Automatic Location of faults through Remote Monitoring (ALARM)

NIA Closedown Report

September 2021 – May 2022

Electricity Distribution

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Contents

1. Executive Summary

Automatic Location of faults through Remote Monitoring (ALARM) was an NIA project that commenced in September 2019 and ran through to May 2022. It was undertaken in partnership with Lucy Electric GridKey (and included Sentec Ltd). The principle of the project was to test the potential for monitoring devices on the Low Voltage (LV) network to inform us as to the location of developing localised faults – known as Distance to Fault (DtF). The benefits of this project and the technology were perceived as primarily twofold:

1. Technical capability if proven would enable local teams to be proactive in fault identification and thereby reducing Customer Interruptions (CI's) and Customer Minutes Lost (CML)
2. Reduction in costs of digging and repairing faults through better location and the time to fix

The Lucy Electric GridKey system uses an impedance ratio type method of fault location however it has the novel feature that it does not need the cable sizes/impedances to be programmed into the system that was attractive as – this dramatically simplifies the installation process. The ALARM project was aimed at proving this system capability – a hardware and communications implementation which provided adequate waveforms needed for the DtF algorithm and the ability of the algorithm to determine a fault location. Every time a pecking event happened a DtF location was identified and this was added to previous locations identified on the same feeder/phase resulting in a likely location and an uncertainty figure which could be provided to the field teams.

The project was carried out over two distinct phases

- a proof of concept phase that enabled the team to carry out an initial assessment of the DtF algorithm using a simple hardware modification (addition of a small passive daughter board to the GridKey MCU)
- the second phase added a more capable "active" daughter board in the MCU that increased the waveform sampling rate and included changes to the DtF algorithm learnt from the first phase.

During both Phases the support of the local teams was used to test whether the devices could help locate faults accurately and then during phase 2 there was a short verification phase with another device with differing technology to see if the results were similar.

This was a new approach for us and was generally proven to be successful and provided some good learning opportunities not just in the technology but also in how we approach these sorts of technology capabilities in business as usual. More detail on this and the specific learning can be found within Section 9.

The trials were largely successful with enough evidence gathered to suggest more follow up work would be advantageous within business as usual. Some of the notifications received had an accuracy level that was within metres of the fault location and as such this would suggest that the product and its capability have proven the success criteria and objectives of the project as being met. One of the key learnings though that did emerge is that when trialling these sorts of device it can be easier to have specific named resources within the operational teams to support delivery and work on the trials as often you can be working around current operational priorities.

The system (and other systems from other suppliers using a similar principle) works by generating a location based on a historic set of pre-fault pecking faults – the more history the better the location accuracy. Waiting until there have already been fuse operations means missing a lot of the historic data. As low voltage monitoring is installed across the WPD network this project recommends that consideration be given to equipping the monitors with DtF capability thus allowing that historic data to be collected. This would also allow classification of likely faults so that preventative measures can be taken before even the first fuse operation.

The project was delivered to time, cost and quality despite some of the legacy effects of the recent global pandemic, which did provide some challenges and in particular during the verification phase. Despite this though the principles of the objectives were still met and the devices are now going to be compared with other devices on the market to determine how the business benefits can be achieved.

2. Project Background

It is widely understood that underground LV networks regularly experience pecking faults – short duration arc faults typically caused by water ingress at partially damaged cable sections or connection/transition points in the network. Different ages and types of cables can be prone to this effect. Such events rarely immediately cause Customer Interruptions (CIs) or permanent faults, but each pecking event progressively damages the cable system and protection fuses. Over time the arcs persist for longer, potentially causing noticeable voltage disturbances on the network. This can progress to the development of fuse-operating transitory faults (with customers off for the time required to change fuses), or directly to a permanent fault with longer customer outages occurring for reactive fault location and repair to occur.

Historic Fault data shows that there have been c. 331 LV feeders with four or more fuse incidents in total in the East Midlands region of WPD. These 331 feeders have suffered a range of number of incidents: 141 feeders have had four incidents in total (threshold for inclusion), 45 LV feeders have had six incidents, and one feeder has had 21 reported incidents over four years (18 in 2017-18).

In total, 1850 fuse incidents have occurred on these 331 LV feeders, of which 526 occurred after there had already been four incidents.

However it is also recognised that there are considerably more circuits that have breakdown issues which are yet to operate the fuse or that have had one, two or three fuse incidents.

2.1 Approach

The Automatic Location of Arc-faults through Remote Monitoring (ALARM) project sought to demonstrate a technical alternative and lower cost approach to identifying the location of transient faults, before they developed in severity to a persistent fault that required immediate repair.

The project installed 26 LV substation monitors within the East Midlands region of WPD. Each monitor consisted of three Rogowski Coil based phase-current sensors per LV feeder (for up to five LV feeders) together with voltage taps, connected to a GridKey Metrology and Communications Unit (MCU) which processed the sensor data and generated and logged substation loading and condition parameters. Rogowski coil sensors were used (rather than Current Transformers) as they were very easy to retrofit to a wide range of existing LV boards and the technology allows an almost unlimited range of current measurements – the size of the transient faults can exceed 20kA in certain cases.

Each monitor captured and retained voltage and current waveforms from the monitored LV feeders when pre-set triggers were activated (e.g. rate of change of voltage or phase current). Three cycles were acquired – the one before the event, the cycle where the event actually happened and the cycle afterwards. These captured waveforms were forwarded via a GPRS/mobile data connection to a processing data centre where inductance values for the faulting network were estimated which was then used to establish a distance to fault estimate.

The monitoring devices were connected at distribution substations as outlined in Figure 1.

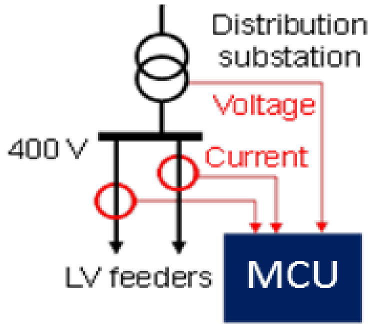


Figure 1 Schematic for the connection of LV monitors for distance to fault assessment

The project conducted this over two phases with the first phase being a proof of concept test ahead of a more rigorous second phase also with third party verification units being used to additionally prove the findings. Whilst this verification phase was hampered to quite an extent due to the recent pandemic, this worked well in terms of learning as a number of “bugs” were able to be ironed out ahead of the more complex second phase.

3. Scope and Objectives

The project had a set of predetermined objectives and has fulfilled them all as follows, the detail behind them is within Section 6:

Table 3-1: Status of project objectives

Objective	Status
Identification of pecking faults within monitoring data, reliably distinguishing them from other network transients and disturbances	✓
Capture of sufficient pecking fault data to estimate confidence in distance to fault indications for transient arc-faults;	✓
Quality of captured auxiliary data (e.g. upstream and downstream network impedance indications) is sufficient to support reliable distance to fault calculations	✓
Quantitative understanding of the frequency and magnitude of transient arc-faults on monitored LV feeders	✓
Automatic generation and notification of distance to fault indications; and	✓
Distance to fault indications are successfully used by local teams to guide repair of faults ahead of permanent faults developing.	✓

4. Success Criteria

The ALARM project sought to deliver against a set of success criteria as detailed below:

Table 4-1: Status of project objectives

Objective	Status
Identification of pecking faults within monitoring data, reliably distinguishing them from other network transients and disturbances	✓
Capture of sufficient pecking fault data to estimate confidence in distance to fault indications for transient arc-faults;	✓
Quality of captured auxiliary data (e.g. upstream and downstream network impedance indications) is sufficient to support reliable distance to fault calculations	✓
Quantitative understanding of the frequency and magnitude of transient arc-faults on monitored LV feeders	✓
Automatic generation and notification of distance to fault indications; and	✓
Distance to fault indications are successfully used by local teams to guide repair of faults ahead of permanent faults developing.	✓

5. Details of the Work Carried Out

The project was planned over two phases, these were intended to ensure that the second trial was as successful as possible by using the first phase to iron out any issues with the technology given that it relatively developmental. This proved to be a successful approach. More on the details of the plan are included later in this section.

The high level plan is shown in Fig 5-1 below:

