFD is deployed over the full range of rural powerline types, including the 50,000 kilometres of rural polyphase powerlines, though the most critical of these are covered by Victoria's REFCL deployment.

13.3 EFD data can support pre-emptive asset replacement and maintenance programs

The EFD SWER Trial confirmed that EFD technology can track the location and development of deterioration across a network of powerline assets. A combination of trend analysis of multiple aspects of EFD data (waveforms, FT Chart patterns, occurrence patterns, energy level, etc.) can identify assets that warrant special attention. Of the 924 poles and 311 substations in the Trial, less than two per cent were identified as sources of regular bursts of abnormal signals. These assets could be prioritised over the other 98 per cent that showed no evidence of problems to better optimise network inspections and pre-emptive asset replacement and maintenance programs.

Among other signs of risk, the EFD system detects partial discharge (PD) within assets. Partial discharge is inherently destructive – it causes the progressive breakdown of insulation, whether in transformer windings, switches, surge arrestors, fuses, or simple insulators. However, not all PD warrants early action – the rate of breakdown may be quite slow and may not lead to a breakdown within the normal service life of the asset. Nevertheless, knowledge of which assets are affected by PD together with continuous monitoring of its progress can guide replacement and maintenance responses to avoid faults. Over time, EFD data will reveal the life cycle of specific types of assets in different operating conditions and regions to support improved asset life and more effective risk management in real time.

As further experience is gained and more case studies documented, guidelines and policies can be developed to ensure fire-risk and asset-failure outage risks are managed by focusing maintenance and pre-emptive replacement funds and effort on the one or two per cent of assets that warrant more intense scrutiny.

13.4 EFD technology has been greatly improved by the EFD SWER Trial

The EFD SWER Trial stimulated a major step forward in EFD technology. The EFD system developed for the Trial and continuously improved over its duration is a dramatic enhancement of earlier versions and can be delivered at a much lower cost. The basic concept of continuous monitoring and accurate location of network signal sources has been confirmed and the implementation has been radically upgraded.

The EFD SWER Trial marks a change of emphasis from further enhancement of data capture hardware (the sensor and EFD unit on the pole) to development of ever-more sophisticated algorithms in the EFD portal that distil the mass of raw data to produce more and more valuable information for network owners in their risk management decisions. Just as important will be the evolution of better and better visualisations in the EFD portal so network business users can quickly see the essence of EFD's assessment of the health of network assets.

14 The EFD SWER Trial leads to clear recommendations

To obtain maximum benefit for Victoria from the EFD SWER Trial, the following actions are recommended for consideration by stakeholders:

14.1 Consider EFD SWER Trial findings in the context of Victoria's powerline bushfire safety regulatory processes

Victoria's regulatory regime for powerline bushfire safety is built around the concept of annual Bushfire Mitigation Plans (BFMs) submitted by network owners to the safety regulator, Energy Safe Victoria. Prior to the EFD SWER Trial, the potential for EFD technology to cut fire risk was a matter of opinion informed by only a few trials in urban networks. Now the results of the Trial are available and the potential benefits are clear, EFD technology should be added to the list of powerline bushfire safety technologies already considered in the drafting of BFMs and their review by ESV.

14.2 Retain the EFD SWER Trial installations for a longer period of learning

During the period of the trial a number of other large scale EFD systems have been installed or are currently being installed, but the SWER Trial facility is the only one focused exclusively on SWER powerlines – a type of powerline that featured so prominently in the Black Saturday tragedy.

The 61 EFD units on SWER powerlines and the associated secure cloud infrastructure and web portal are still operational and continue to generate data and valuable insights. Funding to allow this to continue is not secure. It is recommended that the two HNOs work with IND.T to identify options to continue to learn from the facility created for the EFD SWER Trial. As a minimum, ongoing monitoring of the identified intermittent hot-spot sites is desirable to see how the activity develops. It is also possible that further incipient faults may suddenly occur.

To continue operation of the EFD SWER Trial facility, some upgrades may be required, especially to solar power supplies. Also, the original plan to install an EFD unit on a SWER kiosk substation in the Porcupine network could be pursued to completion.

14.3 Develop new procedures skills and tools to investigate signal sources

The EFD SWER Trial revealed that current fault investigation and response processes and tools used in rural networks struggle to meet the challenge of pre-fault information. For example, the EFD system revealed a number of intense signal sources that could not be pin-pointed by traditional site inspections. There are two challenges here:

1. The signal tends to occur in intermittent bursts and is rarely active when a crew visits to investigate. This implies some form of local monitor is required that can be simply placed at a site for a few weeks if necessary, to work out what is happening; and
2. The primary benefit of EFD is to locate the signal source within ten metres. However, the signal is often from a source that offers no visible sign, even to close scrutiny. It may be inside equipment or inside the pole. It may even be on the low-voltage wiring to the premises or inside the premises. Crews are accustomed to attend fault sites where the damage from the fault is obvious – strewn pieces of assets, assets on the ground, burn marks, animal remains, etc. EFD technology finds faults before they happen, so none of this evidence is available to the inspection crew. Only in the two incidents at Ross Creek was the evidence visible – a broken conductor strand, a low-voltage service destroyed by arcing between adjacent wires. Network owners face a similar challenge with faults found by EFD technology as they face with faults that trigger REFCL action – there is often no visible evidence at the fault site.

It is recommended that new tools and techniques be developed to enhance the ability of crew to find a signal source identified by the EFD system when they visit a site.

The second aspect to this recommendation is to combine EFD data with metering and network real-time SCADA[31] data to help in the identification of a detected issue. This was done to a very basic level in the EFD SWER Trial when Thieke 3 metering data was used to test for correlation of the EFD signal with network voltage and customer load. It is likely there is considerable benefit to be had in use of metering and EFD data to create a holistic picture of a detected issue in order to better identify the root cause.

14.4 Consider EFD systems to support REFCL operation

On the limited evidence available to date, the deployment of REFCLs on the 45 highest-risk networks in rural Victoria has been successful in cutting fire risk. However, it is already apparent that the challenge of locating low-energy faults which leave no visible evidence (but trigger REFCL operation) is very real. The EFD SWER Trial has demonstrated the ability of EFD technology to locate a fault at least to the pole supporting the faulty asset.

This more-granular location capacity would be a great improvement on current REFCL arrangements where a low-energy fault during high fire-risk periods on a REFCL-protected network can only be located to a particular feeder. Unless it is visible, after a lot of network switching it may be located to a particular feeder section. This can mean that hundreds of customers may be denied power for hours in extreme heat because the consequence of restoring power would be to start a fire. If the fault is located to an individual pole then actions are available to resolve the situation and restore power more quickly.

14.5 Review standard substation designs to reduce deployment cost

In the SWER Trial, EFD units were located sub-optimally to avoid the time and cost of changing the standard design of SWER termination substations to accommodate the EFD sensor. A new design which allows an EFD unit to share a pole with a substation transformer and high-voltage fuse/switch would increase network coverage and cut the cost of EFD deployment. It would also greatly reduce or completely remove the dependence of EFD system performance on solar conditions. Time was not available during the EFD SWER Trial to modify the standard design for SWER termination substations and it is recommended this be done for any future deployment of EFD technology on SWER networks.

[31] Supervisory, Control and Data Acquisition data – the data that drives control room screens.