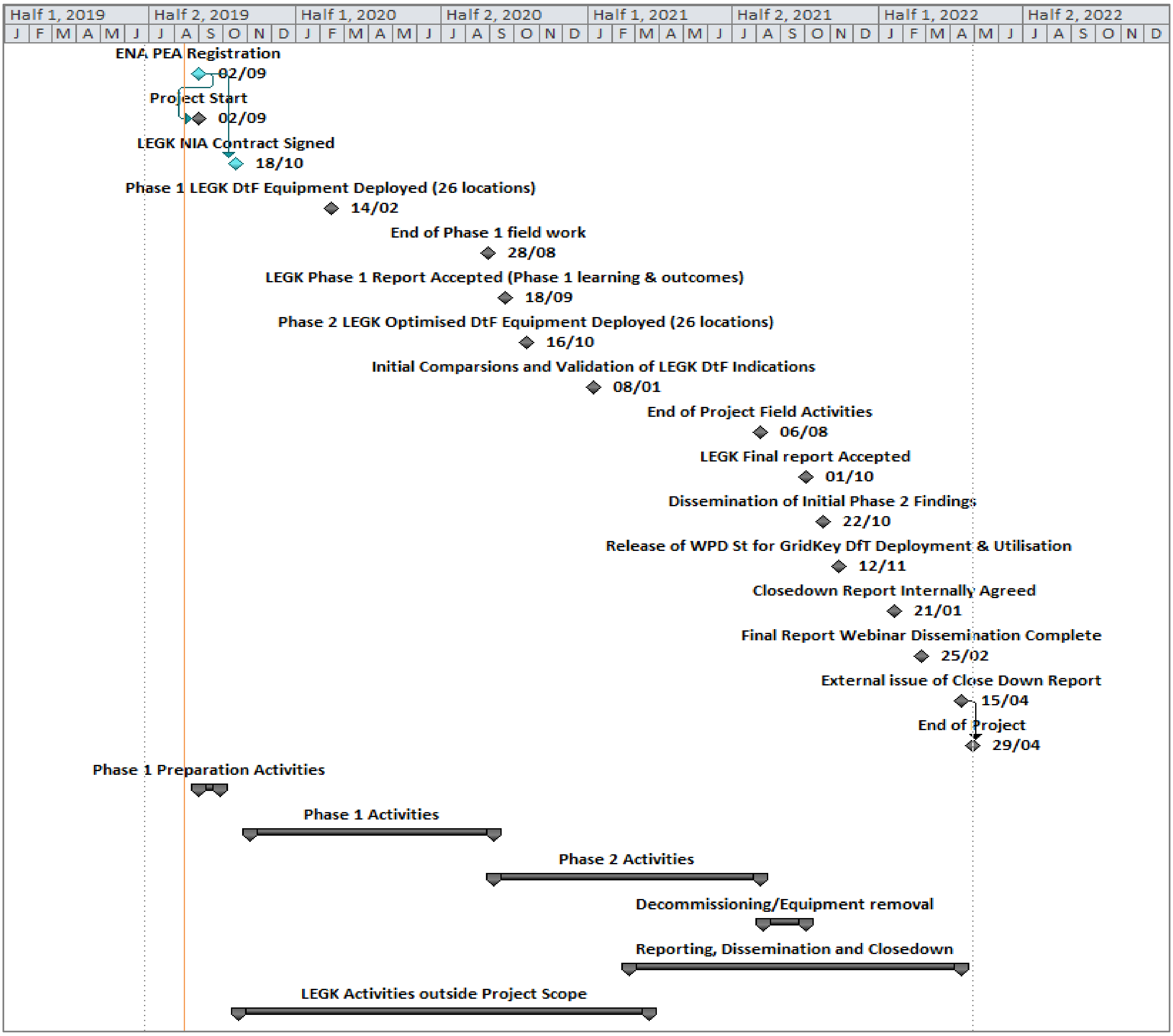


Fig 5-1: High Level project plan

5.1 Phase 1

Phase One was undertaken during the period of September 2019 through to September 2020. During this phase the principles deliverables were:

1. Site Selection and Asset Installation
2. Data Collection
3. Project Learning Report
4. Update to devices and software
5. Planning Phase 2

The site selection work was undertaken in conjunction with Lucy Electric GridKey and the local teams in the East Midlands- specifically Milton Keynes, Leicester and Coventry. This took some time and planning but we successfully rolled out devices to 26 key sites all of which had had a history of faults on one or more feeders.

The standard GridKey MCU318 monitors were fitted with a small passive daughter board which acted as an attenuator allowing the magnitude of high fault currents to be measured. Installation of the monitors was undertaken by local WPD Network Service personnel. This was carried out according to WPD's Standard Technique SP2KD/2, and all other normal working practices. The monitors were installed in a range of LV board arrangements.

Commissioning of the monitors principally consisted of ensuring that correct alignment of phase current measurements with phase voltage measurements (from installation), confirming remote data connection, and applying appropriate substation and feeder names, plus a geographic reference for the site. This was initially checked using a Windows based configuration tool although an iOS version was also used for the later installations which allowed the WPD engineers to use it on their corporate iPads. The type of current sensor used (i.e. SlimSense or FlexiSense) was automatically detected by the MCU. The absence of the need to "calibrate" the MCUs with the cable impedances meant that the installation was very straightforward and quick.

Remote collection of routine data measurement was confirmed by checking receipt of data by the GridKey Data Centre. Throughout Phase 1 a few "bugs" were able to be resolved with the hardware/software without any real impact on the quality of the outcomes.

The Phase One deployed equipment successfully captured pre-fault "pecking" events on most of the 26 deployed monitors, consistent with capability expectations of the Phase One installed equipment. In total 7,990 pecking events (including phase to neutral and phase to phase events) were analysed. The first stage of the analysis is to compare the captured waveforms with a mathematical model to check that the waveform is for a pecking fault (as opposed to a motor start-up or arc welder for example). Applying this first stage of analysis 2,647 events were found to be good quality fits with the mathematical model.

Further analysis of these waveforms showed that 77% of these 2,647 events occurred on just 13 of the monitored feeders, each of these feeders all had 20 or more pecking events. This was a consistent theme throughout and during Phase 2 we took advantage of this and moved quieter devices to other sites where we were told there was more activity.

Phase One achieved its fundamental aims of proving the data collection and analysis concept, and informing the development of assessment processes that would be more fully tested in Phase Two of the project, when enhanced hardware became available.

One general learning point was when fitting Rogowski current sensors around the fuse handle. In one installation the fuse itself was very hot and melted through the insulation of the sensor – this was corrected using thermal sleeves to protect the sensors when fitting them this way.

The waveforms that complied with the mathematical network modem were then fed in to the GridKey Distance to Fault algorithm, so that each waveform generated a distance from the substation to the fault. These results were recorded and used to generate a separate histogram for each of the feeders. As the number of waveforms analysed increased it was possible to generate both a likely position and an uncertainty (error) number – this created a simple graph that was available on the GridKey Data Centre.

One issue that was encountered was the correct identification of the feeder which had got the pecking fault on it. The system monitored each of the feeders and whilst there was a large current spike on the affected feeder we also noted smaller “pecking events” (i.e. current spikes) on some of the other feeders. A considerable amount of effort was expended by the team to understand this issue and improve the algorithm. We had expected that all the energy to be fed into the fault would come from the transformer however upon some experimentation we discovered that only some of the energy came from the transformer – the rest was coming from the other feeder cables that were in effect acting as capacitors. When these “capacitors” discharged to provide energy into the fault, the GridKey system saw these as current spikes.

The detailed learning reports from Phase 1 can be found here:

Phase One Report

https://www.westernpower.co.uk/downloads-view-reciteme/595954

Results and Learning:

https://www.westernpower.co.uk/downloads-view-reciteme/595951

5.2 Phase 2 and Verification

Phase 2 commenced in late 2020 and continued throughout 2021. The verification phase was due to finish at the end of Q3 but we extended it to the end of the year due to the pandemic. This has meant that the closedown activities have continued over into 2022 but this has not impacted on the deliverables or budget.

Phase 2 consisted of:

- The addition of a more capable daughter board in the GridKey MCU which allowed higher resolution current and voltage waveforms to be captured and transmitted back to the data centre as we expected this to result in more accurate location calculations. The board also allowed multiple waveforms to be stored locally on the device so if there was a series of events in a short period of time, it could save waveforms whilst others were being transmitted
- Continued monitoring of the devices
- Project Learning Report
- Verification
- End of Field Activities
- Closedown

As we had already undertaken an extensive Phase 1, this phase was just a continuation of the work being done but with the benefit of the improvements made to the devices as we went through the Phase 1 lifecycle. We continued to monitor the sites as we did in Phase 1 but during Q3 2021 we were able to remove some devices in Milton Keynes and move them to Coventry where we had other operational issues and these produced further valuable results.

Working closely with the operational teams themselves enabled us to quickly undertake some removals in the morning and then go to Coventry to install the devices in the afternoon. This was an important key learning of the second phase and one that we think can be taken forward for any future projects. The operational teams used tended to have not only the experience of course but also an understanding of how best to locate them to get the maximum benefit and this is how we managed to get the verification device installed at White Street Flyover as well.

Although we had expected the accuracy of the locations to be improved by have the ability to capture the waveforms at higher resolution, analysis of the results showed that it actually made very little difference – we verified this by continuing to run a Phase 1 system on the same substation as a Phase 2 system and then comparing the results. For this system it was clear that the extra acquisition cost of the system and also the increased data requirements to send these higher resolution waveforms was not required to provide an accurate fault location.

The Verification Phase utilised the Kehui T-P23 device and whilst the impact of the pandemic hampered our ability to roll out the devices we were able to site them at Paddock Way, Fairefield Crescent and White Street. More information on the results can be found in Section 10.1

The Phase 2 detailed learning report can be found here:

https://www.westernpower.co.uk/downloads-view-reciteme/595948

The trials finalised at the end of 2021 and the devices will remain in situ for now and certainly whilst we undertake the broader assessment project of these devices.

We continue to keep an eye on developments in this technology, whilst the pandemic did impact on our ability to do a fully-fledged verification, there was enough evidence from the trials to suggest that they do add value to the business.

6. Performance Compared to Original Aims, Objectives and Success Criteria

The objectives and measures of success for ALARM were identical and so for ease the table below summarises the achievements against the aim:

Objective/Success Criteria	Commentary
Identification of pecking faults within monitoring data, reliably distinguishing them from other network transients and disturbances	Achieved - we were able to identify pecking faults in a way that distinguished them from other non-defect related anomalies and moreover as detailed below were able to then rectify them in both a business as usual context as well as team attendance on site visits to progress activities.
Capture of sufficient pecking fault data to estimate confidence in distance to fault indications for transient arc-faults;	Achieved-the team were able to generate a variety of representations of the data to highlight the location of the fault.
Quality of captured auxiliary data (e.g. upstream and downstream network impedance indications) is sufficient to support reliable distance to fault calculations	Achieved- Phase 1 and 2 monitoring calculated upstream and downstream impedance estimates that are comparable to transformer nameplate data and cable data.
Quantitative understanding of the frequency and magnitude of transient arc-faults on monitored LV feeders	Achieved- Data was collated on the number of events that occurred on an individual monitor/feeder/phase and is available for all monitors. The magnitude of individual events can be seen from the waveforms captured for each event as shown through this report and both Phase learning reports.
Automatic generation and notification of distance to fault indications;	**Achieved- Within the Phase 1 monitoring period, automated scripts were run to screen and assess captured events. These scripts estimated a distance to fault for an individual event, plus process metrics associated with an individual event. Histograms of numbers of events versus DTF are also automatically generated. Learning from Phase 1 monitoring was used to refine this assessment process. Further work was undertaken throughout Phase 2 to automatically generate and appropriately display DTF indications, and provide associated automated notification (e.g. current DTF indications on a regular basis, and upon specific events such as a fuse operation). Further work is required to integrate this capability into business as**

	usual but this was outside the scope of this NIA project.
Distance to fault indications are successfully used by local teams to guide repair of faults ahead of permanent faults developing.	Achieved- The devices and subsequent verification phase did allow us to identify and locate faults on the network and carry out subsequent repairs.

7. Required Modifications to the Planned Approach during the Course of the Project

No variations were required to the planned approach other than a short extension to the verification phase due to some difficulties with scheduling work with the local teams. There was plenty of time contingency within the plan and so therefore, this had no consequential impact on delivery (time, cost and quality).

8. Project Costs

Costs for the project were broadly in line for both Project Management and Contractor costs. For Labour and Equipment a more efficient use of resourcing at the outset led to an underspend.

Table 8-1: Project Spend

Activity	Budget	Actual	Variance (£)	Variance (%)
WPD Project Management and Dissemination	161,314	152,863	-8,451	-5.2
Contractor Costs	139,100	139,100	0	0
Labour and Equipment	177,796	78,162	-99,634	-55
Totals	478,210	370,125	-108,085	-22.6

9. Lessons Learnt for Future Projects

The project successfully and accurately located a number of underground cable network faults and provided learnings about the real world performance of the DTF system on a live network with all of its quirks and features, and insight into how best to integrate information about potential issues on the network into the workflow of managers and field teams. The learnings below are summarised by category.

9.1 Event classifications and patterns

The 26 substations chosen for this trial all had a history of fuse operations so we expected there to be pecking events detected on all of them. The system could monitor up to 5 feeders simultaneously. The learning from the project was two-fold

- The pattern of pecking faults over time varied considerably – some sites would produce a continuous stream of events and others would produce a sudden burst of events and then no further events would be detected for a considerable period of time – often several months.
- Some of the feeders monitored had no history of a fuse operation but regular pecking events were detected on them – this indicates that a fault is developing and it is likely over time to deteriorate further and eventually cause a fuse operation – this capability provides a mechanism to identify these feeders so that preventative action can be taken

9.2 Classification of transient events

The events recorded comprised (in approximate order of most to least common):

- Pecking events Phase to Neutral
- Pecking events Phase to Phase
- High inductive load start transients (e.g. motors)
- Fuse operation transients
- Fuse replacement transients

One of the key aims of the project was to automatically classify these transients to ensure only the pecking events were considered in the algorithm – e.g. load start transients were not misclassified as pecking events. The GridKey solution successfully isolated pecking events from other types of transients based on the specific characteristics of the transients and the majority of pecking events fitted the expected model and could be analysed.

9.2.1 Patterns of transient events

A number of distinct patterns of behaviour were observed across different installation sites:

- Regular pecking as single events, spaced by hours to days or even weeks
- Bursts of pecking events with e.g. 10 strikes in the space of a short period (seconds) with long gaps (days/weeks/months) between

As expected there were also large variations between sites in both peak currents and overall duration of arcing leading to large variability in likely cable damage (and ozone gas generation – hence why using a “sniffer” or IR camera is not always successful in locating the fault).

Despite the sites having been selected as having a history of faults, some substations had no pecking events at all however at other substations there were hundreds pecking events per month.

Whilst there were occasions where there were fuse operations without any or only a few previous pecking events the trial proved that in the majority of instances, pecking events did occur, and with sufficient frequency to build up statistics to locate the event on the network with a known prediction uncertainty in a reasonable timeframe. Where events happened more frequently, this allowed the location uncertainty to be reduced more quickly.

The trial showed a wide range of variability in correlation with prior pecking events, but where there were significant prior pecking events, there was a strong chance that the permanent fault developed at the location of the prior pecking events, as the pecking events were eliminated after the fault was repaired. However, there wasn't a strong indication of the timing of an impending fuse operation from the immediately preceding frequency of pecking events although physics would dictate that the more energy in the faults would tire the fuse more quickly and make it more susceptible to operating.

A learning was that some measure of the cumulative damage impact on the cable would be valuable in prioritising intervention or further investigation. This would be based on the frequency, current and duration per event, so distinguishing between the damage caused by lower current events at the far end of long feeders and high current events close to the transformer, and between short duration arcs and sustained multi-cycle arcing.

9.3 Equipment performance

The GridKey equipment performed well in the field where the existing hardware was supplemented with an additional circuit board to allow the magnitude of the current spikes to be accurately measured. Two variants were trialled, differing primarily in their analogue resolution, and in their ability to manage multiple successive transients.

It was found that the higher resolution captures did not materially improve location statistics, whilst reducing the time between captures did allow fewer transients to be missed during bursts of transients and hence quicker location statistics to be gathered but again this did not improve the overall location statistics.

9.4 Analysis of transient events to determine cause and location

9.4.1 Analysis and modelling learnings

Prior to this trial, it was expected that phase-phase arc transients would be common because the electric field levels are highest between adjacent phase conductors, but the trial showed that phase-neutral were far more common. The Northern PowerGrid Foresight NIA project report suggested that typically faults often started as phase to neutral but developed into larger phase to phase faults just before the fuse operated. This was not really observed in this project – an example was the fuse operation at Nottingham Road on 2nd March 2021 which was preceded with around 20 seconds of phase-neutral fault before the fuse operation. We have also seen phase-phase events leading to a fuse operation however (at least during the period we were monitoring them) there had been no phase-neutral faults detected.

Also when there was a large pecking fault on one feeder/phase, we observed large current transients on different feeders but the same phase as the feeder with the pecking event. These had not been expected prior to the trial of the equipment and we initially suspected instrumentation issues such as cross-talk within the electronic components. However, after carrying out some additional testing at one of the substations we observed that these other transient events were genuinely coming from the cables (not due to an internal electronics or software issue within the GridKey units). When this was understood, the team reviewed the mathematical network model and this explained that the other feeders were acting as capacitors which discharged to provide energy into the fault event. As a result these "parasitic" transients were eliminated from subsequent location analysis, eliminating some early misidentification of feeders with events. In fact, the presence of these transients further validated that the network model used by GridKey was correct.

9.4.2 Location statistics

The statistics (repeatability) of location for an individual pecking source varied significantly from one installation site to another. Some sites created relatively tight distributions, others relatively broad distributions. For those locations with broad distributions, a larger number of transients needed to be collected to achieve a reasonable degree of confidence in the actual location. A number of root causes of this variability were considered and eliminated:

- Equipment cross-talk
- Equipment resolution
- Level of load on the affected feeder
- Time of day
- Quality of fit for individual events

Whilst we were unable to determine a root cause there are some potential hypotheses for why this occurred including the variability of the return path through ground of phase-to-neutral events leading to variability in the return path impedance and the distribution of loads on the affected feeder. Further work would be required to better understand both the cause and also whether there was any practical solution to reducing the variability.

9.4.3 Network Maps

The DtF algorithm created a distance from the substation measured in metres. We then used the WPD on-line data portal that allowed the network map to be displayed and we would then manually use the distance from the substation to locate a location on the map.

During the experience of using this on the project, a series of small errors were observed – these would typically be <5m (although slightly larger errors were sometimes seen) and could be caused by slightly varying routes compared to the maps including different bend radius on the cables etc. This resulted that sometimes, despite identifying the distance errors could be seen in the actual location of the fault found.

In addition we also found other errors in the network map – an example was when trying to locate a property at the end of the feeder on a specific phase – in this case we used a phase identification tool to correctly locate the specific phase end point we were trying to find.

9.4.4 Dealing with multiple events at a location

In some instances where there appeared to be a broad distribution, we found that a single feeder could have more than one fault on it at different locations. These faults were initially displayed just as a single fault but due to the multiple locations this gave a large position of uncertainty. As a result GridKey introduced a clustering algorithm to separate out events associated with different locations on the same feeder, and to analyse the statistics of these separately to give multiple sets of location information.

An example of this is shown in the figure below from Gulson Road in Coventry where there were actually faults on all three phases and two faults on the black phase.

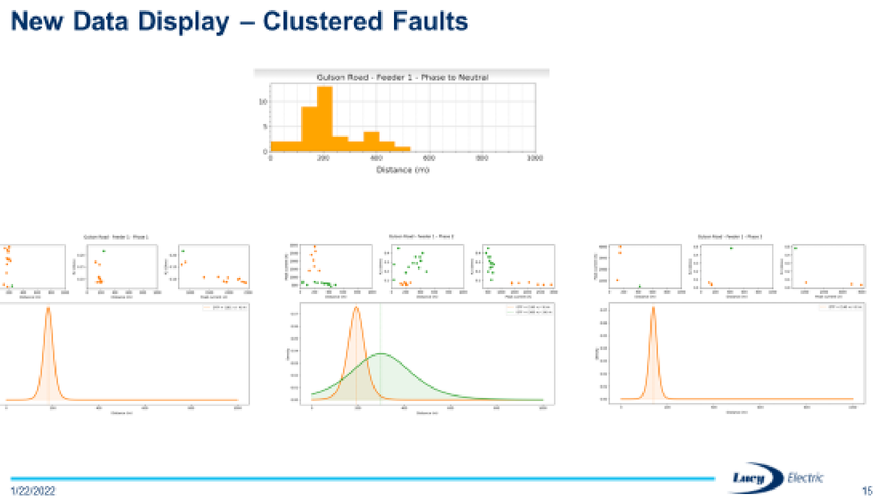


Fig 9-1: Example Multi fault location analysis

9.5 Validating the location information

A key part of this project was the validation of the locations identified using the GridKey system – this was done using different technologies or as a result of an actual repair. Below are some of the real case studies that occurred during the project.

9.5.1 Fault repair in the cases of permanent faults

There were five instances where fuse operations followed a number of pecking events on a feeder and multiple instances of the pecking events with a subsequent cable repair. Learning from the project was that the waveform that was captured when the fuse actually operates is complex and does not match the pre-cursor events so GridKey eliminated all of these fuse operation waveforms. Having done this the agreement between the predicted and actual fault location was generally good.

9.5.2 Gulson Road, Feeder 1

A fuse operation occurred on Sat. 18th April, 2020 and the fault was classed as a permanent fault as the replacement fuses blew immediately. Repair work was carried out the same day to repair the fault.

When this fault happened, the project was still in its early stages and only a limited number of waveforms preceding the fault were collected, as shown in the following histogram:

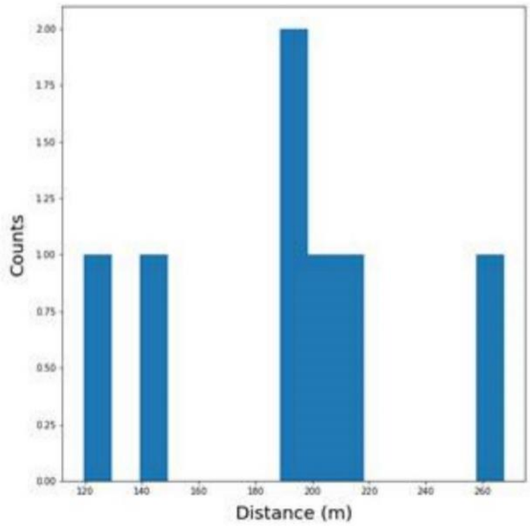


Figure 9-2: Histogram for Gulson Road

A distance assessment was undertaken after the fault was repaired using available data from before the 18/04. The analysis suggested the most frequent pecking fault analysis distance of 190-210m, and that three additional events were also captured at 120 m, 140 m, and 260 m. The waveforms corresponding to the 120-m distance, yielded a very good fit, with low residuals. That distance was also offered to the repair team as a possible location.

The repair team confirmed that the repair took place at a location of that was 200m from the substation. This agreed with the most frequently observed location as shown in the histogram fig 9-2 above.

9.5.3 Rosemary Hill, Feeder 3

A fault occurred on 22/03/2020 on Feeder 3 at Rosemary hill substation. The ALARM system recorded a limited number of waveforms with peak currents in excess of 8 kA which were all captured prior to the fuse operation.

Notwithstanding the small data set (3 waveforms), the small spread in the data allowed us to estimate a fault distance of just 13 m from the substation with an uncertainty of ±2 m.

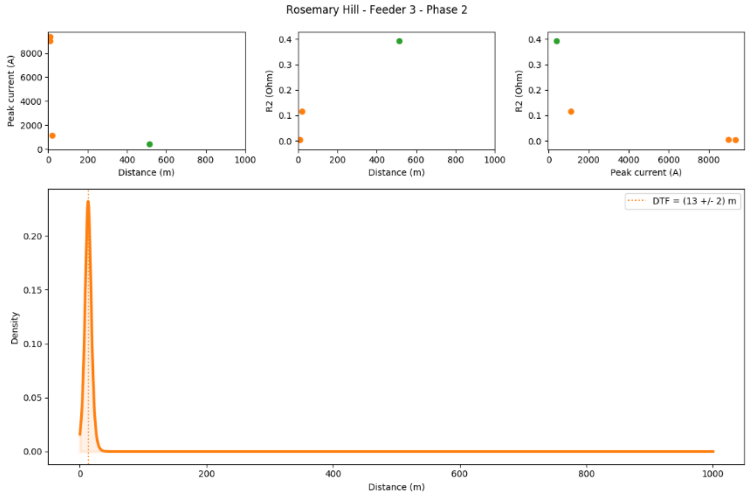


Figure 9-3: Histogram for Rosemary Hill

Feedback from the repair team indicated that a location of c.13m from the substation.

9.5.4 Ravenstone Road, Leicester, Feeder 2

A fuse operation occurred on Mon. 13th Jul, 2020 and the fault was classified as permanent as the new fuses tripped immediately after replacement. Most events recorded before the fault were phase-to-phase (L2-L3). The analysis of the data available to that date indicated a most-likely distance-to-fault of 280 m ± 20 m as can be seen in the figure below.

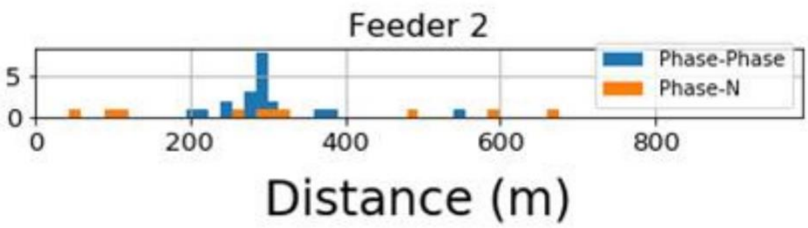


Figure 9-3: Histogram for Ravenstone Road

Applying this to the branched structure of Ravenstone Road, as shown in Figure 9_4 below, Feeder 2 (Western Ave), and a distance from the substation of 280 m suggests that the fault is at the end of one of the branches running down Western Avenue (red and green arrows in the figure below, (red arrow=264m, green arrow=271m).

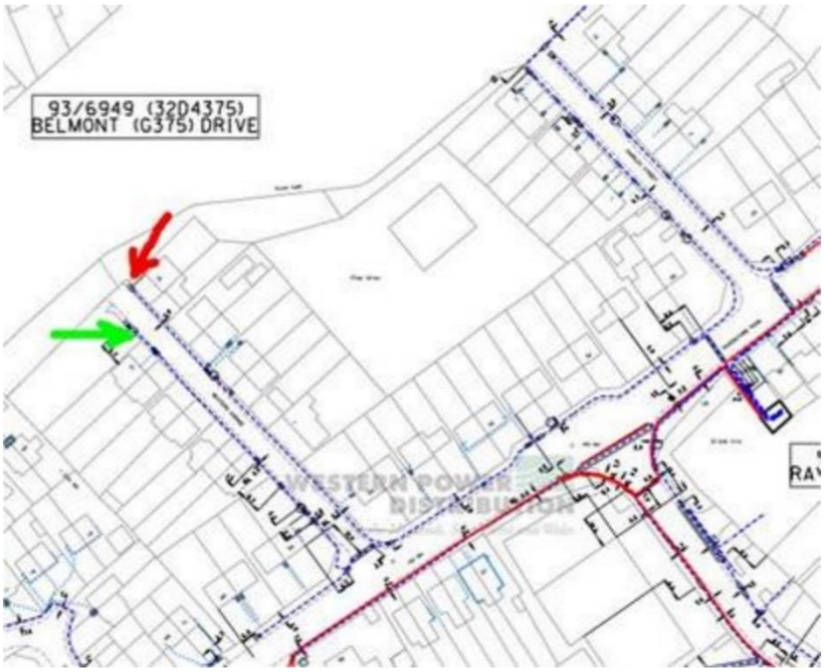


Figure 9-4: Location of Ravenstone Road

Feedback from the repair team indicated that a location of c.280m from the substation.

9.5.5 Nottingham Road, Feeder 2

A fuse operation occurred on 22/11/2020 and the replacement fuses tripped immediately. This was an example of a site where there was a long period with little or no fault activity and then a burst of events as can be seen below. Many of the events captured by the GridKey system relative to feeder 2 happened between the 21st and 22nd of November, highlighted by a dashed rectangle in the figure 9-5 below.

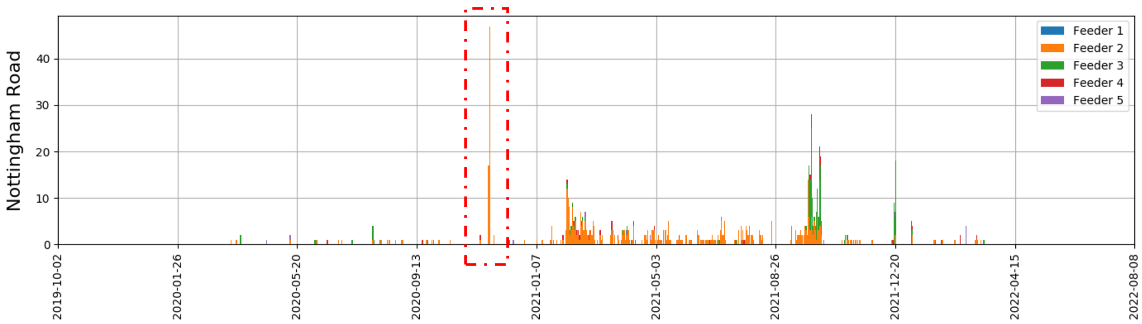


Fig: 9-5 Histogram for Nottingham Road

The analysis of those events yielded an estimated distance of 70 m ± 2 m. The fault was located and repaired at approximately 80 m from the substation.

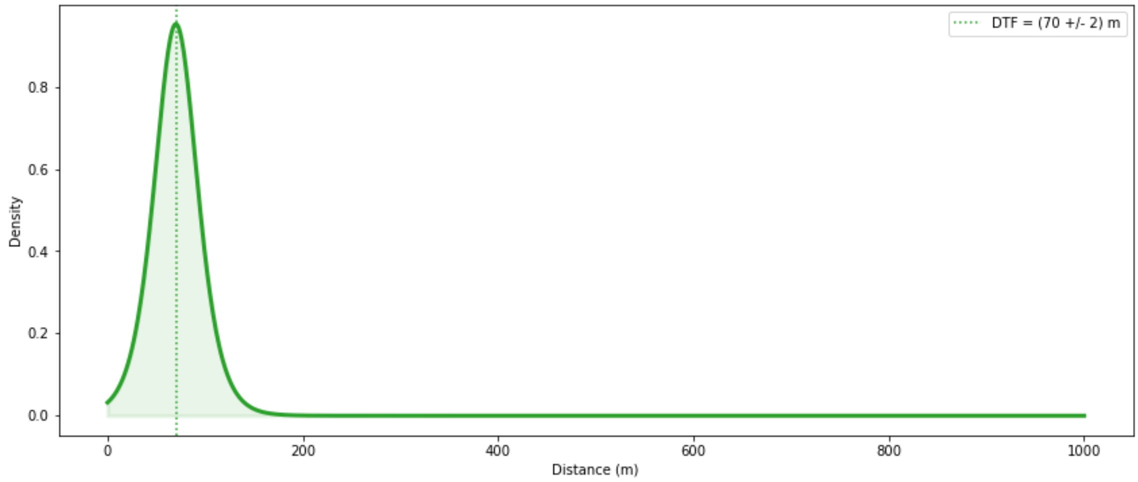


Fig: 9-6 Nottingham Road

9.5.6 Victoria Road, Bletchley, Feeder 3

This feeder developed a fault on 31/07/2021. The temporal evolution of this was significantly different from that of Nottingham Rd., feeder 2, being characterised by a number of high-current "bursts" of events around the following dates preceding the actual fault: 09/11/2020, 07/02/2021, 24/05/2021, 19/07/2021.

The analysis yielded a distance to fault of 91 m ± 5 m as shown by the green curve on Figure 9_7 below. We believe there is also a second fault on the cable (as shown by the orange curve) which is also starting to be detected

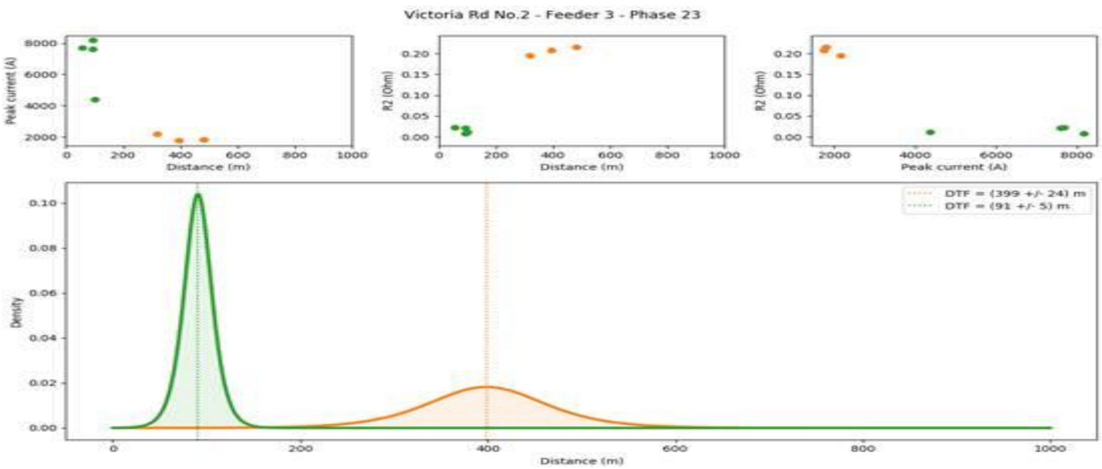


Fig: 9-7: Histogram for Victoria Road

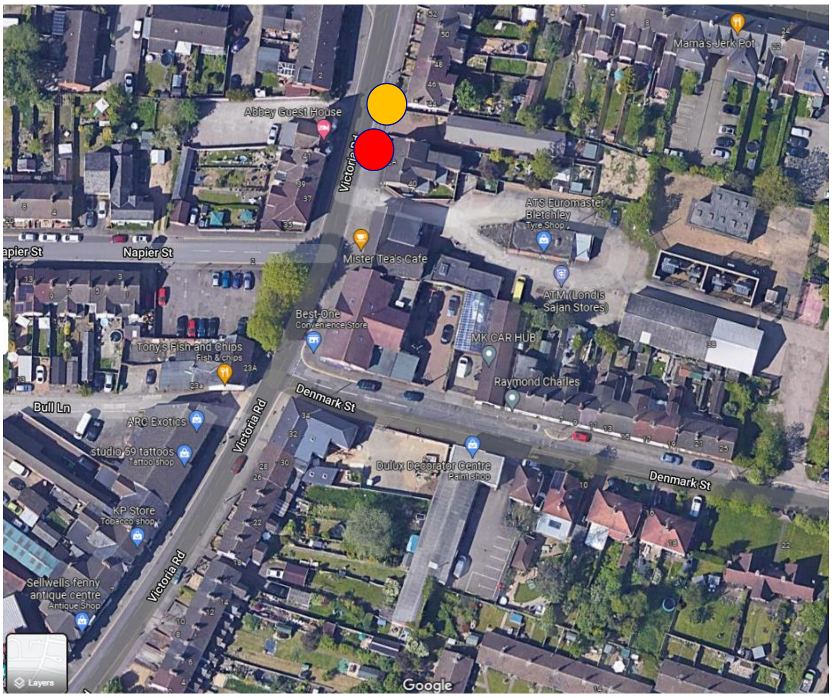


Fig: 9-8: Location of Fault in relation to ALARM system calculation

The actual fault was located at approximately 74 m from the substation.

The red dot in Fig 9-8 represents the actual fault location, while the yellow dot is the ALARM system prediction. The size of the dot is approximately the statistical uncertainty.

9.5.7 Summary

The verification of the distance to fault provided by the ALARM system was carried out by comparison with the fault locations reported by the repair teams when they were available. The overwhelming feedback from the teams was that the devices were able to accurately determine the location of a fault. However, we accept that the impact of the pandemic and the relatively few real life events means that more work should be done and this is our next step. We were encouraged though that the verification phase was able to prove the veracity of the findings.

Location	Fault date	Error
Gulson Rd, Feeder 1	18/04/2020	< 10 m
Rosemary Hill, Feeder 3	22/03/2020	c.13m
Ravenstone Rd, Feeder 2	13/07/2020	c. 18m
Nottingham Rd., Feeder 2	22/11/2020	10 m
Victoria Rd, Feeder 3	31/07/2021	17 m

Table 9-1: Error on various faults detected

9.6 TDR Verification Equipment

It was important to the team to carry out some verification of the results, in order to at least be able to determine the validity, other than by feedback from the teams. However, this validation with other industry tools was challenging and required experience to interpret the results and use. The Time Distance Reflectometry (TDR) systems when used correctly are able to provide extremely accurate fault location. Typically each TDR unit only monitors a single three phase feeder whereas the GridKey system was monitoring up to 6 feeders simultaneously. There was also a marked contrast between the simplicity of a GridKey system providing a distance and associated uncertainty and the TDR system that required a degree of skill and understanding to both locate the installed equipment correctly and also to interpret the results.

However, there was generally good agreement obtained in those instances where the TDR equipment was successfully deployed. The results from both Victoria Road and White Street have been encouraging with both locations being similar.

9.7 Ozone detection

It was planned to use a CableSniffer to detect the ozone generated when there was a pre-fault pecking event (i.e. the fuse had not operated) however, this was not generally successful. There were two reasons for this:

- Feedback from field crews was that even when there has been a fuse operation, the amount of ozone released is quite small so sometimes a sniffer will not detect the fault as the gas has dissipated quickly. These smaller arc faults produced even less ozone making it harder to detect.
- Lack of a good process to get location information to field crews fast enough before the gases from the arcing had dissipated.

Whilst ozone detection remains a useful tool it is recognised there are limitations especially when trying to locate pre-cursor faults (i.e. before the fuse has operated) due to the small amount of ozone being produced.

9.8 Making use of the location information

The true value of a fault location system is in connecting with maintenance and repair crews, either to enable proactive mitigation before an unplanned outage happens or to speed the process of restoration after a fuse operation.

9.8.1 Presentation of information

Engagement with the WPD team helped to change the representation of the statistics of fault location from a simple histogram based on frequency, to a smooth bell curve, to make the uncertainty of the distance calculations clearer. This bell curve presentation method also enabled potential multiple faults on the same feeder/phase to be shown more clearly.

The local teams use tablet computers to view their network maps. Ideally there would be further development of the mapping system to enable the distance to fault system to highlight predicted fault locations directly on these maps, including where there are multiple possible locations because of branches or links, reducing the time to positively identify the locations of the potential sites to investigate.

9.8.2 Alerting the local field teams

It is clear there needs to be a time efficient process to take the output of systems like the one used in this project and to alert the local fault teams. There are two categories of information – one that we can see a sudden escalation in the number of events which suggests there will soon be a fuse operation and the second to alert that a fuse has operated and provide any relevant information on location. Improving this process will allow the full value of this system to be realised.

10. The Outcomes of the Project

Three reports were produced throughout the project as follows:

Phase One Report

https://www.westernpower.co.uk/downloads-view-reciteme/595954

Results and Learning:

https://www.westernpower.co.uk/downloads-view-reciteme/595951

The Phase 2 detailed learning report can be found here:

https://www.westernpower.co.uk/downloads-view-reciteme/595948

Additional information is provided as well in Appendix 1 on the findings.

11. Data Access Details

Anonymised data will be available to share in accordance with WPD's data sharing policy:

https://www.westernpower.co.uk/innovation/contact-us-and-more/project-data

12. Foreground IPR

In outline, the relevant background IPR will include Lucy Electric GridKey's:

- locally installed monitoring equipment and Data Centre solution;
- the processing algorithm that generates the DtF indication; and
- the methods employed to automatically implement the algorithm to captured data
- GridKey Commercial Products
- GridKey MCU318 hardware and embedded software
- GridKey SlimSensor current sensors
- GridKey GridHound current sensors
- GridKey Flexi Rogowski sensors
- GridKey Passive Attenuation Board
- GridKey Active DTF board hardware and embedded software
- GridKey DTF algorithms and software
- GridKey Data Centre software

The purpose of the project was to test, refine and validate the existing DtF algorithm by using real data collected at WPD LV substations. Any updates to the DtF algorithm were funded by Lucy GridKey/Sentec.

Any relevant foreground IPR generated through this project was expected to relate to the results and findings on the live network trial (not the in-depth workings of the DtF algorithm) and was disseminated through the normal NIA reporting process. Any updates to the DtF algorithm, GridKey system or Data Centre were 100% funded by Lucy GridKey/Sentec.

13. Planned Implementation

The results from ALARM were sufficiently good that we are now looking to do some comparisons between the various technologies that are now on the market at some scale in order to determine which devices offer the best cost and capability fit within the business. We will be contrasting at least 2-3 devices over the coming year to see which serves the needs of the business best. Whilst because of the ongoing impact of the pandemic the trials were at times impacted, we were able to see enough anecdotal evidence that the DtF technology works and appears to offer business benefit. It is now incumbent on the business to verify which device has that balance in terms of function, integration and price. We are also looking at other devices tested by the other DNO's through a number of Innovation field trials.

14. Contact

Further details on this project can be made available from the following points of contact:

Email

wpdinnovation@nationalgrid.co.uk

Postal

Innovation Team

Western Power Distribution

Pegasus Business Park

Herald Way

Castle Donington

Derbyshire DE74 2TU

Glossary

Abbreviation	Term
ALARM	Automatic Location of faults through Remote Monitoring
CI	Customer Interruptions
CML	Customer Minutes Lost
DtF	Distance to Fault
LV	Low Voltage
MCU	Metrology and Communications Unit
TDR	Time Distance Reflectometry

Appendices

Appendix 1 Additional information on the outcomes seen

Phase 1

Phase 1 of the project was successfully completed, with pecking events captured on all of the 26 deployed monitors; these monitors were located in the East Midlands region. Credible locations for the location of the faults were developed for three sites, and validation work was undertaken for these sites. These indications were discussed with the appropriate local teams. DtF indications were also emerging for around 10 further feeders, and cautious indications were offered to local teams for some of these feeders on a “best information available” basis.

The installed monitors captured voltage and current waveforms from LV feeders when pre-set triggers were activated. The captured waveforms were then forwarded via a GPRS data connection to a data repository. The Phase One part of the project deployed equipment that successfully captured and stored thousands of events across the 26 deployed monitors, consistent with capability expectations of the Phase One installed equipment.

The captured data was processed and impedance values for the monitored network at the time of the event were estimated which were used to establish a distance to fault (DTF) estimate for an individual event. DTF estimates were established for all events conforming to a “pecking fault” characteristic, and an overall DTF assessment for a feeder was developed from this set of individual results. The feeder DTF assessments were manually translated to network positions on geographic maps.

A total of 7,990 pecking events (including single phase and phase-phase events) were analysed and 2,647 events were found to be good quality fits compared to the expected electrical behaviour of a feeder with a pecking fault. Some 77% of these 2,647 events occurred on 13 of the monitored feeders, these feeders all had 20 or more events per feeder.

Whilst the individual “fits” for events appeared good, variation existed in the resulting individual DTF indications for any particular feeder. Phase 2 of the project introduced enhanced waveform capture hardware, and the potential for reductions in the range of individual DtF results that form the feeder DtF assessment were examined.

Phase One achieved its fundamental aims of proving the data capture, collection and analysis concept, and informed the development of assessment processes that were further tested in Phase 2 of the project, when enhanced hardware became available as planned.

Phase 2 and Verification Phase

Phase 2 equipment was successfully deployed at 26 sites and in total, the programme collected and analysed in excess of 6500 pecking events. The verification phase was impacted by the pandemic and it would have been better to have been able to verify more sites but Victoria Road, Bletchley and White Street, Coventry provided enough evidence to suggest that the devices do function as envisaged.

Of the 26 sites monitored, two were very active in comparison to the rest, collecting over 50% of the total number of events recorded. A variety of different behaviours were observed, with some sites having regular activity and others with pecking events recorded only in limited time periods with sudden onset and/or cessation.

For some of the monitored substations, the analysis of the data is providing statistically reliable distance-to-fault (DTF) readings. Initial validation using Kehui devices at Fairfield Crescent and other sites was consistent with the ALARM DtF data.

Six of the monitored sites have had fuse operations. Some of these fuse blows were associated with permanent faults that required on-site work to restore normal operation. In one case, (Nottingham Rd) the DtF indication matched the location of the fault found by the local team. At Gulson Rd, although there were only a few events detected prior to the fuse operation, the DTF data was found to be pointing at the correct location. In other cases, because the equipment has not been installed for an extended period, very few or zero pecking events were available therefore no distance indication could be provided.

When pecking events are recorded by the DTF system on a specific phase and feeder, the distance for each event is calculated and common distances counted. A histogram is then generated showing the frequency of events at each distance recorded. The peak of the histogram shows the most likely distance to the cause of the events with the remaining events spreading either side of the peak.

An improvement in the spread of the DTF indications after switching to Phase 2 hardware was observed on Fairefield Crescent, leading to a smaller statistical uncertainty in the location. On Victoria Rd., where a particularly broad distribution was observed, the standard deviation of the data did not improve with Phase 2 hardware, suggesting that the spread does not depend on the accuracy of the hardware. Even in this case, the ability of the DTF boards to capture more waveforms significantly reduces the statistical uncertainty on the fault location. In the case of Victoria Road, the distance error was reduced from 10m to 5.5m demonstrating a significant benefit using the active DtF board.

Additional investigations will be carried out to understand the variability observed in the DTF estimates as part of the follow on work within the business.

14.1 Verification Phase

Whilst the overarching objective of using Kehui T-P23 LV Fault Locators to validate the calculated distance to fault information derived from analysis of GridKey data was not fully achieved due to difficulties associated with Covid19 procedures and other operational factors, there were some useful indicators in the latter stages based on some coordinated site visits with both KEHUI, Lucy GridKey and WPD on site and subsequent data collection.

The T-P23 units captured many ‘transitory’ fault disturbances which were automatically reported to the dedicated iHost server. Listings of the triggers reported from the 4 circuits on which T-P23 were installed: Fairefield Crescent, White Street, Victoria Road and Paddock Way are available on request.

14.1.1 Fairefield Way

This circuit was monitored from a distribution cabinet adjacent to the T & D building of Glenfield Hospital which showed multiple Y phase transitory faults occurring several times per day for over a period of a year which were suspected to be on a single phase service to an abandoned street lamp. All these disturbances had the characteristic LV non-linear ‘arcing’ voltage dip on one or more consecutive cycles within the 200mS record length of the T-P23. Unfortunately, the opportunity to confirm the location was lost after the suspect branch was disconnected when the Y phase disturbance ‘disappeared’. From August 2021 there was a R phase disturbances showing the characteristic quarter cycle dip due to a transitory LV cable fault elsewhere on the system.

Diagram 10-1: Extract of iHost reporting page for Fairefield

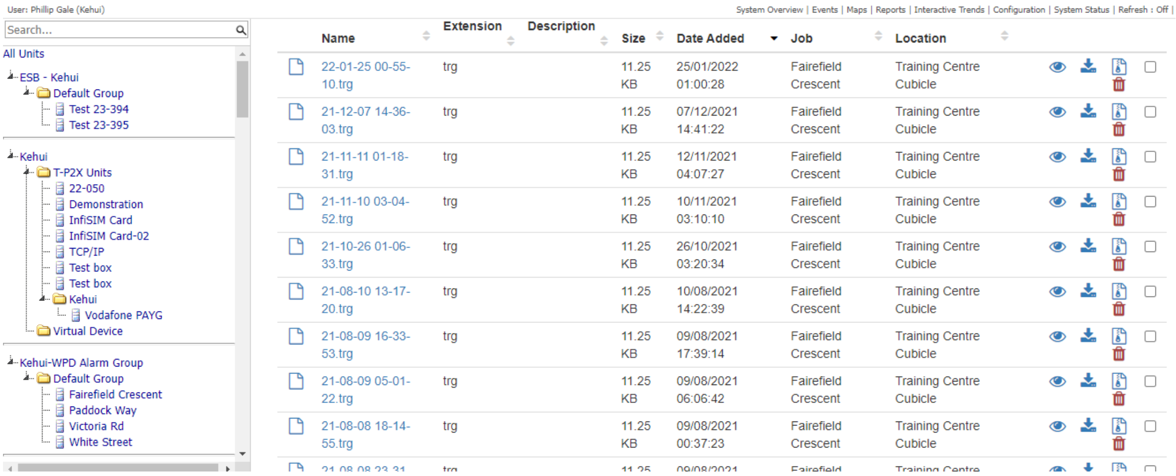


Diagram 10-2: Frequently occurring transient Y phase fault

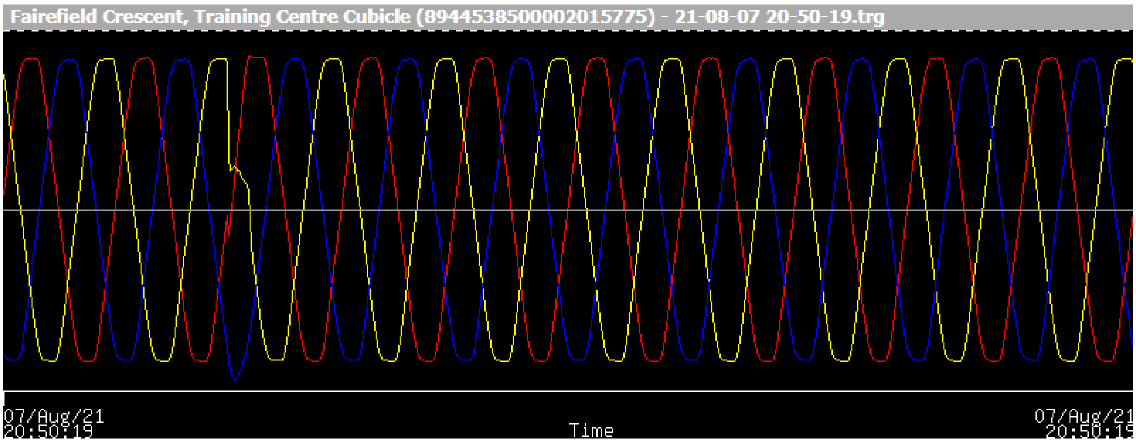


Diagram 10-3: Occasional multi cycle duration transient Y Phase fault

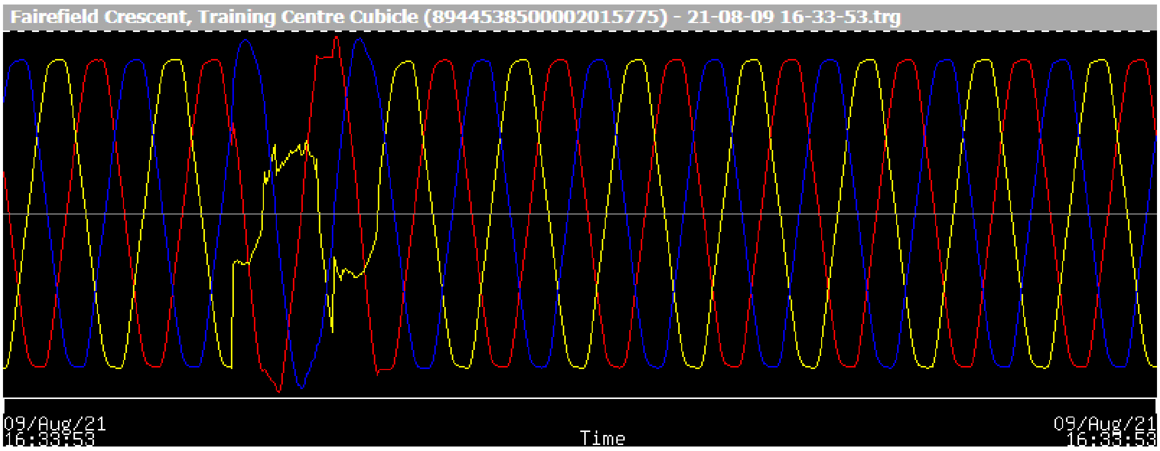
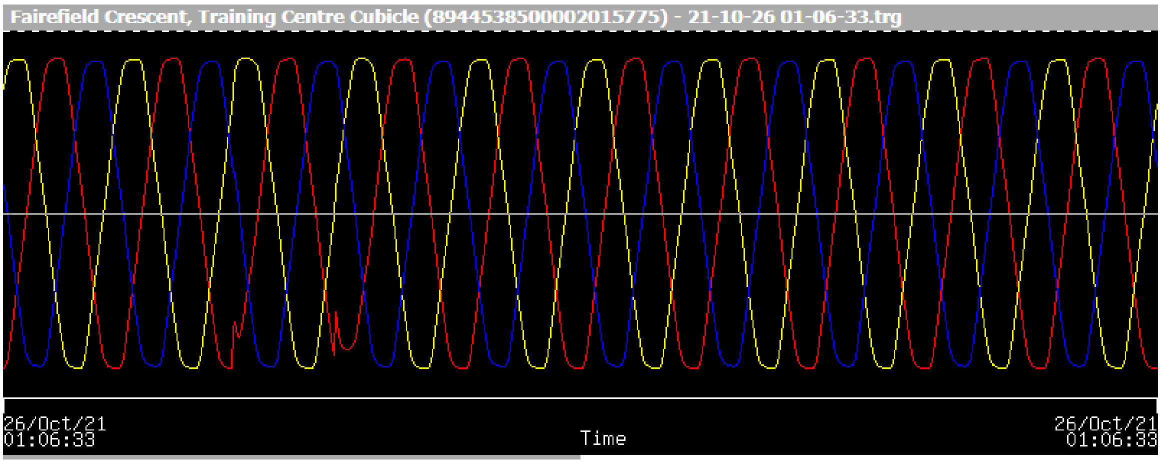


Diagram 10-4: Transient R phase fault elsewhere on system after removal of branch supplying old streetlamp



14.1.2 White Street

The T-P23 installed on this circuit captured 43 event triggers over a 3 month period, examples of which are shown below. These correlated well to the data seen from the Lucy GridKey devices:

Diagram 10-5: Example of close-up R phase transitory fault showing constant 'arc' voltage drop

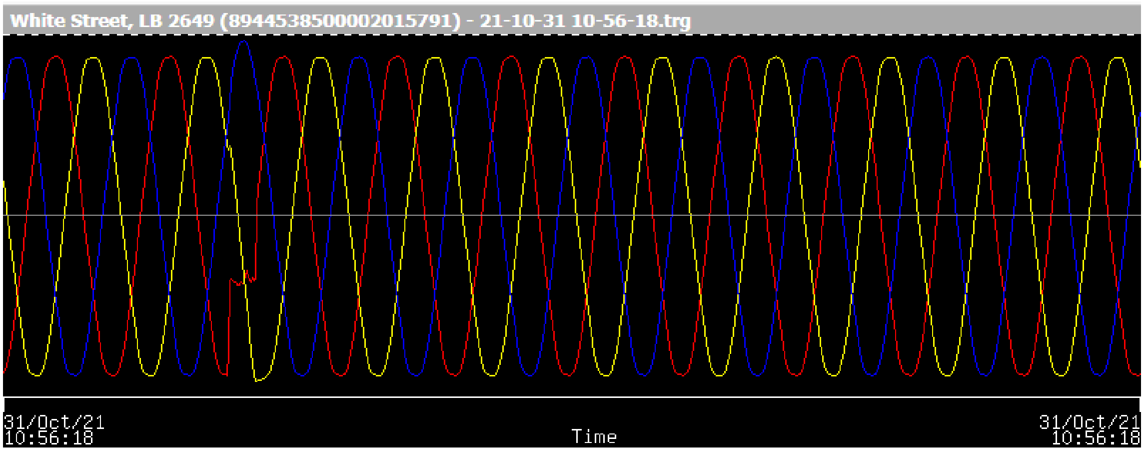


Diagram 10-6 Example of close-up R-Y phase transitory fault

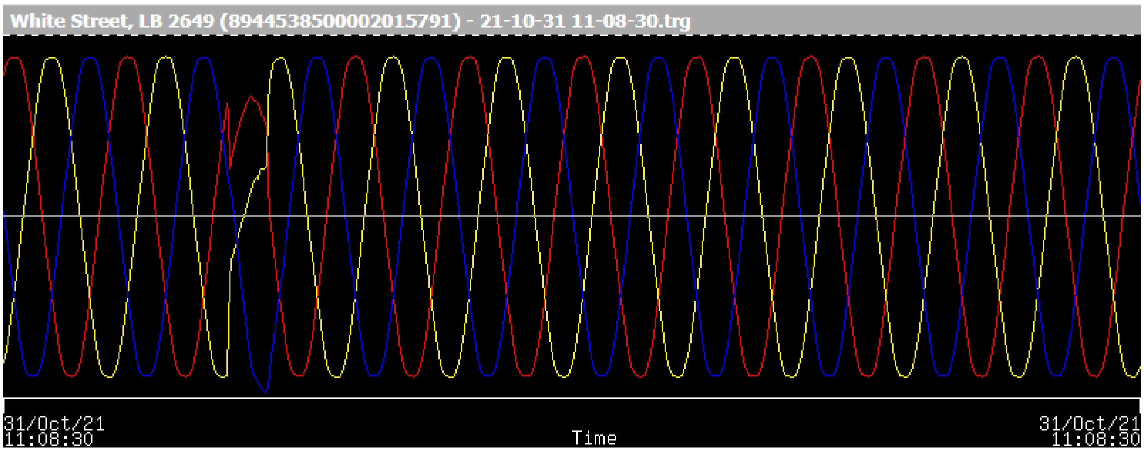
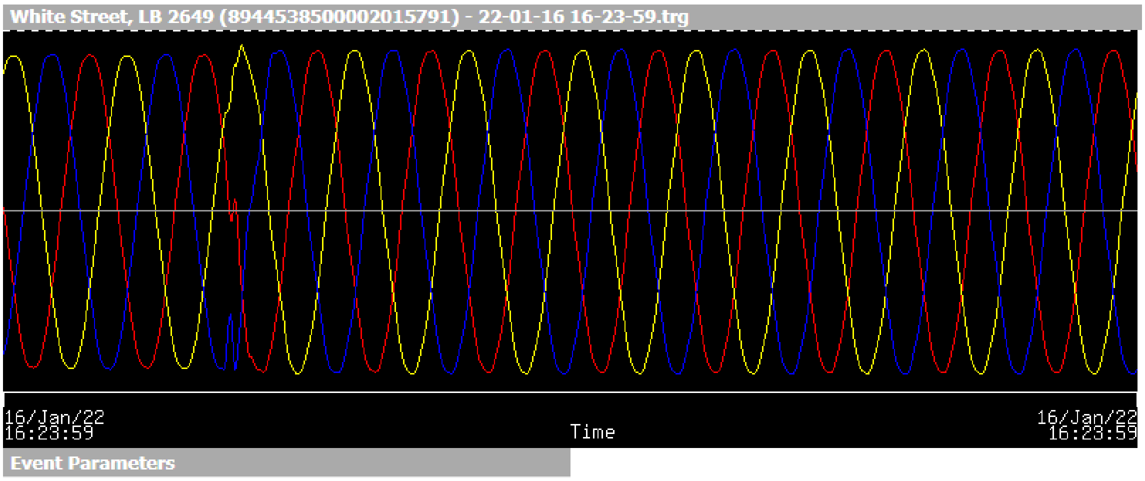


Diagram 10-7: Recent disturbance due to switching of 3 phase load



Victoria Road & Paddock Way

The T-P23 installed on this circuit has captured 53 event triggers over a 6 month period, examples of which are shown below. . These correlated well to the data seen from the Lucy GridKey devices:

Diagram 10-8 Transitory Y phase fault some distance away from substation

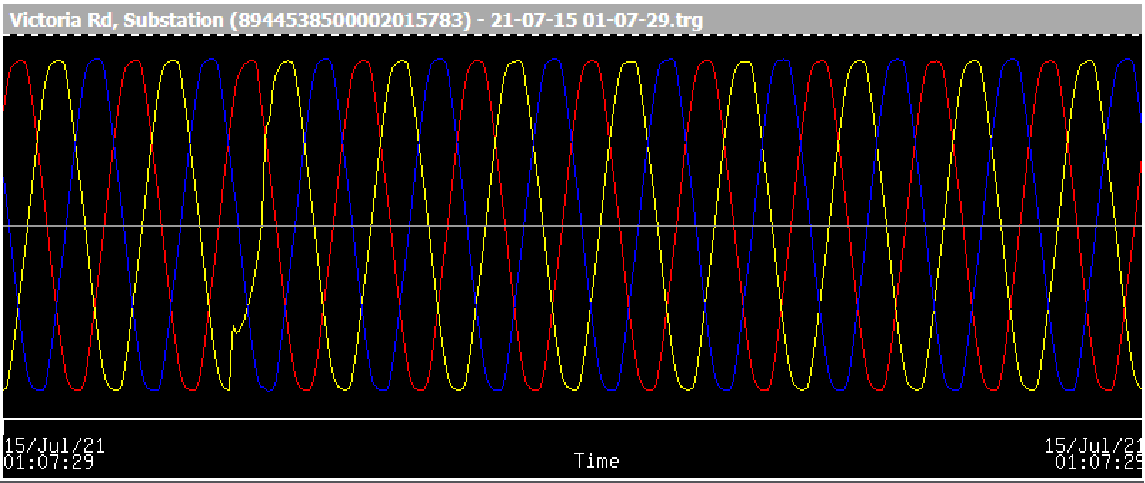


Diagram 10-09: Transitory unstable Y-B phase fault some distance away from substation

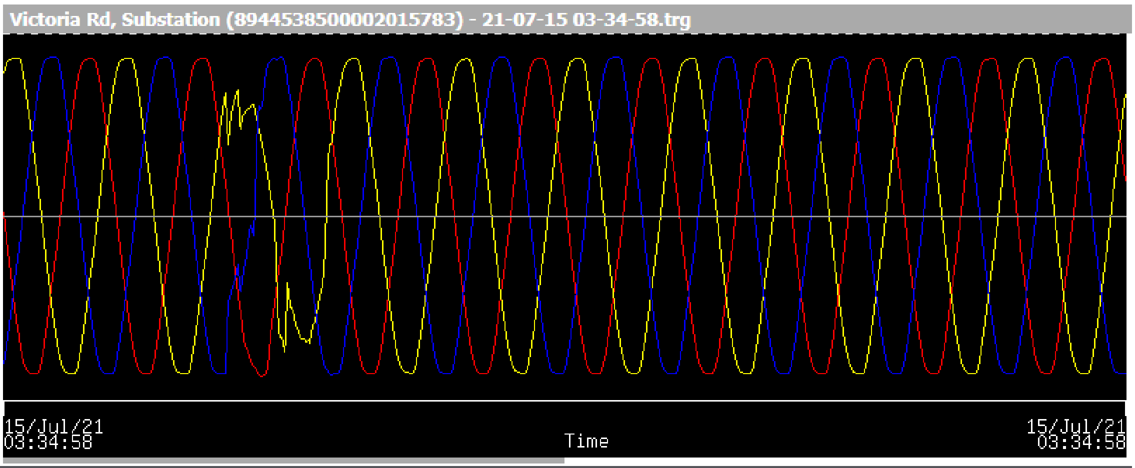


Diagram 10-10-11: Transitory stable Y-B phase fault some distance away from substation

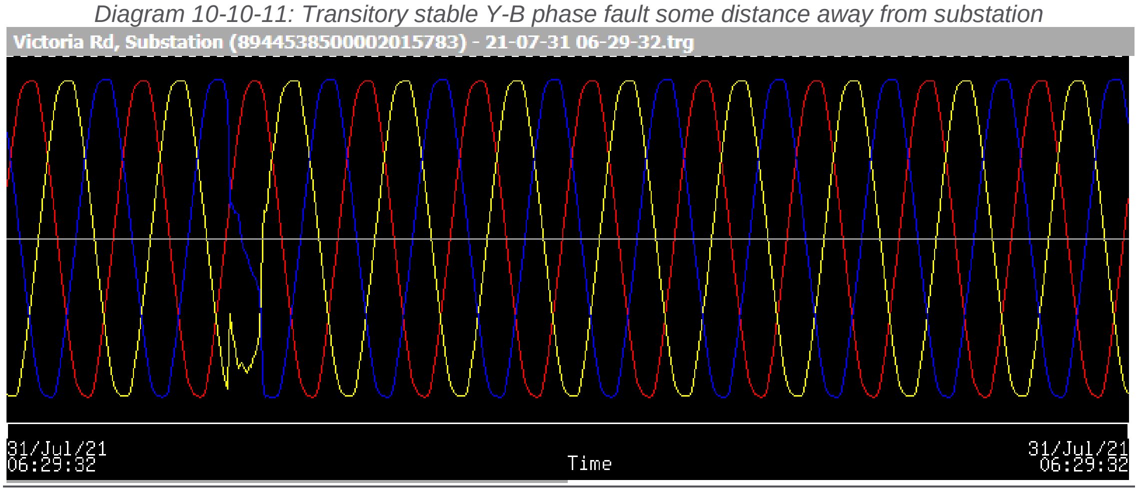
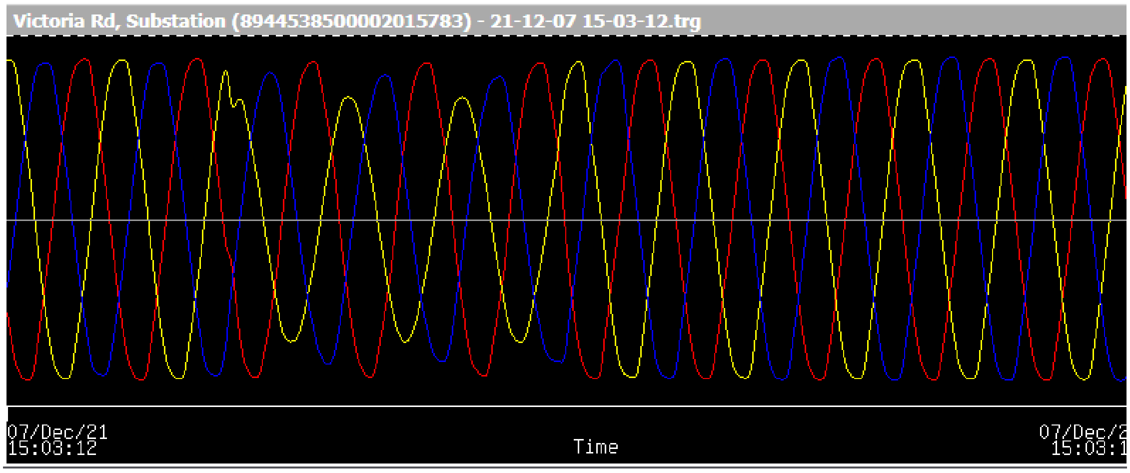


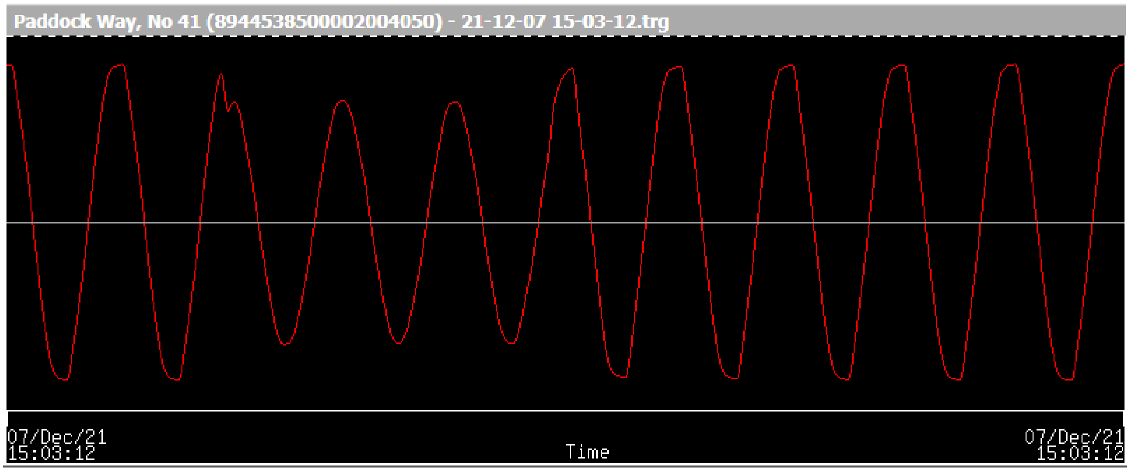
Diagram 10-11Transitory HV system fault on Y phase



14.1.3 Paddock Way

This unit was connected to a single phase consumer cut-out early in December and collected 6 triggers, the earliest of which corresponds to the Y phase HV trigger at Victoria Road, where we had installed the GridKey unit.

Diagram 10-12 Transitory HV system fault on Y phase



Broadly the verification had some success despite the challenges of the pandemic with verification of activity at Fairefield Crescent, Victoria Road and Paddock Way and White Street.

Registered Office: Avonbank, Feeder Road, Bristol BS2 0TB
nationalgrid.co.uk